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A Portable Wireless Particulate Sensor System for Continuous Real-Time Environmental Monitoring

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Airborne particulate matter has been shown to be associated with morbidity and mortality, and may interfere with certain sensitive experiment. Understanding the levels and movements of particulate matter in an enclosed space can lead to a reduction in the impact of this material on health and experimental results. A system of environmental sensors including particulate matter, selected gasses, humidity, temperature, and pressure can be used to assist in tracking air movement, providing real-time mapping of potential contaminants as they move through a space. In this paper we present a system that is capable of sensing these environmental factors, collecting data from multiple dispersed nodes and presenting the aggregated information in real-time. The highly modular system is based on a flexible and scalable framework developed for use in aircraft cabin environments. Use of this framework enables the deployment of a custom suite of sensors with minimal development effort. Individual nodes communicate using a self-organizing mesh network and can be powered from a variety of sources, bringing a high level of flexibility in the arrangement and distribution of the sensor array. Sensor data is transmitted to a coordinator node, which then passes the time-correlated information to a server-hosted database through a choice of wired or wireless networks. Presentation software is used to either monitor the real-time data stream, or to extract records of interest from the database. A reference implementation has been created for the National Institutes of Health consisting of a custom optical particle counter and off-the-shelf sensors for CO_2, CO, temperature, humidity, pressure, and acoustic noise. The total environmental sensing system provides continuous, real-time data in a readable format that can be used to analyze ambient air for events of interest.

I. Introduction

Wireless sensor network (WSN) research for environmental monitoring has taken off in the last decade. The convergence of improvements in sensor, battery, and semiconductor technology has made the design and deployment of these networks feasible. Sensor technology for measuring environmental factors such as gas concentrations, pressure, humidity, and temperature are all readily available in small form factors and for reasonable prices. One key factor in environmental air quality missing from this suite is a real-time particulate matter sensor.

Airborne particulate matter consists of chemically and physically diverse solid or liquid particles suspended in the air. Particulate matter exists as discrete particles, and originates from a variety of natural and man-made sources. The particles may be emitted directly from a primary source through a chemical or physical process, or may form from the transformation of secondary components such as sulfur oxides, nitrogen oxides, or volatile organic compounds[1]. Natural sources include bacteria, pollen, fungal spores, plant and animal debris, dust, and ash. Man-made sources include combustion by-products from the burning of wood and fossil fuels, tobacco smoke, cooking exhaust, and cleaning activities[1–3].

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Particulate matter has long been studied in an attempt to gain a better understanding of its effects on human health. A significant number of studies conducted over the last several decades suggest connections between concentrations of ambient particulate matter and increases in morbidity and mortality, including potential connections with chronic obstructive pulmonary disease (COPD) and Asthma[4–6]. In the United States, it is estimated that 22,000 – 55,000 deaths per year are caused by particulate matter[7]. Short-term increases in particulate matter concentration have been shown to correlate with increases of 1-8% in deaths per $50\mu g/m^3$ increase in outdoor particulate concentration[8]. Recent studies also suggest that reducing long-term exposure to particulate air pollution can increase life expectancy[9].

In the United States, the Clean Air Act of 1970 authorized the establishment of the National Ambient Air Quality Standards (NAAQS). These standards for outdoor air quality are set and regulated by the United States Environmental Protection Agency, which actively monitors particulate matter for compliance across the country. In 1987 the EPA introduced regulations on particulate matter with diameters less than 10µm, termed PM_{10}. Particles of this size are commonly referred to as "thoracic particles", in that they may travel past the larynx to reach the lung airways. Smaller particles that may reach the gas-exchange regions of the lungs are commonly referred to as "respirable particles." Evidence of serious health effects associated with exposures to respirable particles with diameters less than 2.5µm prompted the EPA to introduce additional regulations in 1997[1]. The new regulations defined a category for these particles termed $PM_{2.5}$, and set distinct limits for their concentration.

The EPA does not currently regulate indoor air quality. The American Conference of Governmental Industrial Hygienists (ACGIH) has established sampling conventions and recommendations for exposure levels in industrial settings[10], but these are not typically applied in residential or office environments. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) publishes standards for building ventilation with the intent of maintaining acceptable air quality[11], but these are not federally mandated in the U.S.

The lack of emphasis on indoor air quality may seem ironic given that most people in the U.S. spend 90% or more of their time indoors[12], resulting in a greater exposure to indoor particulate matter than direct exposure to outdoor levels[13]. When indoor sources of particles are not present, indoor levels of particulate matter tend to show similar behavior over time as outdoor levels. However, when indoor sources are active, the correlation no longer exists, making it impossible to estimate indoor levels from outdoor measurements[14]. In short, depending solely on outdoor measurements may be misleading in determining personal levels of particulate matter exposure.

Particulate matter can also have a significant impact on sensitive property and industrial, experimental, and medical processes, and is much studied in terms of particle deposition onto sensitive surfaces[15]. For example, particle deposition onto the reflective surfaces of sensitive optical equipment can degrade the images produced[15]. Particulate matter in semiconductor manufacturing can greatly impact process yield since circuit feature sizes can be much smaller than suspended particulate[16]. Elemental carbon particles in the form of soot can produce perceptible soiling of museum artwork over time frames that are relatively short in relation to the desired lifetime of the art[17]. Particulate in medical operating theatres has the potential for negative health impacts on both the patient and the operating staff[18].

While sensors for measuring real-time particulate matter concentrations have been available for decades, most of the commercially available devices have serious drawbacks for incorporation in a WSN. These devices tend to be relatively large, with even the smallest units being just small enough to wear somewhat uncomfortably on a belt. They are also intended for use as stand-alone units, and are generally not appropriate for integration within other compact devices. Most of the devices are also fairly expensive, with typical starting prices greater than two thousand U.S. dollars. These factors can make it difficult to include multiple devices into an environmental study, and prohibit the inclusion of a particulate matter sensor in each wireless sensor node.

In this paper we present a WSN design that incorporates a low-cost implementation of a particulate matter sensor. The following sections discuss the applications for particulate matter WSNs (Section II), previous work relating to this topic (Section III), overall system design (Section IV), WSN design (Section V), sensor node design (Section VI), visualization and sever software (Section VII), and test data from our reference system (Section VIII).

II. Particulate Exposure and Wireless Sensor Networks

The creation of a WSN that includes particulate matter sensors opens many possibilities for new applications that provide benefits spanning areas from health and wellness to material concerns. In this section we discuss a few of these potential applications.

The impact of particulate matter on individual human health is perhaps one of the most compelling arguments for understanding exposure. Most individuals have access only to outdoor air quality data provided by government agencies such as the EPA. While the outdoor air quality is important, the general lack of correlation between

outdoor and personal exposure makes reliance on this data problematic. For individuals suffering from health problems such as COPD, asthma or severe allergies, understanding personal exposure to particulate matter can lead to improvements in quality of life and even increases in life expectancy. A set of particulate matter sensors installed in a personal space has the potential to help identify and control particulate sources, leading to the improvement in air quality experienced by the individual.

Even for individuals without health problems, raising awareness of personal air quality can have long term benefits. Providing effective tools for visualization of air quality can lead to action that benefits the individual and those nearby[19]. A WSN that monitors air quality, along with the appropriate visualization hardware and software has the potential to positively affect human behavior. For example, a smoker may not fully understand the impact that this activity has on others. Providing information about the quantity of particulate generated from smoking could help the person alter their behavior to the benefit of those around them.

Many studies that include the measurement of personal particulate matter concentrations rely on single measurements within a space with the assumption that the introduction of new particulate matter will quickly equalize. This assumption may not always hold true, since local concentrations of particulate matter can take minutes to disperse depending on airflow and features in the room[20]. A WSN containing particulate matter sensors would enable further studies of dynamic particulate matter movement within personal spaces, helping to track contaminants and identify locations where particulate matter concentrations might reach levels that could negatively impact health. For example, there has been recent interest in understanding diesel particulate matter exposures of children on school buses[21]. Outfitting a school bus with such a WSN could indicate how particulate matter enters the bus and where it lingers, and sensor nodes positioned near the bus entrance could show levels for children waiting to board the bus. The information gained could help identify countermeasures for controlling exposure.

The investigation of airborne contaminant movement within the highly dynamic environments of aircraft cabins has been facilitated by the use of WSNs. Past studies have deployed WSNs containing suites of gas and other environmental sensors[22]. The addition of a particulate matter sensor to this set would provide another important environmental factor determining the air quality of an aircraft cabin. For example, there is significant interest in the measurement of the microbial content of cabin air[23]. A particulate matter sensing WSN would aid in the understanding of the movement and concentrations of these and other particulates in the aircraft environment.

Electronic equipment failures can cause significant loss in productivity, which can multiply when not quickly discovered. Equipment failures may cause at least partial oxidization of components, which could be detected by particulate matter sensors local to the area. A particulate matter sensor equipped WSN could potentially detect increases in particulate released by the oxidization of a component, providing an early failure warning. This could be particularly useful in large data centers commonly built for today's cloud computing needs. A WSN installed in such a facility could help pinpoint equipment failures and increase the uptime of equipment.

The quest for energy efficient homes has led to improvements in insulation to minimize heat and air exchange with the outside environment. Unfortunately, this can have the undesired impact of not allowing fresh air to naturally infiltrate the building and dilute indoor pollutants. In these newer buildings, mechanical ventilation may be required to bring in fresh air[11]. Work has been done on intelligent systems that take advantage of the difference between indoor and outdoor air to cool a home[24]. Future smart homes may include the additional ability to detect air quality both inside and outside the home, to determine when to perform an air exchange or when to circulate the indoor air through filtering. Affordable particulate matter and gas sensing WSNs can help to enable this vision.

III. Previous Work

One might say that the measurement of airborne particulate matter has been performed since early humans first noticed the haze from dust and smoke. Equipment specifically designed for this purpose has been developed that employs multiple methods with various tradeoffs for each. The U.S. federal reference method (FRM) for sampling PM_{10} and $PM_{2.5}$ involves inertial particle size separation, capture on a filter, and weighing the filter before and after sampling to determine the mass gain[25]. This method is capable of providing very good mass measurement but does not provide real-time data. Other mass measurement methods such as the Tapered Element Oscillating Microbalance (TEOM)[26] can provide more timely data but are typically large and must use a selective input to resolve particle size.

Devices using optical methods to measure particulate matter can be split into two main categories: those that operate on the scattering and extinction of light from single particles, and those that operate on the scattering and extinction of light from an ensemble of particles[27]. Devices operating on an ensemble of particles are typically unable to resolve particle size. Single particle devices are commonly referred to as optical particle counters (OPCs). These devices operate by illuminating a sample volume with intense light, where particles intersecting the light will

scatter some portion of the light. The scattered light is sampled with a photodetector, producing a signal that can be analyzed to detect particles. This technology has been developed for multiple decades, with many commercial devices available or described in patents [28,29]. Most of these devices are relatively expensive and have form factor limitations that make them impractical for inclusion in a WSN. A low-cost optical particle counter is available from Dylos Corporation[30], but this unit is also relatively large and does not include networking capabilities.

Several new technologies of interest that are under development have the potential to reduce both cost and size of currently available equipment. These include thin-film bulk acoustic wave resonator (FBAR)[31] and MEMS resonator[32] particulate sensors. These technologies may be of significant interest in future developments of particulate matter sensing WSNs.

At the time of writing, the authors are unaware of any other wireless sensor network systems that integrate particulate matter sensors.

IV. Sensor System

The sensor system incorporates many parts to create an entire solution, including sensor nodes taking environmental measurements, communications infrastructure to relay the measurement information, storage for measurement data, and methods for representing the collected information to the end user. Each of these pieces must work together to achieve the sensor system's mission. At the highest level, this mission is to simplify the collection of high-quality environmental data from a distributed set of points and present it to the user in an understandable form.

Figure 1 shows an example deployment of our sensor system. There are many possible deployments, with multiple wireless mesh networks connected in several different ways to either a database server or an end user's computer. In the example arrangement, three WSNs are attached to the Internet. WSN-A connects to the Internet through a serial connection to a PC, WSN-B through a Wi-Fi access point, and WSN-C through a GSM connection to the cellular network. In the first case, the sensor data from the WSN is passed from the coordinator to the PC which is running software to pass the sensor data on to the database server through the Internet. In the second case,
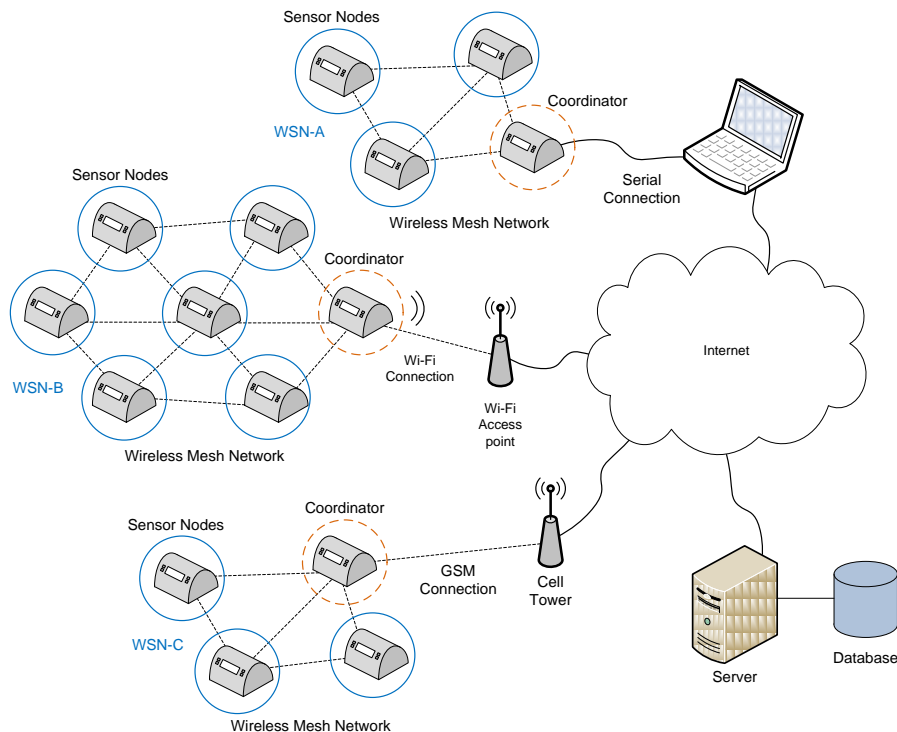
Figure 1. Sensor system diagram. *Three wireless sensor mesh networks are shown, each connected to a server through a different path. WSN-A connects through a serial link to a PC, then to the server through the Internet. WSN-B connects to the server through the Internet using Wi-Fi. WSN-C connects to the server through the Internet using a GSM modem. Sensor data is stored in a database at the server.*

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the WSN connects directly to the Internet through its Wi-Fi connection to a local access point and sends its data directly to the database server. Alternatively, the server does not need to be used at all. Data may be passed directly to an end user's PC for viewing with the appropriate visualization software. Data may also be collected only on the end nodes with no transmission, and retrieved from each sensor's local storage at a later time to be merged into a single view.

A goal not explicitly stated in the system mission has to do with cost. When designing research systems, focusing on component cost often may not be the first priority. However, in the case of the particulate matter sensor, this is one of the more important goals. Some of the components used would not typically be chosen to produce the highest quality results. Working around the resulting issues with a low-cost design contributes to the uniqueness of the solution.

Much of the work in building the reference system described here came about as part of a project for the National Institutes of Health, associated with its National Children's Study. This project involved the creation of the In-Home Air Quality (IHAQ) monitor, a sensor system for measuring several environmental factors in a residential home. While this project did not require the inclusion of a WSN, it did specify the need for a particulate matter sensor, gas and other sensors, and much of the framework required to build the described system.

V. Wireless Sensor Network

Many advantages are gained by connecting multiple sensor nodes together with a network. Perhaps of most interest is the ability to provide temporal and spatial aspects to data collection. Linking the multiple nodes can provide much information regarding the environment that cannot be learned with a single sensor. For instance, one might wish to know how quickly particulate matter moves from an indoor source to a room on the other end of the building.

Multiple options exist for building a wireless sensor network[33], including using standards-based implementations or creating a custom network. A standards-based implementation brings many benefits, including behaviors that are typically well defined and tested as well as off-the-shelf hardware and software support. For our WSN implementation, we have chosen to use the ZigBee/IEEE 802.15.4 standards which define a robust, low-power wireless mesh networking solution. Mesh configurations in particular have the benefit of not requiring all nodes to be within communication range of the final destination (coordinator) node of the WSN. This can allow very complex and distributed sensor deployment topologies that cover large areas. Several functions built on top of the WSN allow our sensor system to meet some of its critical goals, including flexible data delivery mechanisms and time synchronization.

Within a WSN, the flow of sensor data often moves from the sensor nodes across one or more wireless hops to a single coordinator node acting as a data sink. The IHAQ sensor nodes implement a network layer on top of the WSN that performs best effort delivery with a relatively small amount of buffering. The buffering is intended to handle limited periods of disruption or congestion. The IHAQ network layer creates a virtual socket interface between a sensor node and the coordinator. This allows the coordinator to recognize and manage the connections to multiple sensor nodes, and provides a framework for reliable delivery.

For visualization and long-term storage, the data must be delivered from the WSN to a device capable of these functions, typically a personal computer or server. Transferring the data out of the WSN is the responsibility of the coordinator node. For an IHAQ node, multiple options are available for connecting the WSN to the outside world. The IHAQ coordinator can use USB or a serial port for a wired connection with a PC or server. An 802.11g module may be installed for direct connection to a local wireless access point. If no local Internet connection is available, a GSM data modem can be used to connect into the cell network. When no wired or wireless connection exists or if communication is interrupted, each node may store its data on a local SD card for later retrieval.

A key aspect of any WSN is the ability to temporally correlate measurements between nodes. Each measurement must be time stamped in some way to indicate its location in the data chronology. A local time can be maintained at each node through the use of a time-of-day clock, but these will drift over time without synchronization. Many well-tested clock synchronization algorithms are already in existence and can produce very good results[33]. The IHAQ sensor system currently synchronizes times by simply pushing the time out to the sensor nodes from a coordinator unit. For relatively small test deployments, this method has typically resulted in synchronization with sub-second accuracy. This algorithm will be modified in the future to provide more accurate and consistent synchronization.

VI. Sensor Node

The IHAQ sensor node was designed to operate both as a standalone unit and as part of the larger sensor system. As such, it has components that may not be typically seen in a WSN. In particular, each sensor node has a liquid

crystal (LCD) display for viewing current measurement data. While this adds to the cost of each sensor node, it can be seen as a superset of the functionality required for any given implementation of a sensor node. Future implementations may include sensor nodes that have only a subset of the functionality of the current design, omitting the unnecessary sensors and components as the application allows. Figure 2 shows a picture of one of the sensor nodes in operation along with the dimensions of the unit.

A. Sensor Node Hardware

The major electronic components of the sensor node hardware are the processor, communication, data storage, user interface, and power management. While each component is critical to the operation of the sensor node, the processor choice stands out due to its broad impact to system performance and development. There are many microcontrollers available today with relatively high performance, low power consumption,

Figure 2. In-Home Air Quality Monitor. *The monitor measures 150x150x115 cm and weighs 700g.*

and rich peripheral integration, making this class of device a good choice for the main processor in a WSN node.

The processor used to control the IHAQ sensor node is an Atmel AVR32UC3A3256S 32-bit microcontroller, which contains a RISC CPU that is capable of 1.51 Dhrystone MIPs per MHz[34]. The part includes 256 kB of Flash, 128 kB of SRAM, and many other integrated features. This particular microcontroller was chosen due to its many internal peripherals, relatively large internal memories, good performance/power ratio, and available software framework. This feature set allows a large portion of the sensor system to be implemented with the microcontroller alone.

Communication of sensor measurements and status information is a critical function of any sensor network. For the sensor node design, multiple communication options have been provided for both wired and wireless connection. All sensor nodes are configured with a UART connection, a USB port, and a ZigBee radio. Coordinator nodes may also be configured with either an 802.11b/g Wi-Fi transceiver or a cell modem, enabling remote data collection and the extension of the sensor network beyond a single ZigBee mesh.

Many sensor deployment situations require the integrity of data regardless of the state of the communication connections. A sensor node's connection to the rest of the system may be lost or interrupted, leading to the loss of transmitted data that may be critical to the application. For this reason, all sensor nodes are equipped with local data storage in the form of an SD card slot. With the current availability of relatively low cost multiple-gigabyte SD cards, a significant number of measurements can be stored directly on the sensor node.

As previously mentioned, visualization can be a key component in modifying human behavior. Often, sensor nodes will provide little in the way of visual feedback to indicate the sensor measurement values. Early prototypes of the sensor node provided little in the way of direct visual feedback to indicate their status, and gave no indication of the sensor measurement values. To improve on this situation, the current version of the sensor node implements a backlit LCD panel that can give indication of multiple sensor values simultaneously.

The design goals for the sensor node dictated that the device be able to run in stationary positions for extended periods of time, and in mobile environments for short periods of time. With this in mind, the sensor node was designed to run off of either an external wall transformer or an internal 1400 mAh rechargeable battery. The sensor node consumes approximately 1.3 Watts of power when operating with sensors and the ZigBee network active. With a full charge, the unit can run for up to 8 hours from the internal battery.

B. Optical Particle Counter

The goal of the optical particle counter design was to create an inexpensive implementation that provides results similar to those of commercial particle counters. As previously mentioned, achieving these goals potentially opens up many applications for particle counting that are not obtainable with devices that can cost thousands of dollars each.

The optical particle counter design operates on the principles of Mie scattering, wherein a single particle intersecting a beam of light scatters photons onto an optical sensor[27]. The optical sensor converts the photons into a measurable signal, which is analyzed to determine the particle size. The amount of light received at the sensor will

be dependent on the particle size, shape, and index of refraction. Since the shape and index of refraction of each particle may not be known, optical particle counting in uncontrolled environments contains some inherent uncertainty in measuring particle size. The count of particles in each size range is divided by the volume airflow through the measurement area to determine the particle concentration.

1. Laser Module

Several challenges exist in designing a particle counter for low cost. Since the intensity of scattered light decreases with decreasing particle size, a high intensity light source is desired to detect small particles. Unfortunately, increasing the power output of a laser typically also increases the cost. From a cost standpoint, we would ideally like to use the cheapest lasers, which are typically found in the near ubiquitous red laser pointers. These devices have the additional advantage of being relatively small to fit inside a thin pen or even on a keychain. Unfortunately for our purpose, the power output is relatively low.

Most of the least expensive lasers have a fixed collimated focus for use as a pointer, but some lasers of this class can be purchased with an adjustable focus. This allows us to concentrate the light on a smaller focal point, increasing the local intensity in a smaller measurement space. Though it does decrease the overall sampling area, it allows the detection of small particles that cannot be detected with a low power collimated beam.

2. Particle Counter Electronics

The IHAQ particle counter creates an airflow using a simple DC fan. This airflow is pulled across a large-area photodiode. A low-cost 3mW, 650nm laser assembly is used to generate a beam that is focused to a narrow point just above the photodiode, intersecting the airflow. A portion of the photons scattered from particles intercepted by the beam will reach the photodiode, which covers a solid angle of 1.2 steradians as measured from the optimal position of the laser focal point in the channel.

Current from light reaching the photodiode is converted to a voltage using a high-gain transimpedance amplifier. Two second-stage amplifier channels are fed from the transimpedance amplifier. The first channel has a high gain for detection of small pulses, corresponding to small particles. Since this channel may saturate for bright pulses caused by large particles, a second, low gain channel is provided to extend the range of measurable large particle sizes.

The two particle counter amplifier channels are connected directly to two analog-to-digital converter inputs on the sensor node's microcontroller. The microcontroller contains just a single analog-to-digital converter, but it can automatically switch up to eight inputs into the converter. The two inputs are read repeatedly by the analog-to-digital converter at 50,000 samples per second and a direct memory access (DMA) channel is used to move the samples into main memory, freeing the processor from most of the transaction overhead.

3. Airflow and Optical Path Design

The airflow and optical path are shown in Figure 3. Air enters the sensor from the flow inlet, moves past the laser and photodiode, and exits through the outlet fan area. The fan is not shown in the drawing, normally fitting into the outlet fan area. The laser light passes the photodiode and enters the light trap area where it is absorbed.

In order for the particle counter to make accurate measurements, the airflow channel was designed around the sensor that allows for a consistent, smooth flow of air. Using the ANSYS computer software suite FLUENT, computational fluid dynamics (CFD) analyses were conducted to optimize this flow channel. Due to the size constraints of the monitor, the volumetric flow rate of the fan guiding the air flow, and the small size of the particle counter sensor, a turbulent flow is inevitable through a uniform channel. Using an inflation mesh algorithm provided by the software package, the air channel was designed to minimize the boundary layer thickness which forms
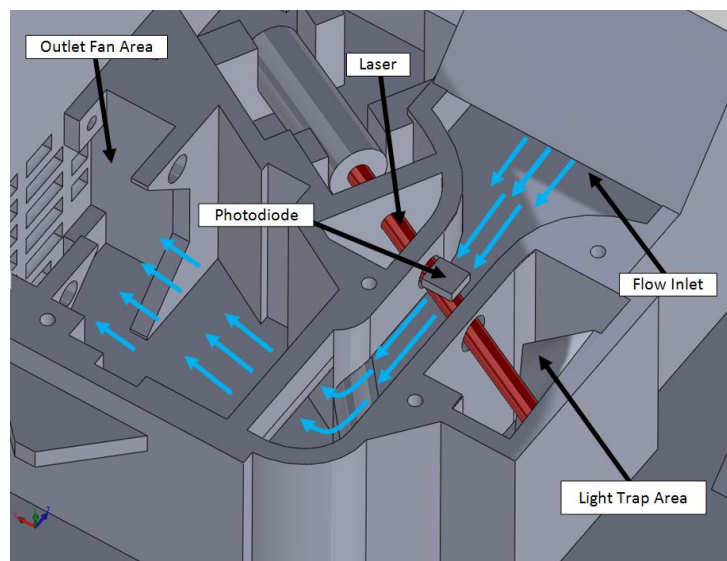
Figure 3. Particle counter airflow and optical path. *Air moves from the inlet, past the photodiode and laser, and through the outlet fan area (fan not shown). The light trap deflects and absorbs the laser light, preventing it from reflecting back into the photodiode.*

inside the channel. Airflow within a boundary layer is difficult to predict and inconsistent, which could have negative effects on the sensor's resolution. To minimize this condition, the length of the uniform channel containing the particle counter was reduced, which keeps the boundary layer from fully developing inside the channel.

Even though the nature of the flow was the driving factor for shaping the flow channel area, there were also other considerations that affected the design. The ambient light entering from the vented inlet and fan outlet needed to be minimized, which was accomplished by having a sloped inlet entrance, and by adding a light deflection wall near the fan outlet. Another consideration was the positioning of the laser, which had to be set in a specific inclined position to allow the beam to pass over the particle counter diode with minimal clearance. The low-cost laser optics produce light artifacts that are outside of the desired beam path, so the framework around the laser had to be designed to block this light from reaching the photodiode. Once the laser light passes the photodiode, it must be captured by a light trap to keep reflections from reentering the measurement area and polluting the sensor. All of these factors, coupled with keeping the overall size to a minimum, were assessed and balanced in the flow channel design.

4. Particle Counter Firmware

The DMA pulls data from the analog-to-digital converter, filling 512-sample buffers approximately every 10 milliseconds. A circular list of these 512-sample buffers is maintained in main memory, with each sample buffer processed in its entirety once filled. The digital stream is analyzed for deviations above the average level. If a deviation exceeds the average level by a predetermined amount, then the leading edge of a particle is detected. Once the leading edge is detected, both the height and duration of the pulse is tracked. The pulse is considered to be complete once the deviation reaches a second, negative going threshold.

Both the pulse height and duration are currently used in determining the particle size. At present, all particles are lumped into one of two possible bins, with a single cut point between them. Further refinements to the detection algorithm may lead to finer granularity in particle size binning.

5. Particle Counter Calibration

Ideally, the particle counter will be calibrated using particles of known size, shape, and index of refraction. At the time of writing of this paper, BSU is still working to complete a calibration chamber that can generate a stream of aerosolized particulate from a known particle standard. To date, a rough calibration has been performed by comparing results with commercial particle counters. Comparative testing has also been performed by our collaborators on the National Children's Study project, looking specifically at diesel engine emissions using commercial optical particle counters.

6. Particle Counter Cost

The starting premise for the particle counter design was that it had to be low cost to enable inclusion in a WSN. To reach the lowest price points, the components needed to be simple off-the-shelf parts, preferably those that were already being mass produced. Most of the electronics for the detector system, dedicated power supply, and fan control were readily available and sourced by multiple vendors, including the large area photodiode and amplifier components. By far the greatest expenses come from the DC fan and the laser module. Single-quantity prices for even small, sleeve bearing fans are on the order of US$10. Small, low power laser modules typically intended for laser pointer use can be purchased for very low prices, but they are typically fixed with a collimated focus. It is much more difficult to find small, low cost laser modules that have adjustable focus, but they can be found for prices on the order of $10-$15.

The approximate component cost for adding the particle counter to an existing sensor system is shown in Table 1, and is on the order of $30-$35 when purchasing components in small, prototype quantities. This does not include the cost of additional PCB area for the circuit or the enclosure plastic for the airflow, since these factors are highly dependent on the rest of the sensor system. This cost also does not include the two analog-to-digital converters used for the two size channels, since these are often included in common microcontrollers that might be used for a sensor system.

Were this system to be mass produced, it is highly likely that improvements both in lowering cost and increasing quality of components could be achieved. The laser module in particular might be custom sourced, with tighter tolerance on the lens assembly and output power that would improve the quality of the system.

Table 1.   Particle counter approximate component cost.

Component	Approximate Cost
Laser Module	$15.00
DC Fan	$10.00
Detector Circuit	$5.00
Power Supply	$1.50
Other	$1.50
Total	**$33.00**

C. Other Sensors

Besides the optical particle counter, the IHAQ node includes sensors that measure CO, CO_2, humidity, pressure, temperature, and sound intensity. These particular environmental parameters were chosen to meet the needs of the National Children's Study program.

The sensors used in the IHAQ nodes have been selected to allow monitoring of various environmental conditions related to air quality, health, and comfort. Table 2 lists the sensors incorporated in the design, along with some of their key datasheet parameters. The parameters for the particulate matter sensor are listed here as well, and are estimated based on comparisons with commercial equipment. The sensors in the IHAQ monitor were chosen to measure conditions in a range relevant to human comfort and safety. In particular, the gas sensors cover a range near the conditions expected to be seen during normal activity. The CO sensor also covers ranges that are dangerous to human health, but the intent is to provide relatively high accuracy at low exposure levels.

**Table 2. IHAQ node sensors and their key parameters.**

Sensor	Technology	Range	Resolution	Accuracy	Response Time
CO	Electro-chemical	0-500 ppm	0.1 ppm	2 ppm	40 seconds
CO_2	Infrared	0-2000 ppm	1 ppm	10% of reading or 75 ppm	< 120 seconds
Humidity	Capacitive	0-100% RH	0.03%	+/- 3%	5 seconds
Pressure	Diaphragm, capacitive	30-120 kPa	3 Pa	+/- 150 Pa	0.55 seconds
Sound	Electret microphone	48-110 dBA	0.02 dBA	--	< 1 second
Temperature	NTC thermistor	$-40^{o}C$ - $+125^{o}C$	$< 0.01^{o}C$	5% of reading	1.2 seconds
Particulate Matter	Optical scattering	$0-10^{7} Liter^{-1}$	0.3-2.5 μm, > 2.5 μm	--	1 second

D. Sensor Node Firmware

The development model for sensor systems can dictate rapid changes to system components, including sensors, communication interfaces, and even the base microcontroller. Systems may require customization for a particular application or environment, leading to multiple unique instantiations of the same base system. Such a model often requires multiple developers working on the same code base simultaneously, creating challenges with division of labor and change coordination.

Architecting a set of embedded system firmware to handle these conditions requires solid interface definitions and a high level of modularity. The embedded firmware architecture for the IHAQ sensor node is shown in Figure 4. The layered, modular architecture is designed to meet the challenges posed by the sensor system development model.

The lowest level of the sensor node firmware is the device driver, which is responsible for interfacing with the system hardware. The device drivers abstract the details of the underlying hardware, presenting a concise interface to upper layers and enabling a simplified programming model. An interrupt-based scheduler sits on top of the device drivers, providing critical high-level timing for the system and all firmware modules. The firmware architecture for sensor management provides a framework for quickly and easily adding new sensors to the
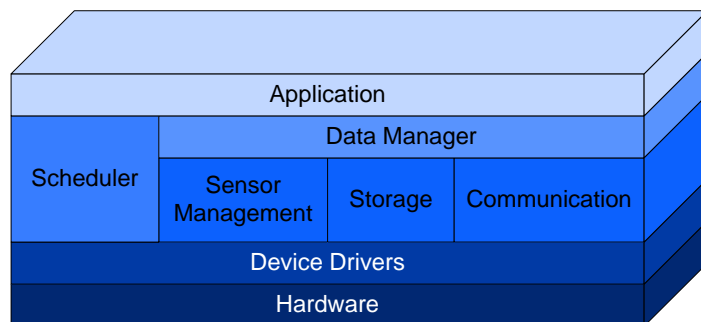
Figure 4. Firmware architecture diagram. *A layered, modular architecture is used to facilitate rapid component changes and multiple developer environments.*

system. The sensor manager collects data from each sensor, passing it on to the storage and communication modules through the data manager. At the logical top of the firmware architecture, the application layer controls the overall functionality and behavior of the system.

VII. Software

For many applications the ability to collect sensor data is useless without the ability to store and visualize it effectively. With this in mind, a set of software applications has been developed to provide these functions for the IHAQ and other BSU sensor systems.

The BSU Sensor Monitor application is the primary software used to visualize data generated by the sensor system. The application is capable of receiving data directly from a standard PC COM port, or alternatively can load stored data from a flat file. The sensor data can be plotted by unit, by sensor, or with custom groups that allow simultaneous visualization of multiple types of data at once. Much of the data in the next section has been created using this application.

As with many sensor networks, a key problem to be addressed in the IHAQ system involves what to do with the copious amounts of data that are generated by the near continuous monitoring of environmental parameters. The server function shown in Figure 5 is responsible for handling the long term storage of the data collected by the IHAQ sensor network. The server receives data passed in from coordinators and stores it in a relational database. The current implementation of the server function uses Perl scripts running on a standard Linux desktop PC, storing the data in a MySQL database running on a separate blade server.

To date the concentration of the team developing the IHAQ system has focused on the sensor nodes and their related firmware. A significant amount of work remains in developing the server software to perform node management, maintain data security, and manage the amount of data being collected and stored.

VIII. Data

A small set of example data is included here to demonstrate how the IHAQ wireless sensor network can be used. Figure 5 shows a set of particulate matter data taken from three different sensor nodes placed within a single-family home. The plot displays particle counts per cubic liter in size ranges from 0.3μm to 2.5μm. Two of the sensor nodes were positioned inside the main house, with one unit in the kitchen and one unit in a study approximately 15 meters away. The third unit was placed in an attached garage, which was separated from the other two units by a closed door.

As noted on the plot at approximately 16:00 UTC, a meal was prepared in the kitchen. This activity generated a large spike in particulate matter that could be seen moving into the study several minutes later as the particulate
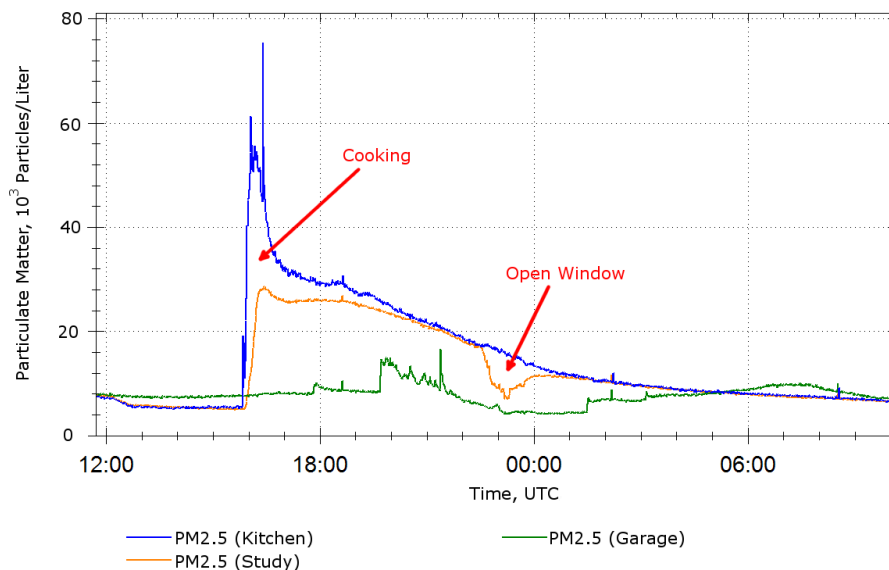
Figure 5. Small particulate measurement from multiple sensor nodes. *Data taken from a single-family home with two nodes positioned indoors and one node positioned in an attached garage.*

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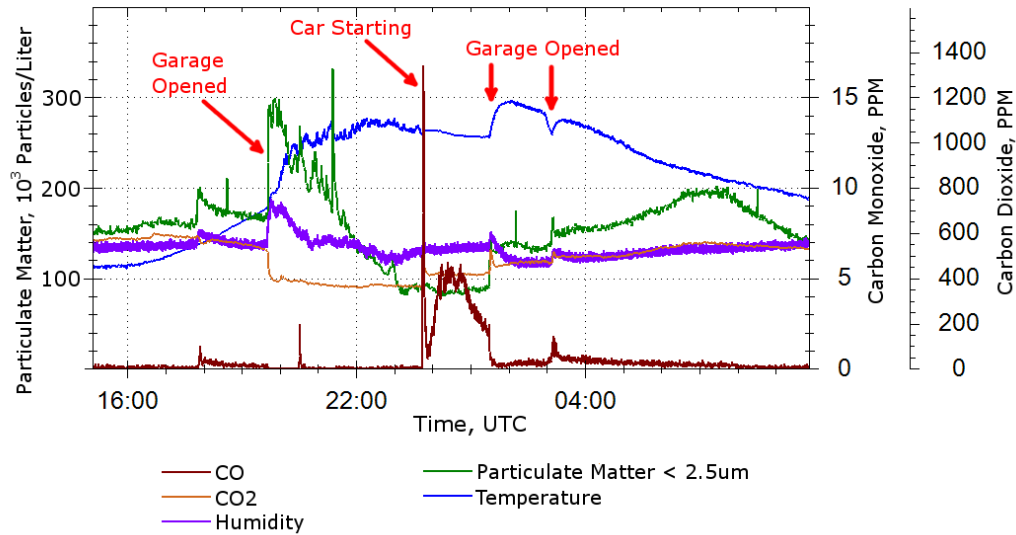
Figure 6. Multiple sensor measurements from a single sensor node. *Data taken from the attached garage of a single-family home.*

dispersed throughout the house. Once the particulate generation ended, the concentrations eventually equalized. At approximately 23:00 UTC, a window in the study was opened, allowing air exchange with the outdoor environment. The particulate in the study was reduced during this time period, but the overall particulate in the household was not significantly impacted. The third sensor in the attached garage clearly measured a concentration of particulate that was unrelated to the concentration observed in the home. During the described period there was no forced air circulation in the home.

This data demonstrates the sensor system's ability to track the movement of particulate matter through an enclosed space. Though only a small number of nodes were available for this experiment, increasing the node density in the home would give better indication of particulate motion.

The data plotted in Figure 6 is taken from a single sensor node, but shows data from multiple sensors concurrently. Notable events include the garage door opening and closing, and the starting of an automobile in the garage. The first time the garage opens introduces a spike in particulate matter, which remains unstable for several hours until the garage door closes. The automobile starting significantly impacts the CO levels in the garage. This time also corresponds with the garage door closing. The temperature, which exhibited quite a bit of instability when the door was opened, stabilized once the door closed. With the door closed, the residual CO from the automobile starting was trapped within the garage. The first indicated point where the garage door opens coincides with the return of the automobile. At the point the trapped CO in the garage escapes, and the automobile's residual heat increases the temperature in the garage. While limited to a single set of events, this data shows how sensor data may be fused to detect events that impact the local air quality.

As previously mentioned, most of the particle counter calibration at the time this paper was written has been performed in comparison with commercial devices. Figure 7 shows a representative sample of comparison data using ambient indoor air. Particle concentrations in blue are from the commercial device and the data in red is from the IHAQ particle counter. The upper plot shows concentrations of particles with diameters in the range of 0.3 μm to 2.5 μm, and the lower plot shows particles with diameters greater than 2.5 μm.

Although the IHAQ counter does track the commercial unit relatively well, there are some notable deviations. The large particle counts in particular shows some inconsistencies between the two counters. Some of this may be due to the uncontrolled nature of the particulate source. Once a particle generation chamber becomes available at BSU, a more controlled test can be conducted. The deviations in the small particle counts correspond with the appearance of relatively high concentrations of large particles. Two such occurrences can be seen at the 100 and 500 minute marks in the plot. Deviations of this nature are still being investigated as future work, and may be due to the quality of the laser optics and particulate flow channel.

IX. Conclusion

Particulate matter concentration is a key factor in determining ambient air quality. Many studies over the last several decades have linked particulate matter exposure to increases in morbidity and mortality. While government agencies such as the U.S. Environmental Protection Agency actively monitor and regulate outdoor air quality, this does not always correlate well with personal exposures for people spending the large majority of their time indoors.

Even though sensors for measuring particulate matter have been available for decades, there are still no readily available, cost effective particulate matter sensors suitable for incorporation into a wireless sensor network. To resolve this dilemma, we have designed and constructed a relatively inexpensive optical particle counter and incorporated it into a WSN. Operating independently or as part of a network of particle counters, our device provides data essential to understanding particulate matter exposure in both indoor and outdoor environments. Measurements obtained with the system are useful for applications including personal health impact awareness, dynamic particulate matter mapping, and airborne contamination movement within aircraft cabins.
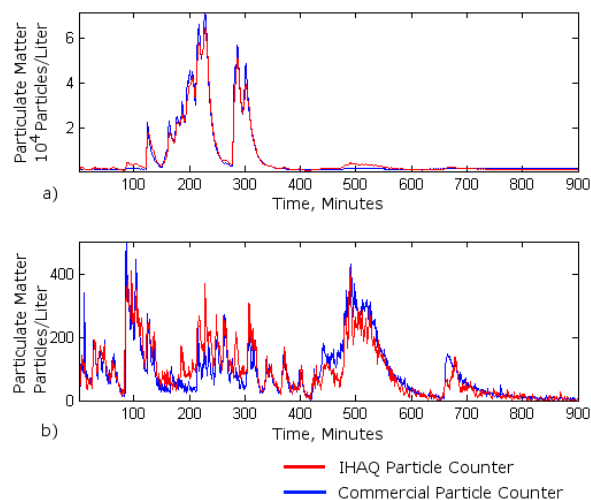
Figure 7. Particle counter comparison with commercial device. *Data in blue is from the commercial device and data in red is from the IHAQ particle counter. a) Small particle count including particles from 0.3 μm to 2.5 μm. b) Large particle count including all particles > 2.5 μm.*

X. Acknowledgments

XI. References

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