Wireless Measurement Node for Dust Sensor Integration

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***Abstract*—The presence of particulate matter of various sizes, generally classified as dust, is an important factor affecting air quality in outdoor and indoor scenarios. Many industrial processes require clean rooms where dust concentration has to be kept below certain thresholds in order to assure the success of the manufacturing process or the quality of the finished product. Applications which need precise dust quantity measurement presently use complex and expensive systems. In the mean time, wireless sensor networks (WSN) have emerged as a tool which promises higher resolution spatial measurements than conventional devices. Beside usual sensors, many WSN producers offer data acquisition expansion modules which supply general purpose analog and digital inputs allowing for the connection of external sensors. This paper proposes combining the two technologies by integration of an optical interferometer dust sensor with a conventional sensor networking platform through a data acquisition module. The system design and description as well as an experimental evaluation in a laboratory setting are presented. We evaluate the results obtained by comparison to a high precision laser air quality monitor for 0.5 and 2.5 micron particles. The results are encouraging and show that our approach is viable for testing outside the laboratory environment, in a real world deployment.**

***Keywords*-dust sensors; data acquisition interface; wireless sensor networks; embedded software;**

I. Introduction

Dust affects many sectors of human activity and it is widely present in the galaxy. Ambient radiation heats dust and re-emits radiation into the microwave band, which may distort the cosmic microwave background power spectrum. Dust in this regime has a complicated emission spectrum, and includes both thermal dust emission and spinning dust emission. Dust samples returned from outer space may provide information about conditions in the early solar system. Also dust has effects on aviation, in the past 30 years, more than 90 jet-powered commercial airplanes have encountered clouds of volcanic ash and suffered damage as a result. The increased availability of satellites and the technology to transform satellite data into useful information for operators have reduced the number of volcanic ash encounters. One of the more important and common effects of dust is the influence on environmental pollution and human health. Most industrial dusts contain particles of a wide range of sizes. The behavior, deposition and outcome of any particle after entry into the human respiratory system, and the response that it produces depends on the nature and size of the particle. Breathable dust approximates to the fraction of airborne material that penetrates to the gas exchange region of the lung. The breathable fraction varies for different individuals; however, it is possible to define a target specification for sampling instruments that approximates to the breathable fraction for the average person. Moreover there is a big effect of dust in industrial environments, especially in the case of high precision industries such as integrated circuits and nanoelectronic fabrication. In industrial plants, where combustible dusts or dust containing goods are produced, processed or stored, there is a risk of explosion. Mixtures of dust and air with concentrations above the Lower-Explosion-Limit (LEL) and below the Upper-Explosion-Limit (UEL) together with various modes of ignition (electric sparks, hot surfaces) can cause an explosion.

Networks of wireless sensor devices are being deployed to collectively monitor and disseminate information about a variety of phenomena of interest [1]. A wireless sensor device or mote is capable of sensing, limited amount of computation, signal processing and data storage and wireless communication. Advances in integrated circuits design have led to a reduction in the size, weight and cost of sensor devices, with an improvement in their resolution and accuracy. At the same time, modern wireless networking of large number of wireless capable sensor devices can work collaboratively to achieve a common objective. At its core, a WSN is meant to enable high temporal and spatial measurement of the surrounding environment. Some of the applications in which this technology has been deployed so far include: environmental monitoring, military surveillance, biosensors for health applications and smart sensors to monitor and control manufacturing facilities. Integration work with other systems is very important in order to provide a reliable tool for domain specialists interested in the provided data [2].

The rest of the paper is structured as follows. Section 2 elaborates on the theory of dust measurements, with focus on optical measurement devices and describes the context of our work through related work. Section 3 presents the system design along with the main components used to implement the wireless dust measurement node. Section 4 presents the monitoring results achieved with reference to a precision air quality monitoring device. In Section 5 we conclude the paper and highlight directions for future work.

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II. Optical Dust Measurement and Related Work

The best known principles of dust measurement devices are: gravimetric, triboelectric and optical measurement. Each of these are best suited to specific application domains which differ in the intensity of dust pollution, water vapor proportion and the surface of the investigated area.

The optical dust measurement principle which we study in this paper is based on the attenuation of the intensity of a light beam by absorption and dispersion upon penetrating a cloud with solid particles. It is based on the attenuation of the intensity of a light beam by absorption and dispersion penetrating a cloud with solid particles. Figure 1 shows a diagram depicting the conversion from dust concentration to useful output using a fixed light emitter. Lambert-Beer's law [3] describes the relation between the light transmission and the dust concentration c according to the following equation:

$$I = I_0 \cdot e^{-\varepsilon \cdot c \cdot l} \tag{1}$$

where:

- I_0 = initial intensity
- I = resulting intensity of the light beam
- ε = coefficient of extinction (a specific constant accounting for dust type and application)
- l = distance
- c = dust concentration

For the light source with rectangular pulses, an efficient GaAs-Luminescent-diode with its maximum spectral sensitivity at 950 nm is used. Consequently, a photo diode of the same spectral sensitivity is used for receiving. The clock frequency should be chosen in a way that even rapid changes or momentary peak values of the dust concentration up to about 3 kHz are exactly reproduced [3].

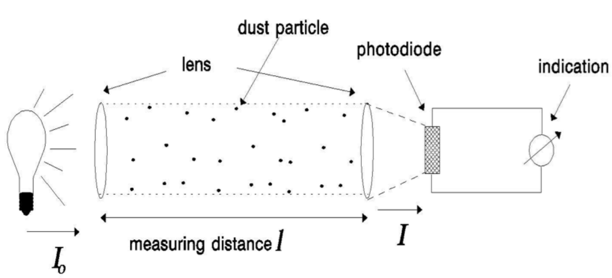

Figure 1. Optical Dust Measurement Principle Schematic

Zhang et al. [4] propose a forest fire monitoring system based on a designed ZigBee [5] wireless sensor node. The main goal is to measure smoke and humidity levels while benefiting from specific advantages of safety in data transmission, network establishement and low cost and energy requirements. The topological structure of the system is an adaptation of a cluster-tree. Compared with a reticular structure, a cluster-tree structure can be built more easily and the information path takes less memory space. At the same time, the chain structure needs to be stable and its scale is limited, which needs to be improved in future investigations. The proposed system is described as a first attempt and complement to existing forest fire monitoring and prevention methods. It provides a solid basis in terms of hardware for the application of advanced wireless sensor network technology. It is pointed out that, in order to extend the potential of the system and improve forest fire monitoring technology, the problems of energy consumption, nodes location and clock synchronization have to be addressed in the future. These are some of the remaining problem areas to be considered, before the level of forest fire monitoring can be improved. In comparison to our work, the focus is rather on networking aspects of the deployed system than on sensor integration. Also, smoke, as a type of dust, is inferred from temperature measurement and not from actual particulate matter detectors.

In [6], a comprehensive overview of smart home instrumentation systems (Figure 2) along with suitable hardware developments are presented. The authors state that air quality assessment and the thermal comfort sensation depend on numerous variables which are difficult to measure precisely at low cost. They present the core of the sensor system as a comprehensive monitoring system which continuously measures the indoor and outdoor air quality and through gas leakage detection and early fire warnings also address essential security matters. The conditions for indoor air quality control and the assessment of subjective thermal comfort are sometimes contradicting. For example, if the CO_2 concentration exceeds a certain level, commonly 1000 ppm, then the air quality control must have priority over the adjustment of thermal comfort. In our view, the wireless measurement node that we developed is suitable for hardware and software integration into such an environment. The advantages of low power wireless communication, small device size can be used to achieve significant savings in retrofitting existing homes and prepare them for smart house technology.

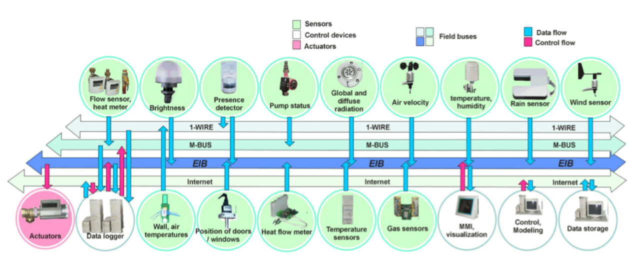

Figure 2. SmartHome Instrumentation Overview [6]

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III. System Design

The high level architecture of our proposed system is shown in Figure 3. It consists of a mesh network of wireless measurement nodes relaying data towards the sink. At the gateway level, the data is collected, stored and presented for interpretation or further processing.

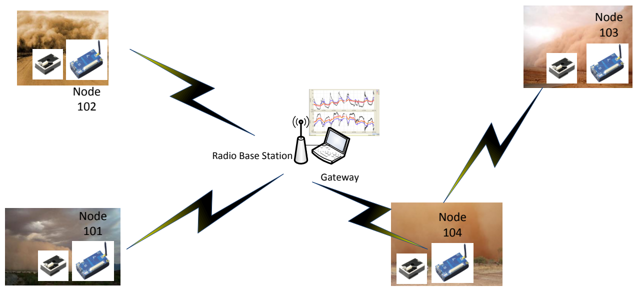


Figure 3. Wireless Dust Measurement System Architecture

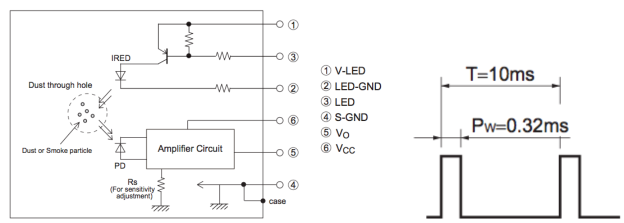
A wireless measurement node consists of four parts: a processing/radio board, a mote data acquisition board, a optical dust sensor interfaced with a microcontroller development board. The most relevant characteristics of the hardware that we have chosen are described next.

The IRIS XM2110 is the main processing/radio board, which hosts an ATMega 1281 8 bit MCU and a IEEE 802.15.4 compliant RF230 radio transceiver operating in the 2.4GHz Industrial Scientific and Medical (ISM) band. This is the newest module in the line of the original Berkeley motes and is supported by the open- source community under TinyOS 1.x and 2.1 an event-based, low footprint operating system for resource constrained devices. Compared to the previous iteration MicaZ, the producer mentions better performance in terms of radio coverage and improved energy efficiency. The 51-pin connector provides stackable expansion possibilities to connect to the MCU peripherals.

The MDA300 [7] is a generic data acquisition expansion board for the IRIS platform. It offers analog input channels, digital input and output channels, relays and external sensor excitation. This opens up a whole range of new applications such as remote process control. The complete feature list is the following:

- 7 single-ended or 3 differential ADC channels;
- 4 precise differential ADC channels;
- 6 digital I/O channels with event detection interrupt;
- 2.5, 3.3, 5V sensor excitation and low-power mode;
- 64K EEPROM for onboard sensor calibration data;
- 2 relay channels, one normally open and one normally closed;
- 200 Hz counter channel for wind speed, pulse frequencies;
- external I2C interface.

The Sharp GP2Y1010AU0F [8] is a dust sensor with optical sensing system. An infrared emitting diode (IRED) and a phototransistor are diagonally arranged into this device. It detects the reflected light of dust in air. Especially, it is effective to detect very fine particle like cigarette smoke. In addition it can distinguish smoke from house dust by pulse pattern of output voltage. The features that have recomended it are the compact size envisioned for integration in air purifiers or air conditioning units which is also suitable for our design. Very important for wireless embedded application is the low current draw of 20mA. We employ a popular Arduino board to handle the interfacing of the sensor in this initial iteration. The microcontroller board is based on the ATmega328. It has 14 digital input/output pins, of which 6 can be used as PWM outputs, 6 analog inputs, a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button.The board has the task of enabling the duty cycling of the command for the optical sensor LED according to the pattern in Figure 4. Basically, a digital output controlling the led of the detector has to be set to low for 0.32ms in a 10ms time period, afterwards a analog voltage output can be read.



(a) (b)

Figure 4. Optical Dust Sensor (a) Internal schematic (b) PWM Excitation

We place the dust sensor in our region of interest and air starts flowing naturally through the measurement space. The microcontroller board runs the embedded software loop to activate the light source and read the sensitive element processed output. Once a value has been read, it is output in the form of an analog signal captured by the ADC0 channel of the MDA300 board and interfaced to the appropiate input channel of the mote. The mote is tasked with broadcasting a radio message containing this voltage value. This happens either directly to the base station or, if the networking protocol decides that there is no direct or poor connectivity to the base station, via multi hop communication with neghboring nodes acting as relays for the source of the data. Our system communicates directly with the radio base station but multi hop is supported without any additional configuration. The overview of the components is shown in Figure 5. We have also employed auxiliary elements such as resistors and capacitors to build the sensor power supply circuit and the pulse width modulation to analog output for the microcontroller board.

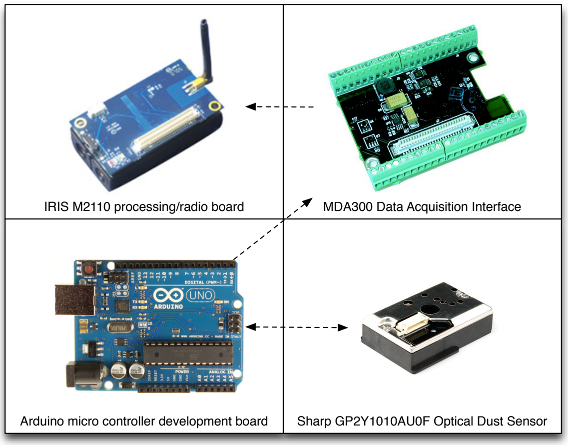


Figure 5. Components Overview

IV. RESULTS: VISUALIZATION AND EVALUATION

Figure 6 illustrates the experimental laboratory deployment. As a reference system, we use the Dylos DC1100 Air Quality Monitor which is a professional grade laser particle counter. It offers two measurement channels, one for small particles in the range $0.5\mu m - 2.5\mu m$ such as bacteria and mold and one for large particles, $2.5\mu m - 10\mu m$ like pollen or thick smoke. In comparison, the datasheet of the low cost optical dust sensor states more vaguely that it detects particles over $1\mu m$. Our version includes an RS-232 connector to communicate with a dedicated logging software on the host PC which records particle concentration every minute for both channels. The device is factory calibrated and we rely on this calibration to perform comparison to our measurement node. The default measurement unit is a count thousands of particles per cubic foot which has to be converted in milligrams per cubic meter. For the wireless node, the application handling the data is called MoteView [9]. Data logging and display is supported via MoteView user interface. The software is designed to be the primary interface between a user and a deployed network of wireless sensors. It provides an intuitive user interface to database management along with sensor data visualization and analysis tools. Sensor data can be logged to a database residing on a host PC, or to a database running autonomously. One important factor to consider is that the voltage values are scaled to adapt to the MDA300 input range of 0 to 2V as compared to the maximum saturated output of the dust sensor of 3.7V.

We follow the conversion procedure [10]. The assumption it follows are:

- particles are spherical, with a density of $1.65E12\mu g/m^3$;
- the radius of a small particle is $.44\mu m$;
- the radius of a large particle is $2.6\mu m$.

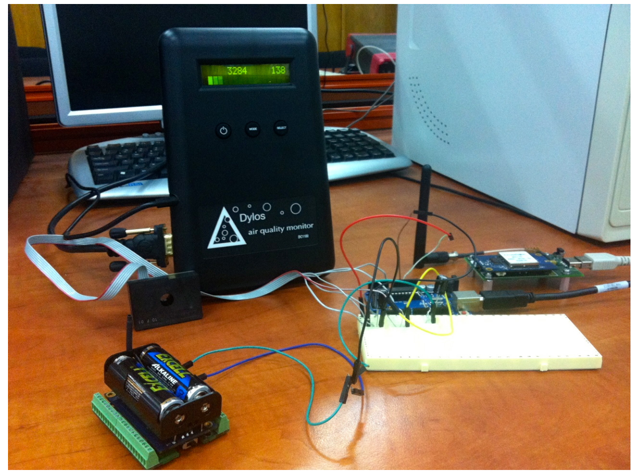


Figure 6. Laboratory Implementation of the Proposed System

Table I
DYLOS DC1100 PARTICLE COUNT VALUES

Channel	Small	Large
Average	666329	95512
Low	68300	8000
High	5157300	850900
Average mg/m^3	0.0139	0.4097
Low mg/m^3	0.0014	0.0343
High mg/m^3	0.107	3.64

so that the formula for deriving mass density from particle count is:

$$c[mg/m^3] = \frac{n}{0.0283} \cdot \frac{4 \cdot \pi}{3} \cdot r^3 \cdot \rho \qquad (2)$$

where n is the particle count per cubic foot, r the radius of a particle and ρ the specific density of the particles.

Therefore, Table 1 shows particle counts per cubic foot for the small and large channels of the air quality monitor over the experiment period. The average, low and high values for both channels are also converted to mg/m^3 to enable comparison with the observed peaks of the Sharp dust sensor response.

The main experiment that we have performed consisted of a continous 30 minute monitoring period with the results illustrated in Figure 7. In this time span we have acquired 31 samples from the professional device and 632 wireless measurements from our node, with a 3 second sampling interval. We can see that the peaks are correctly identified by the measurement node which outputs a saturated value of around 1.72V. Comparing this to the characteristic output curve of the sensor in Figure 8, we assimilate the voltage output of our system for a maximum concentration of particles of $0.55mg/m^3$. An interesting fact is that, over the saturation limit we can still evaluate higher concentrations of dust due to the prolonged width of the high output signal.

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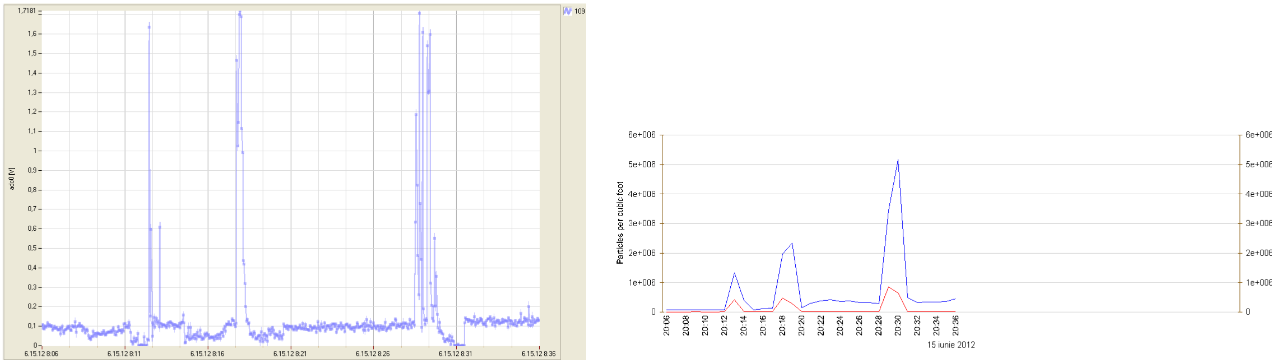

(a) (b)

Figure 7. 30 Minute Particle Monitoring Results (a) Wireless Measurement Node (b) Dylos DC1100 Air Quality Monitor

In practice, after the first smoke event the spike in the sensor answer seems somewhat isolated but for the next two experiments there are more similar high value readings in the corresponding time frame.

In order to establish a dust concetration baseline, we alternate steady periods with high particulate matter events in the form of smoke resulting from paper incineration. The spikes in the data analysis show the response of both systems to such events. The increasing baseline certifies that the dust sensor we use is sensitive to the steady increase in ambiental particulate concentrations resulting from paper burning events. The baseline voltage ranged from 0.05V to 0.15V in the later stages of the deployment.

Fine grained analyisis can be performed only in a given volume enclosure with a pre-measured quantity of particles. In our case we relate to the room volume and place the two measurement systems close together. It it to be noted that the Dylos device uses forced supply by means of a small fan while the measurement node relies on natural air flow.

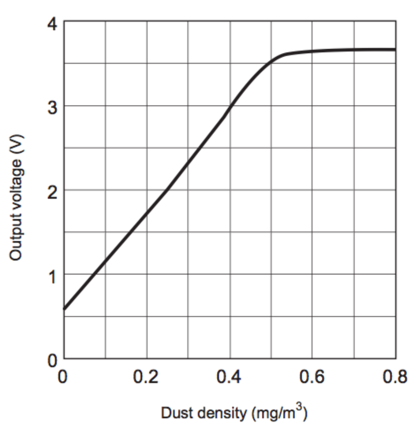

Figure 8. Dust Sensor Output Characteristic

After this experimental evaluation, we can conclude that initial testing has showed promising results regarding the response and sensitivity of the Sharp optical dust sensor and, implicitly, of our wireless measurement node. The professional grade air quality monitor provided a trustworthy calibration reference which has enable us to establish a baseline for dust concentration and effectively measure particle counts and equivalent mass densities.

V. CONCLUSION AND FUTURE WORK

In this paper, we have reported how to create a wireless node to measure dust concentration at any industrial site or other areas, by combining smart data acquisition technology and wireless sensor networks. All the components in the laboratory have been connected in one system to create a smart node, and were adjusted according to their specific purpose. By using specialized software we collected the results from the nodes and we created the wireless link with the available network by self configuration with the network. In addition to the low cost, a smart node has many advantages: it runs on batteries which can operate for long periods of time, it is scalable, allowing the addition of nodes to additional features and to expand the network up to tens or even hundreds of nodes. We have used a professional grade air quality monitoring device in order to validate the experimental data coming from our system in low and high particle concentration environments.

Future work direction is two fold. First, we want to make the microcontroller development board redundant by implementing TinyOS components and modules directly on the mote processing board to handle sensor reading tasks. Its sole role as an intermediary in the current iteration of the system can be removed and thus enable the node to operate independently. Second, we propose to evaluate an alternative to the Sharp sensor in the form of the Shinyei PPD4NS particle sensor. Literature review has pointed out that in some situations, it is better suited to certain application due to enhanced sensitivity. Also, the pulse width modulation of this sensor works in a more reliable manner than the analog output voltage of the Sharp version.

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