



## Wireless sensor networks as part of a web-based building environmental monitoring system

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### ABSTRACT

The presented research shows how advanced wireless sensor technology can be used by engineers to monitor conditions in and around buildings. The objective is split into three different tasks. First, wireless sensor hardware is programmed to process signals from sensors and transmit the data in a suitable format. This task was accomplished through an open-source operating system and a programming language designed specifically for wireless sensor hardware. The second task involved the processing of signals sent by the wireless sensor nodes. In this application, a Java program was written that deciphered messages transmitted from a wireless receiver over a computer's serial port and then placed the data in a database. The structure of that database is discussed to help identify the key pieces of information that are needed to make use of the data. The third piece of the proposed monitoring system is an interface to review the data. A Web-based system was developed that allows a user to mine the database using parameters such as the type of data, location of sensor, and the time of data acquisition. It is anticipated that this research will demonstrate the potential of using wireless sensor networks for monitoring buildings.

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### 1. Introduction

Emerging wireless sensor technology promises to enable enhanced monitoring of conditions in and around buildings [1]. Wireless data communication between the sensor and a viewing or storage location opens up a range of possibilities because of the ease and the low cost by which the sensors can be deployed. There is no need to run unsightly signal wires through various parts of a constructed building, and significant time savings can be obtained in setting up the sensors. With these sensing possibilities, one can think of the scenarios in which such information could be used. For example, forensic analyses within buildings to determine the cause of problems would greatly benefit from the ability to deploy wireless sensors on a short term basis. Wireless sensors could be placed on critical pieces of equipment in buildings to help detect and diagnose faults. Buildings lacking a whole building automation system could utilize more sensing points to more efficiently control its lighting, heating, ventilating, and air-conditioning (HVAC) equipment, and plug loads [2]. In hazardous situations such as fires, deployment of wireless sensors could provide more information about the conditions within and around a building for first responders.

Researchers, investigators, or maintenance personnel can use a variety of methods to monitor conditions in a building by measuring such quantities as temperature, relative humidity, light, or energy consumption. Wired sensors could certainly be installed at each

sensing location, but such a step requires significant effort and an additional set of wires throughout a building. Additionally, estimates of the cost to run signal wire in 2002 ranged from \$2.20 per meter for new construction to \$7.19 per meter for existing construction [3]. Another example of the costs involved in wired systems can be found in a recent structural monitoring system, where up to 75% of total testing time and 25% of system cost involved the installation of signal wire [4]. Anecdotal evidence suggests the costs to be much higher for more critical facilities, such as nuclear power plants. One way to avoid the need for signal wires is through the use of small data loggers with integrated sensors at each location. These devices do not have signal wires running to and from them, but they require personnel to periodically download their data. This step adds to the cost and difficulty of using these devices. Transmitting the data wirelessly provides a significant benefit to those investigating buildings by allowing them to deploy the sensors and monitor the data from a remote location [5]. Wireless systems, however, have their own set of disadvantages, such as higher equipment cost, the potential for radiofrequency interference to damage the data stream, and the need to provide power to these “wireless” devices. All things considered, however, the potential applications for wireless sensing abound.

A wireless sensor network consists of various pieces of hardware and software. At the heart of the system is the wireless sensor device. This piece of equipment consists of the physical sensors, a micro-processor to analyze the raw data signal and generate the data message, a radiofrequency transmitter to deliver the data, and a power source. The package will often be referred to as a node or “mote.” A key

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aspect of a wireless sensor network is that the microprocessor on each mote can be programmed to ensure that all sensors in a given region work as a coherent system. While sensor nodes in a wireless sensor network are capable of exchanging information with other nodes, most applications will involve the delivery of data and information from each sensor node to a central data collection point. That point will typically be a computer that archives the data, and software is needed to ensure that the data delivered from the wireless receiver is interpreted, displayed, and stored in a usable manner. The third component of any successful wireless sensor network system involves retrieval of the data produced from the sensor network. Software applications must somehow be able to query the data generated by the sensor network in a logical manner. This work will discuss issues related to data acquisition, storage, and retrieval from wireless sensor networks.

With current wireless technology, a great challenge arises because of the level of expertise needed to fully make use of the sensors. The most sophisticated hardware has emerged from university laboratories and often requires advanced knowledge of embedded programming to achieve the level of performance desired. Such knowledge is not common among the civil and mechanical engineers who are often tasked to use the devices on construction sites or in buildings. An added complication lies in the fact that much of the work involves proprietary programming methods, which makes it difficult to develop a standardized method of setting up a sensor network or to customize the sensor network for a particular application.

The purpose of the present work is to explore methods to make wireless sensors more easily used by engineers involved with buildings and construction. Initial discussion will focus on the programming of wireless sensor hardware using open-source software. The second aspect of the work will discuss database specifications for storing the data. The manuscript will conclude with a description of a method to easily view the data via a Web browser. It is hoped that the present work will describe a system that can effectively be used in a range of applications for monitoring purposes and will present a clear path that engineers can take to use existing wireless sensor technology in their particular application.

## 2. Background

A number of articles in the literature have discussed the use of wireless sensing for buildings and monitoring. Kintner-Meyer and Brambley [3] and Kintner-Meyer et al. [6] installed 30 temperature sensors throughout an office building and additional sensors on a rooftop HVAC unit to monitor its performance. For an office building such as the one discussed, wiring costs (labor plus material) make up approximately 45% of the installed cost for a new building and nearly 75% of the installed cost for a retrofit application. Healy [7] examined the use of wireless sensing devices to monitor conditions within a residence, finding that the sensor networks were easy to set up but required more programming than desired for easy deployment. Wills [8] discusses the move towards wireless technologies for control applications in buildings, foreshadowing the move by the BACnet committee of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) to work with the ZigBee wireless standard committee [9] to implement wireless communications in building controls. Raimo [10] discusses the emergence of mesh networking for connecting controllers in a building. Ruiz [11] discussed a range of ways to implement various wireless applications in buildings, from voice communications to low data rate monitoring. In structural health monitoring, Lynch [12] reviews the emerging interest in using wireless sensors for monitoring structures. The article indicates that visual inspection of steel structures can cost between \$200 and \$1000 per welded connection, while deployment of wired sensors to monitor structural health in a building can cost up to \$5000 per sensor for a system with 12 to 15 sensors. The use of wireless sensors would greatly cut this cost through savings in the labor

required to install the system. From the range of articles, it is apparent that the building industry is very curious about the use of wireless in buildings, but questions still remain about the ease of use, the dependability, and the cost of wireless monitoring.

Recent advances in wireless technology have made deployment of these systems easier; these advances are documented by a number of authors (Pottie and Kaiser [13], Akyildiz et al. [14], Estrin et al. [15], Hill et al. [16], Szewczyk et al. [17], Azia et al. [18]). Of particular note is the use of mesh networking. Mesh networking describes a topology of a sensor network in which each sensor node communicates with its neighbors and can relay messages from that neighbor through the network. A contrasting topology would be a star network, in which each sensor node communicates directly to a base station that collects the data. The benefit of the mesh networking scheme lies in the fact that each sensor node need only communicate with a neighboring node as opposed to directly to a base station. The most advanced mesh networking schemes allow the sensors to arrange themselves in an ad-hoc manner, so that the routing path of a message can change should an obstruction prevent communication between two nodes or should another radio enter the network. This type of system adds robustness to the sensor network and permits it to be easily expanded. The downside of such a system is the increased complexity in the software (and corresponding increased cost of the system) and the fact that each sensor node serves as a repeater and therefore consumes more energy.

When considering sensing of the building environment, a large range of constituents could potentially be of interest to engineers. Of these, the most significant are likely to include temperature, relative humidity, light, carbon dioxide, carbon monoxide, power, smoke, occupancy, and flow rate. Numerous companies produce products that will archive data from such sensors and present the data via a graphical user interface. Such systems, however, are typically developed using proprietary protocols, and customization by the user is difficult. Alternatively, systems may follow common standard communication protocols such as BACnet [19], but such a system may not be appropriate for all applications around a building. Standard methods of exchanging and storing data and metadata from sensors for use by software applications would encourage the development of interoperable solutions to improve monitoring in buildings.

## 3. Methodology

Data representation challenges arise when dealing with wireless sensors. First, the data must be packaged by the wireless sensing node and sent in an understandable manner over the airwaves. That signal must be interpreted at a computer that stores or displays the data. To assist in making the data accessible by a large range of applications, efforts should be made to determine the best structures for storing the data in databases. To encourage interoperability between the different components of a sensing and monitoring system, standard data formats for the message being sent by the sensor, the database storing the sensor data, and the data stream from the database to the end application are needed. As part of this effort, the formats for transmission of data from the sensors and for storage of that data will be discussed.

To explore these questions, freely available, open-source tools for software development were sought. The software platform that was selected for programming the sensor nodes was the TinyOS operating system along with the nesC programming language (Culler [20], Gay et al. [21]).<sup>1</sup> These platforms were developed at the University of California at Berkeley specifically for sensor nodes [20], and an active user community has developed various software tools. While many programming languages could be used for developing software to run

<sup>1</sup> Certain commercial software are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the software identified are necessarily the best available for the purposes.

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