

# Making Everyday Life Easier Using Dense Sensor Networks

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**Abstract.** Advances in hardware are enabling the creation of small, inexpensive devices and sensors. Hundreds or thousands of these devices can be connected using low-power multi-hop wireless networks. These networks foster a new class of ubiquitous computing applications called proactive computing. In proactive applications, computing occurs in the background without requiring human interaction; humans participate to access information or to modify control policies. This paper provides an overview of the application of a large wireless network of sensors to solve everyday problems in the workplace. It describes the implementation of one application that allows people in the workplace to easily find empty conference rooms (e.g., for impromptu meetings). Drawing on this experience, we identify technical challenges and possible directions for building dense networks of sensors that enable proactive computing.

## 1 Introduction

The current generation of interactive devices and networks fosters a class of interactive ubiquitous computing applications [7]. These applications deliver information or provide services such as email, appointments, stock quotes, or multimedia to devices such as PDAs, cellular phones, and portable computers. Human participation in the compute-loop dominates these applications. Another class of ubiquitous-computing applications has been termed proactive computing [4]. In this class, computing occurs without human interaction; data is pre-processed and available on demand. Many of these applications connect users with the real world using networked sensors.

Today millions of sensors are deployed throughout the world. These include climate-monitoring sensors, safety and security devices, and traffic monitoring sensors that detect vehicles at intersections. In most cases, sensors are local to a specific application and access to sensor output is only available at that location. While these sensors serve many useful purposes for the individuals who rely on them, many new

applications emerge if these devices are made available through remote access and can be controlled through the network. These applications make everyday tasks easier and enhance our ability to examine and optimize the environments in which we live and work

Our research project in Intel Architecture Labs is investigating the network protocols and architectures required to realize ubiquitous access to sensor networks. To drive the investigation of the sensor network research space, we have identified a number of compelling applications in the Intel facilities, which we consider to be typical of many office environments. These applications are built using networks of low-cost, low-powered radios that are well-suited for connecting large numbers of sensors in an office environment. This paper describes these ubiquitous sensor network applications and implementation and provides an overview of the challenges that need to be solved to realize the widespread deployment of the underlying sensor network.

## **2 Ubiquitous Sensor Network Applications Making Everyday Life Easier**

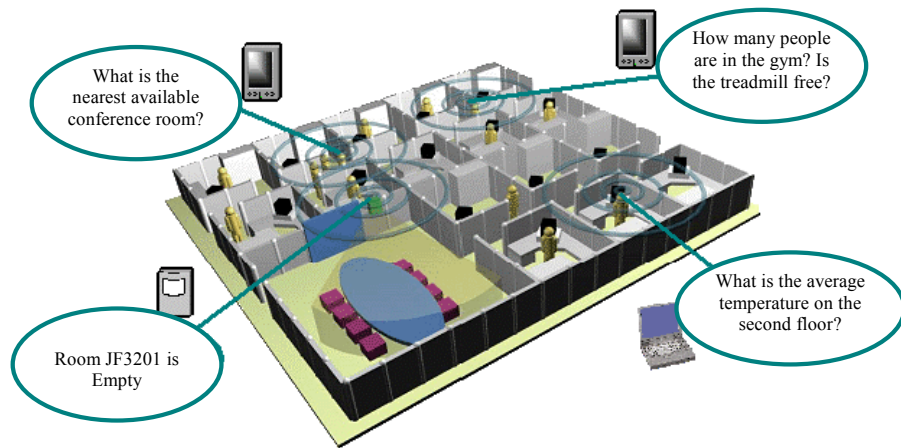
Figure 1 (a) illustrates several sensor network applications that make life easier in an office building, ranging from alleviating congestion in popular facilities to monitoring and maintaining environmental conditions. In large buildings, it is difficult to maintain uniform environmental conditions across entire floors. On occasion people may complain about the ambient temperature in cubicles or conference rooms. For example, people near windows may feel too warm due to direct sun, while others in the interior of the building may complain that it is too cold. Deployment of a wireless network of inexpensive temperature sensors provides us with a system that can support temperature-sensing applications and services in such an environment, to benefit people in the building as well as assist in maintenance.

It is also a common problem for people to encounter congestion and long lines in day-to-day use of facilities such as cafeterias, conference rooms, exercise rooms, vending rooms, and restrooms. Mostly, this is not due to the lack of facilities in a building; instead it results from a non-optimal usage pattern. For example, when one vending/microwave room is full of people, another down the hall may be empty. Motion detectors and sensors in doorways can be deployed to monitor and count the number of people occupying various facilities. By networking these devices and making their real-time output available in a pervasive fashion, people can quickly identify available resources, saving valuable time and eliminating frustration. On the other hand, such a network may also be used for identifying locations with large collections of people, implying that something interesting may be happening in that area.

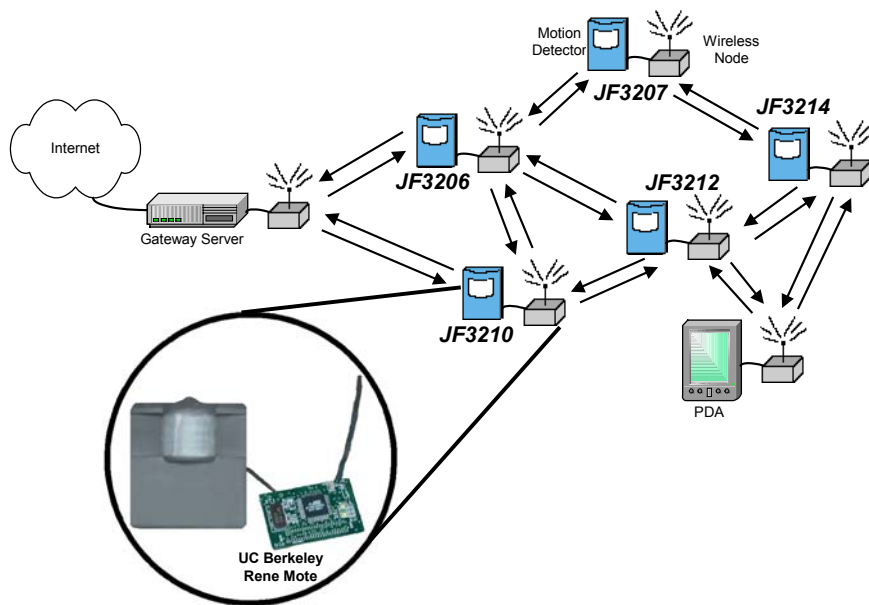
The following is a description of the implementation of one particular sensor network application that enables people to quickly find empty conference rooms.

### **2.1 Implementation of a Sensor Network Application to Help People Find Empty Conference Rooms**

In modern office complexes such as Intel, closed-wall offices have been replaced with high-density cubicles to inspire an atmosphere of open collaboration and accessibility among people in the building. However, the lack of private offices generates a problem



(a)



(b)

**Figure 1.** Example sensor networks. (a) Applications to make life easier in a typical large office environment. (b) Multi-hop wireless topology of a sensor network to help people find empty conference rooms. This sensor network is comprised of motion detectors interfaced to UC Berkeley Rene Motes (<http://tinyos.millennium.berkeley.edu>). At the time of writing our network consists of 36 motes; we are in the process of creating a network with 150 motes.

when people wish to have impromptu meetings. Buildings are equipped with conference rooms, but these rooms may be reserved days or weeks in advance and it is often not possible to reserve a room with little or no notice. However, meetings commonly do not last the entire reservation time, thus it is common for people to wander around a building in search of an empty room for an impromptu meeting. We have built a system that provides people access to room usage status and allows them to find empty rooms from handhelds and PCs.

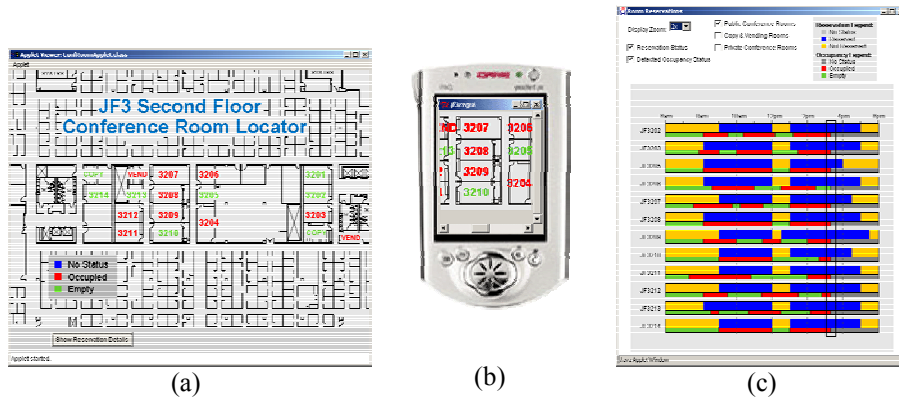
Many conference rooms are equipped with motion detectors that turn off the lights in an empty room. In most cases these motion sensors are hard-wired to the light switch in the same room and are not accessible from outside. In one building at Intel, we have networked motion detectors together using multi-hop network protocols implemented on a collection of inexpensive, low-power wireless radio nodes [1,2]. Each node has a transmission range of approximately 20 to 30 feet, and our initial prototype uses controlled multi-hop flooding to enable communication and the sharing of room occupancy status throughout the building. The topology of this prototype sensor network is shown in Figure 1 (b).

In this network, a gateway node receives sensor data which is aggregated and stored on a server to provide status information to desktop users over the web. Figure 2 (a) shows a sample screen shot from a web application that provides people with live occupancy information for rooms in a particular building floor. By referring to this webpage before leaving their desks to search for conference rooms, people are able to save time by walking directly to rooms that are reported empty.

We have connected PDAs directly to the sensor network, allowing mobile users to obtain usage information from the nearby conference rooms themselves. Due to the multi-hop nature of the network, contextual location information can be presented to mobile users, without the need for GPS, simply by querying only those sensors within a few radio hops of their location. Figure 2 (b) illustrates a PDA application showing the occupancy status of nearby conference rooms.

In addition to providing live occupancy data, motion detector data may also be compiled across days or weeks for future analysis. Figure 2 (c) illustrates an application to compare actual detected room usage statistics to reservation data from the online conference room reservation system. Such data provides the opportunity to automatically identify individuals who consistently reserve rooms without canceling reservations for rescheduled meetings. Moreover, collected usage data can be analyzed by facility analysts to understand usage patterns in a typical office building. Building planners can use this information to plan the design of buildings by providing statistics on the typical usage pattern of conference rooms.

It is worth noting that several other systems have previously been developed for locating people in an office environment, such as the Active Badge [5] and Active Bat [6] location systems. While these systems have different goals, they could be adapted to enable similar facility usage-monitoring applications. A primary difference between our multi-hop approach and the Active Badge system is the infrastructure cost and deployment effort. The Active Badge sensors were connected by a wired network, resulting in a very high labor cost for deployment of an active badge system in a typical industrial setting. Wireless sensors are far better suited to retrofitting existing buildings. Another difference is that by using simple inexpensive sensors to monitor the office environment, instead of identification tags, our system maintains the anonymity of



**Figure 2.** Conference room status monitoring applications. (a) Webpage showing live conference room occupancy status for rooms in the second floor of the JF3 building. (b) PDA application showing status of rooms in the vicinity of the mobile user. (c) Occupancy history application comparing actual usage data to conference room reservations.

people in the building, reducing the privacy concerns of individuals who do not wish to be tracked as they move through a building.

By adding inexpensive networking capabilities to pre-existing motion detectors that are designed for a particular application, a whole new range of applications are enabled that enhance the day-to-day lives of people in the building and provide the opportunity for optimization of facility usage. Our work uses these applications to explore the challenges in networking sensors and enabling ubiquitous access to information obtained from them.

### 3 Challenges For Widespread Deployment Of Sensor Networks

The prototype implementation and deployment of the conference room occupancy monitoring sensor network demonstrates the power of communication to greatly increase the utility of simple sensor devices. Our objective when building this application was to develop a hands-on understanding of the real-world challenges related to deploying dense sensor networks. In this section, we provide an overview of the challenges in this space and the direction we are taking to solve them.

As we increase the size of our motion detector network toward a total of 150 nodes, it has become clear that we want to avoid the tedious requirements of optimally placing each individual node and configuring each node with topology and routing information. Based on this experience, dense sensor networks must have the ability to self-organize. As long as enough nodes are deployed to enable redundant communication paths, the network should be able to automatically configure routes and reconfigure itself when nodes fail or are added to the network. Such self-organization will significantly lighten the burden on administrators and increase the rate of deployment of compelling new applications.

Another challenge we encountered is that it is not always feasible to constrain sensors to be located near power outlets, even in buildings where these outlets are

relatively abundant. For example, motion detectors are best positioned high on a corner wall to have a clear view of an entire room. Running new wires to sensors is expensive and time consuming, thus they must be able to run using batteries or scavenge their energy from the environment. In our motion detector network, the seemingly simple job of replacing batteries at every node also turns out to be very tedious. Under these circumstances energy is an expensive commodity, requiring network architecture and protocol solutions to conserve energy, maximize the lifetime of the network, and work in a resource-constrained environment.

While controlled flooding provided a convenient communication solution for the initial prototype of the conference room network, this technique does not scale well and is inefficient in the use of energy and bandwidth. Efficient data acquisition mechanisms [3] must be implemented to allow data to be gathered. To minimize communication in an effort to preserve energy, application-specific processing may be implemented within the network to aggregate and compress data as it is being routed toward a consumer node. In the conference room application, data was proactively acquired at a gateway server, aggregated, and made available to people and services over the Internet. This is the first step toward realizing the ubiquitous computing vision of data available anywhere at anytime. Protocols must also support mobile local consumers within the sensor field, who generally benefit from location-context support. As demonstrated in the conference room application, radio connectivity is one method that can be used to obtain information relevant to mobile user locations.

## 4 Conclusion

On a closing note, it is important to note the importance of maintaining the privacy of people who live or work in environments monitored by sensor networks. This particularly becomes a problem, for example, when networks and applications are able to track individuals as they move through a building. However, a number of interesting applications exist, such as those described in this paper, that provide useful information about the conditions and use of a building environment without gaining knowledge about the individuals who are in that environment.

The wide deployment of dense collections of networked sensors has the potential to greatly impact our everyday lives by making mundane tasks easier and enhancing our ability to examine and optimize the environments we inhabit. Just as modern computing systems are analyzed and optimized by instrumenting them with code to track their performance, inexpensive sensor networks provide the opportunity to instrument the real world around us. The conference room occupancy monitoring sensor network deployed at Intel has provided the opportunity to demonstrate the benefits of sensor networks in the everyday lives of people in a large office building. At the same time, this prototype network has served as a learning tool to investigate the challenges involved in progressing this technology to the point where it can be widely adopted.

We would like to acknowledge David Culler and Jason Hill at UC Berkeley as well as Marc Davis, Steven Fordyce, and Jasmeet Chhabra for their assistance in building the UC Berkeley motes used to implement the conference room monitoring sensor network.

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