The Design of a Portable Kit of Wireless Sensors for Naturalistic Data Collection

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Abstract. In this paper, we introduce MITes, a flexible kit of wireless sensing devices for pervasive computing research in natural settings. The sensors have been optimized for ease of use, ease of installation, affordability, and robustness to environmental conditions in complex spaces such as homes. The kit includes six environmental sensors: movement, movement tuned for object-usage-detection, light, temperature, proximity, and current sensing in electric appliances. The kit also includes five wearable sensors: onbody acceleration, heart rate, ultra-violet radiation exposure, RFID reader wristband, and location beacons. The sensors can be used simultaneously with a single receiver in the same environment. This paper describes our design goals and results of the evaluation of some of the sensors and their performance characteristics. Also described is how the kit is being used for acquisition of data in non-laboratory settings where real-time multi-modal sensor information is acquired simultaneously from several sensors worn on the body and up to several hundred sensors distributed in an environment.

1 Introduction

A barrier that many researchers face when attempting to conduct pervasive computing research is lack of access to affordable, flexible, robust, and easy-to-use tools for the study of behavior and technologies in complex, non-laboratory settings such as homes. Computing trends such as Moore's Law suggest that at some time in the future it will be possible to deploy small and affordable sensors ubiquitously and inconspicuously throughout homes and on the body, perhaps enabling many novel and useful pervasive computing applications. Further, recent work suggests that many sensors placed throughout a home environment (e.g., [1-4]) in combination with a few sensors worn on the body (e.g., [5-7]) may permit a system to automatically and unobtrusively recognize everyday activities and states as diverse as cooking, "making tea," ambulation, posture, "in conversation," vacuuming, and others. The same types of sensors can also be used to study behavior, providing designers and ethnographers with new data gathering tools.

Despite the promise of pervasive sensing, most researchers today who wish to populate environments such as homes with multi-modal sensors are likely to find this to be a difficult and costly (in time and money) endeavor. Past studies have generally been conducted either in homes that were specially (and laboriously) wired with sensors (e.g., [8, 9]), in homes wired with a small number of sensors for short periods of time, or in controlled laboratory home simulations (e.g., [10, 11]). During prior work installing sensors in homes, we identified a set of design goals for a portable sensing kit that could be easily retrofitted in existing homes and used in longitudinal pervasive computing experiments. We could not find an existing hardware platform that met these goals and therefore designed and built a sensor system optimized for researcher and subject usability. In this paper we introduce MITes: MIT Environmental Sensors, a portable wireless sensor platform that can be used to collect data on people's activities in non-laboratory settings such as homes.

The MITes platform includes six environmental sensor types, five of them being among the most typically needed in ubiquitous and pervasive computing applications [12]: (1) movement using ball, mercury, and reed switches, (2) movement tuned for object-usage detection (using acceleration), (3) light, (4) temperature, (5) proximity [13], and (6) current consumption. The MITes platform also includes five wearable sensors: (1) accelerometers to acquire body motion information, (2) heart rate, (3) ultra violet radiation exposure, (4) an RFID reader in a wristband form factor, and (5) location beacons. All of these sensors can be used simultaneously, and a single receiver acquires the data, which is sent to a PC or mobile computing device for real-time processing.

Usability criteria for researchers, particularly those interested in sensor-driven pervasive computing research, drove our design decisions. The MITes have been optimized to be easy for researchers and non-technical home occupants to "install," wear, and use. Battery life has been optimized for conducting longitudinal experiments. A *single* power efficient receiver connected to a mobile device can gather data from a variety of sensor types. Device size has been optimized for comfort, flexibility, and ease of attachment to home objects. Finally, the entire system is designed so that components can be affordably manufactured and assembled by researchers, even in low quantities.

This paper describes the design and development of the MITes sensor kit and performance of key components in non-laboratory settings. The hardware and software specifications for MITes can be found online for interested researchers [3, 14].

2 Motivation and design goals

Most researchers who have tried to test novel technologies and study the behavior of people in non-laboratory settings have found that testing outside of the lab in complicated environments such as homes is logistically and technically challenging. Testing is particularly difficult when components of the sensing or interface technology must be distributed throughout the environment. For example, recent work by several groups has suggested that very simple and small sensors such as switches [1, 2, 11] and RFID tags or readers [3, 14] non-obtrusively attached to many objects in an environment may enable a computer system to infer contextual information about the home occupant's movement and activities. Developing and testing such systems, however, requires laborious sensor installations and time-consuming maintenance of complex technical infrastructures. It is not surprising, therefore, that most prior work on home sensing has generally been conducted with a single type of sensor tested in a single environment with a single user. Wearable sensor researchers interested in conducting non-laboratory studies with comfortable, multi-modal sensors placed on multiple parts of the body face similar challenges – sensor systems can be difficult to use and maintain in the field for longitudinal studies.

Based on our prior work deploying environmental and wearable sensors in homes, we have identified four usability goals for a portable sensor kit that could be used for non-laboratory pervasive computing studies, particularly for those designed for the home setting. Table 1 lists these general goals as well as the sensor design goals they motivated and the benefit(s) of achieving the usability goals for the researcher and/or the subject in an experiment.

Usability Goals (What)	**Sensor Design Goals (How)**	**Benefit to Researcher(R) and Subject (S) (Why)**
Ease of installation	• Light weight, and small sensor nodes (portable) • Self-contained single point of contact to body/home • Single receiver to collect data from multiple sensors • Real-time simultaneous data -acquisition from high and low sampling rate sensors • No pre-configuration required or threshold setting • Good indoor Tx/Rx range and easy to detect if in range	• Minimizes installation time (R) • Subjects can install sensors themselves (R/S) • Subjects can re-install sensors if they dislodge, simplifying maintenance for researchers during studies (R/S)
Ease of use	• Real-time simultaneous data acquisition from multiple high and low sampling sensors with single receiver • Each sensor does one thing well • Convenient battery life • Robustness to environmental noise	• Facilitates maintenance (R/S) • Low training overhead (R/S) • Facilitates the addition of new sensors(R) • Reduces failure points (R) • Decreases probability of data loss (RS)
Adequate longitudinal performance in natural settings	• Convenient battery life/low power • Robustness to environmental noise • Self-contained, resistant packaging • Good indoor Tx/Rx range and easy to detect if in range • Performance valuated in a natural setting (Section 5.1)	• Decreases probability of data loss (R/S) • Facilitates design of data collection (R)
Affordable for researchers	• Design with low-cost components • Each sensor does one thing well	• Deployment of hundreds of sensors (R)

Table 1: Usability design goals that motivated the development of the MITes, listing benefits to the researcher and the subject. More detail on how the sensor design goals were implemented is found in Table 2 and throughout the paper.

These usability goals have driven our design decisions for the MITes. For example, if sensors are used and tested only in a laboratory setting, then installation time is often a minor concern. Previous studies, even those where sensors have been installed in homes of subjects (e.g., [1, 2]) have often relied upon complex installation of switch sensors. A typical switch sensor that must be installed on a cabinet in a volunteer's home has a microprocessor, a reed switch, and a magnet. All three components must be placed on the cabinet in a way that properly activates the reed switch when the cabinet is operated but also in a way that will not be easily knocked off, cause damage to the cabinetry, or create aesthetic concerns that make the subject uncomfortable. Meeting all these concerns can be challenging, and we have found that a single such sensor takes 5-10 minutes to install and test. Installation of 200 sensors, a number that might be desired for some types of pervasive computing research in a moderately sized home, could require 16-32 man-hours of effort. This is a tremendous inconvenience to both the researchers and the subject in an experiment. Minimization of installation time, therefore, was a key MITes design goal. One way this was achieved was by minimizing points of contact for sensors using accelerometers instead of switch sensors. MITes based on accelerometers are self-contained and sufficiently small so that they can be placed on nearly any household object, and installation requires simply throwing a sensor in a drawer or sticking it with putty to a cabinet door. No multi-point alignment is required, and installation is reduced from 5-10 minutes to 5-60 seconds. Installing 200 single-point-of-contact sensors may take a little as 1-2.5 man-hours of effort, a tolerable amount of time for many subjects.

Ease of use is just as important as ease of installation. Ease of use can be facilitated by having devices with robust communication protocols and good communication ranges so that additional complex devices that introduce failure points such as routers are not necessary. Sensors should require infrequent battery replacement, and when battery replacement is required it should be possible for a non-technical subject to perform this task. Further, it should be easy for a researcher or a subject to add and remove sensors with little or no post configuration. Finally, the system must perform well not only in the laboratory but also in natural settings. Devices should also be packaged robustly, since they can be bumped or jostled (especially the wearable ones), and sensors must perform predictably in realistic conditions, with environmental noise and EMI interference from electric household appliances such as vacuum cleaners, microwaves, cordless phones, WLAN, and Bluetooth devices. We later describe how the MITes system design enabled us to achieve these goals.

3 Existing sensor kits and applicability for in-home studies

When we began exploring the possibility of non-laboratory ubiquitous computing experiments, we were reluctant to invest time in making a new sensor kit given the number of systems that exist and the growing number of commercial sensor network products. Popular wireless sensor network platforms available to the research community include Motes in all their varieties (MicaDOT [15], Micaz [16], iMotes [17], tMotes [18], etc.), uParts [19] (previously Smart-Its [20]), ECOs [21], BTnodes [22], and Millennial nodes [23], among others.

We considered each of the available options relative to the usability goals in Table 1 and the design goals in Table 2. While each of the systems has its strengths, none met our needs. In this section, we explain why.

Goal 1: Ease of installation. Many of the existing platforms were designed to permit multiple sensors to attach to the same wireless transmitter or transceiver. However, making each transmitter multi-functional and expandable adds size, weight, and complexity to the devices. Many use snap-in sensor boards, often with somewhat bulky battery boards (usually based on AA batteries). The iMote snap-in sensor board and battery board, for instance, more than doubles the original node's size and weight. Moreover, some of these wireless platforms work at relatively low Tx/Rx frequencies, such as 433 and 868Mhz, that result in dangling wire antennas of several centimeters long. These cumbersome antennas make the sensors more difficult to install and greatly increase likelihood of breakage or dislodgement. For instance, although the MicaDOT [15] (smallest Mote) and μParts [19] sensor nodes are small, the antenna is large relative to the sensor node, increasing the sensor size in practice.

Goal 2: Ease of use. Most wireless sensor network kits have been designed either to demonstrate novel wireless sensor network architectures (e.g., [15, 16, 18]) or for industrial applications (e.g., [24]). In practice, some of the systems use generic but difficult to customize operating systems, as well as network and MAC protocols that require non-trivial configuration difficult to customize for researchers who are not experts in networked sensors. Quite often, the use of mesh network topologies that promise self-configuration and unlimited coverage area result in increased cost, complexity, points of failure (due to their research/prototype stage), and degraded battery life during research data collections. Existing systems are also not optimized for data collection from multi-modal home sensors. Most available sensor network platforms are designed for either event detection from relatively low sampling rate sensors (e.g., Motes , μParts [19], and BTNodes [22]), or data collection from wearable sensors of relatively high sampling rate (e.g., ECOs [21], MIThril [25], iMotes [26]).

There do exist some off-the-shelf sensor technologies that have been extensively tested in non-laboratory settings by researchers in a diverse set of fields. Examples include actigraphs for aggregate measures of onbody acceleration (e.g., [27]), and power monitoring in electric devices (Watt's Up Pro [28]). These devices do not provide real-time data wirelessly since they were designed as data loggers. More importantly, there is no easy way to integrate data from these multiple devices without requiring a subject to wear an unacceptably cumbersome amount of gear. Acquiring real-time, synchronized multi-modal data simultaneously from low and high sampling sensors is difficult with both wearable and in-home sensor systems that can be easily deployed in the field.

Goal 3: Adequate performance in natural settings. Performance parameters such as Tx/Rx ranges, battery life, and effects of environmental noise have not been reported in the literature for most of the existing sensor systems. Thus, it is difficult for a pervasive computing researcher to estimate resource needs and design a data collection study. The Motes have been extensively tested, but the performance data are not clearly presented by the manufacturer and are scattered among many research publications, making it difficult to find. Moreover, most sensor network platforms are either designed for laboratory settings with no robust packaging whatsoever or with bulky packaging for industrial applications.

Goal 4: Affordability. A significant problem with most of the readily available sensor platforms is their high cost to the researcher. Assuming a installation of 200 sensors distributed throughout a home, the market price for a single system would range from $15,600 (Motes [15, 16, 18, 26]) including only generic node with microcontroller and transceiver) to $26,000 including sensors such as 2–axis accelerometers (commercially available of-the-shelf accelerometer sensor board adds $120 per node in least expensive option for the Mica2DOT [15]).

Of existing wireless sensor solutions, the platforms that most closely meet our usability and affordability design goals are the ECO system and μParts. ECOs are small (12x12x4.5mm, no battery), relatively inexpensive (e.g., $57 production price each including a 2-axis accelerometer) sensors designed for the particular task of monitoring motion in infants. However, their extremely small form factor results in a limited wireless range of 10.7m (testing conditions not reported). Furthermore, ECOs do not allow multi-modal data collection, just 2-axis acceleration. µParts on the other hand, are a system of small sensor nodes (10x10mm) designed for settings requiring a high population of relatively low sampling rate sensors. The sensors were designed for low cost applications with a target market price of $36 (including a light, temperature, and a ball switch sensor for motion detection) in quantities of 100. µParts designers made design decisions explicitly to keep the cost of each device down, such as constraining components to a single side of the PCB and placing the battery on the opposite side. A similar strategy has been employed in the design of the MITes. Despite their low cost and small size, results of testing µParts in naturalistic environments have not yet been reported.

In summary, researchers who want to deploy large numbers of sensors simultaneously in settings such as homes have limited options for robust, affordable, and well-characterized sensor solutions optimized for longitudinal, non-laboratory deployments. This observation led to the development of the MITes.

4 Challenges and achievement of design goals

Designing a system that satisfied our usability goals while maintaining a feasible technical design required carefully balancing all aspects of the hardware design. For example, an adequate battery life could be achieved by selecting high-energy capacity batteries; however, this would lead to unacceptably large sensor footprints increasing installation complexity because such batteries are usually bulky. Sufficient battery life could also be achieved by lowering power consumption, however, power consumption depends on many factors such as the node energy consumption, network topology, and medium access control protocol (MAC). Table 2 indicates how we have achieved the usability goals with the design of the MITes system and the benefit of each goal to the researcher and/or the subject in an experiment.

5 System Overview

The MITes consist of 3.2x2.5x0.6cm and 8.1g (including battery) stick-on nodes that sense environmental or onbody information and transmit it wirelessly to one or several reception nodes. The receiver node(s) collect the sensor data and send it to the host computer (PC/handheld/phone) through the USB or RS232 serial ports. Finally C# and Java code is available to save the incoming data or forward it through a UDP connection for processing in real-time on multiple computers. MITes were designed using a generic communications board with an easy-to-replace sensor connector so that multiple sensor nodes (light, temp, etc.) can be obtained by only replacing the onboard sensor and microcode.

Sensor Design Goals (What)	Implementation (How)	Benefit to Researcher (R) and Subject (S) (Why)
Light weight and small form factor	• Low-profile highly integrated chip components, 3cm Microstrip antenna (possible with 2.4GHz), 3.2x2.5x.0.6cm PCB design, 20mm coin cell battery • Total board size of 3.2x2.5x.0.6cm • Total weight (including battery) of 8.1g	• Facilitates installation (R) • Minimizes sensor dislodgement (S) • Improves portability (R) • Comfortably wearable (S) • Sensors fit on most household objects (R/S)
Self-contained and resistant packaging	• Sensors embedded in low-cost water resistant plastic cases	• Facilitates installation (R) • Physically robust (R)
Self-contained, with single point of contact to body/home	• Single, self-contained acceleration sensor to measure object usage • No dangling antennas • Minimize external sensors whenever possible	• Rapid installation (R) • Easy to reattach if dislodged (R/S) • Attach with only a small bit of putty (R/S) • No parts to break/yank (R/S)
Real-time simultaneous data acquisition from multiple high and low sampling sensors with a single receiver	• FDMA in wearable/high sampling rate sensors, and single channel shared by low sampling environmental sensors • Combination of TDMA and FDMA at receiver to collect data from sensors	• Data acquisition from environmental and wearable sensors (R) • Reduced costs – only one system needed (R) • Rapid installation (R) • Real-time applications possible (R/S) • Many wearable sensors can be used without bulky receiver devices or wires (S)
No pre-configuration required or threshold setting	• Simple star network topology • A featherweight MAC protocol with only one parameter that is fixed (num. of retransmissions) (See Section 4.3) • Receiver outputs simple data format via serial port or USB serial for easy programming	• Minimizes installation time (R) • Subjects can install sensors themselves (R/S) • Facilitates first time setup of system (R) • Decreases points of failure (R)
Good indoor Tx/Rx range and easy to detect if in range	• Transceiver with 0dB output power • PCB design that maximizes antenna ground plane • Optimally cut λ/4 monopole microstrip antenna • Extensive field measurements of outdoors and indoors range (see Section 5.1)	• Reduces cost since a typical home requires few receivers (R) • Facilitates deployment (R) • Facilitate subject mobility (S)
Convenient battery life (mobile MITES > 24 hr; receiver if attached to mobile device >24 hr; other sensors > weeks)	Node • Low power components • Low duty cycles • Embedded intelligence at the sensor node to broadcast information only when necessary Overall System • Simple star topology – no overhead • A Featherweight MAC protocol – no overhead	• Long data collection deployments (R) • Reduce battery replacements (S) • Acceptable weight when worn (S) • Fits in pocket when receiver embedded in mobile device (S)
No dangling antenna	• λ/4 Microstrip monopole onboard antenna and high Tx/Rx frequency of 2.4GHz	• Facilitates installation (R) • Minimizes sensor dislodgement/breakage (S) • Easy to carry/pack (R) • Comfortable and aesthetical form factor (S)
Robustness to environmental noise	• EMI reduction bead cores • Tantalum capacitors where required • Noise efficient PCB design	• Decreases probability of data loss (R/S) • Decreases probability sensor failure (R/S) • Permits deployment in natural settings when noisy appliances are being used (R/S)
Design with low-cost components	• $3 integrated μC and transceiver (RF24E1), $0.01 microstrip antenna, $0.30 CR2032 coin cell battery	• Easy to add as many sensors as desired (R)
Each sensor does one thing well	• One sensor optimized per task (reducing complexity and cost of individual sensor)	• Reduces learning-curve/implementation complexity (R)

Table 2: Sensor design goals (motivated by usability design goals from Table 1) with more detail on how these goals were achieved and the benefit to the researcher and the subject. Some information refers to the mobile and object motion version of MITes only. Some other versions require larger form factors due to external sensor attachments (e.g., a current flow MITes requires a current transformer that wraps around a cable).

The MITes wireless sensor nodes are designed around the nRF24E1 chip by Nordic
VLSI. The nRF24E1 integrates a RF transceiver (nRF2401), an 8051 based microcontroller, and miscellaneous peripherals (9-channel ADC, IO ports, etc.). The nRF2401 transceiver operates at 2.4GHz and data rates of 250K/1Mbps, maximum output power of 0dBs, and 125 Tx/Rx channels. Its cost is only $6 per unit (or $3 in quantities of 10,000). The MITes sensor board also includes the EEPROM program memory, a 16Mhz crystal, a l/4 λ microstrip monopole antenna, and a T matching network. The nRF24E1 is run at 16MHz and the transceiver at 250kbps. The MITes receiver nodes include the same circuitry as the sensor nodes plus a RS232 level converter, a USB to serial converter, and a voltage regulator, so that it can be powered from 3.5 to 12V. The receiver node can also measure 2-axis acceleration onboard or 3-axis acceleration with an attached daughter board. The receiver is powered 100% of the time to avoid data loss and consumes an average of 28mA. The receiver battery life is 43.7hrs using three 1.2V 1400mA NiMH batteries in series.

5.1 Receiver sampling and implications

MITes sensor nodes operate at one of two sampling rates (SR) – low and high. Low SR nodes are those that either transmit only when changes in their sensor's values are detected or those where data need only be transmitted infrequently (e.g., < 10Hz). High SR nodes are those with SRs higher than 10Hz, and in our system include the onbody accelerometers (200Hz). This distinction is important because all low SR nodes operate on a single channel, whereas high SR nodes have dedicated channels, as explained shortly.

MITes receiver node(s) combine frequency division multiple access (FDMA), and time division multiple access (TDMA) techniques to collect the data from the sensor nodes. FDMA is used to assign each high SR rate sensor node a unique Tx/Rx frequency channel so that they can transmit simultaneously without collisions. Furthermore, a single channel is shared among all low SR sensor nodes. Channel 0 corresponding to 2.4Ghz was selected for this purpose, since it provides the higher reception quality given the hardware design (the antenna's characteristics, T matching network, and PCB layout design) as tested in practice (see Figure 3c). Since the master receiver node(s) can only listen to a single Tx/Rx channel at a time, TDMA is employed at the receiver node to collect the data from all the channels by listening a fixed amount of time to each channel. This is possible due to the fast (200μ) channel switching time of the nRF2401 transceiver. Although this is not the most efficient way to use the available spectrum, it allows us to collect data simultaneously from up to 6 high SR (30Hz) sensors using *a single receiver* simultaneously with and a large number (4095) of low sampling rate nodes.[1] Multiple receivers permit additional high SR sensors to be added. The main advantage of combining FDMA and TDMA is that no anti-collision protocol for high SR sensors is required and a simple retransmission strategy can be used to avoid collisions for many low SR sensors in a power efficient

[1] The limitation on the number of low SR nodes results from a packet length restriction made to balance number of possible sensors with likelihood of collision and battery consumption.

manner, as described later.

The behavior of the master receiver node(s) during data reception is as follows: The receiver node spends a time (t_{listen}) of 5.5 ms at each channel currently assigned to sensors present in the system listening for incoming samples. The t_{listen} time should be sufficiently long to allow the reception of samples from the sensor with highest sample rate in the system. In our current configuration, this time is determined by the onbody accelerometers, sampling at 200Hz (5 ms). If no sample is received during t_{listen}, a header sequence is sent to the host computer to indicate a timeout. Once t_{listen} has finished for the current channel, the receiver restarts the t_{listen} timer, checks for incoming PC commands through the RS232 port, and gets the packet received in the previous timeblock from the transmitter (if any) and sends it through the serial port to the host computer. Finally, the receiver changes the reception channel to the next channel in the list and starts reception in it. The process is repeated in the new channel for the maximum number of channels in use. All data is time stamped by the host computer as soon as it is received from the serial port.

The previous design decisions discussed have some practical consequences. For example, our system requires that the list of channels to listen to (low SR shared channel plus one channel per each high SR sensor used) be specified beforehand. Furthermore, the more high SR sensors there are, the lower the effective sampling rate for each channel (due to the TDMA). For example, if there were six accelerometer sensors in our system and the maximum receiver channel switching and sampling rate is 180Hz, the effective SR of the data collected from each would be 33.3Hz (180Hz/6) when only one receiver is used. Another way to think about this is that the channel switching time and t_{listen} introduced by TDMA at the receiver introduce a delay between the sensor samples proportional to the number of channels being listened to. For example, if the receiver listens to two channels, the time between two samples from the first channel would be 11ms ($2 \cdot t_{listen}$) and if listening to three channels, it would be 16.5ms ($3 \cdot t_{listen}$). In practice, we have found the capability to collect data from hundreds of low SR sensors (see plot 1b) and up to 9 3-axis accelerometers (each at 20 Hz) using a single receiver to be sufficient for a variety of research projects. Previous research, for example, has shown that 20Hz is often sufficient for recognizing activities from wearable accelerometers. Adding more accelerometers may provide more value for some applications than increasing the sampling rate of a single accelerometer. Finally, if a higher SR is required, additional receiver nodes can be used.

5.2 Data format and implications

The receiver node collects the sensor data received at the transceiver and sends it to the host computer through the serial or USB ports using the following convention that can be easily decoded by end applications. Each serial port packet consists of a sequence of 7 bytes corresponding to the header (2B), channel (1B), and payload (4B) information. The header indicates the beginning of data packet, and is represented by the ASCII characters 'DD', the channel is the Tx frequency used by the sensor node sending the data, and the payload contains the sensor data.

Different node types encode data slightly differently in the payload, to maximize use of the 4 bytes. Adding a new node type simply requires that a new packet type be defined so an end user application can determine the type of data and then decode it. The payload format for the wearable accelerometer high SR MITes consists of the 10 bit values of the X, Y, and Z acceleration packed into 4 bytes. For the low SR nodes, the payload consists of the sensor ID (12 bits), sensor type (4 bits), and sensor data (16 bits). The system can accommodate up to 16 low SR node types, ten of which are already in use. The sensor data for low SR nodes consists of the sensor value (11 bits), retransmission ID (3 bits), battery low indicator (1 bit), and alive indicator (1 bit). The sensor value is dependent on the node type. For example, the object motion sensor sends the max acceleration (9 bits) and number of continuous activations experienced (2 bits), while the temperature and light sensor only send the sensor value read (11 bits).[2] Even though our current system can only distinguish among 4095 different low SR sensors (IDs) and there are only 16 sensor types allowable we believe these constraints are reasonable given the sensors most typically used in ubiquitous and pervasive computing described in [12], the number of different household objects (3135) found in Open Mind Indoor Common Sense database [12] (a database containing common sense information of everyday objects indoors), and our previous experience installing sensors in real homes.

5.3 Network topology and implications

The MITes networking system consists of a star network topology in combination with a simple featherweight MAC protocol. This design decision was made to minimize overall power consumption, reduce cost, and increase usability of the sensors when deployed in practice by pervasive computing researchers.

A star network topology results when all sensing nodes are in the Tx/Rx vicinity of the master reception node(s). The star network topology is the simplest single-hop network topology available and is widely used for its maximum power efficiency. The use of a such a simple topology has become possible in practice due to advances in transceiver electronics and antenna designs that allow Tx/Rx ranges sufficiently large to cover areas of interest such as one-bedroom apartments, as we have confirmed in practice (See Section 5.1).

Since there are only 125 communication channels available in MITes, it is not possible to assign each low SR node its own channel and still be able to receive data from hundreds of sensors. Thus, given that the probability of collision is low (as we will soon discuss) for low SR nodes that primarily broadcast when changes in their sensor values are detected, we selected a simple featherweight MAC protocol to share a single channel among all low SR nodes. The featherweight MAC protocol, also known as automatic transmission [29-31], maximizes the probability that a packet will be received at the master receiver node(s) by retransmitting it several times. In

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[2] There is currently one exception to the format described for low SR nodes. The RFID wristband node payload format consists of the lowest 30 bits of the RFID tag ID number read.

other words, channel noise and collisions are not avoided but overcome by the retransmission of packets.

Simple retransmission of packets can be highly effective in applications with the following characteristics: (1) the sensors sampling rate or data bandwidth is moderate or low, (2) nodes are physically distributed in a single-hop star topology, (3) the data flow is unidirectional from data collection nodes to receiver node(s), (4) small propagation delays in the order of milliseconds are tolerable, and (5) the application can afford the sporadic loss of data packets during periods of high sensor activity. We believe that these characteristics are mostly true for home deployments with the type of sensors contained in our kit for research studies or activity recognition applications

The advantages of featherweight retransmission are: (1) significant cost savings, since no wireless receiver, carrier detection circuitry, or high precision synchronization clock is required at every sensor node, (2) energy savings, since no time is spent listening for control packets or forwarding data, (3) simple hardware and software implementation, and (4) small network set-up, and maintenance time since almost no time is spent tuning network parameters.

The featherweight protocol retransmits a packet *n* times, using random delays (on the order of milliseconds) between retransmissions to minimize the probability of multiple collisions due to synchronous firings from objects being manipulated simultaneously. The probability of collision is further minimized by the use of short duration packets (8B), and a high wireless Tx rate of 250kps that minimizes time in air (256μs). Note that a Tx rate of 1Mpbs could have been used for a shorter time in air of 64μs at the expense of a reduced Tx/Rx range (due to a decrease of 9dB at Rx sensitivity). Finally, the unique ID of the sensor node is used as the initialization seed for the software random number generator. The random initial and congestion delays introduce an error in the final timestamp of the data of 1-120 milliseconds (for 6 retransmissions and random delays of 20mS). However, this delay is only present for low SR sensors and is negligible for most activity recognition applications.

Assuming that each packet retransmission is independent, the probability of correctly receiving a packet after *n* retransmissions can be computed from $P_{Rx} = 1 - (P_{Loss})^n$. The probability of packet loss depends on the probability of channel impairment (environmental noise, shadowing, fading, reflection, refractions, obstacles, etc.) and the probability of packet collision (due to the simultaneous transmission of different sensor nodes). Figure 1a shows a plot of P_{Rx} vs. *n* (number of retransmissions). For *n*=6 (number of retransmissions used in MITes), P_{Loss} can be as high as 0.3 (30%) and the probability of reception will still be 100%. For a P_{Loss} of 0.6 and 0.7, the probability of reception would be 95 and 88% respectively. Thus, assuming independence between retransmissions, by retransmitting packets channel impairments and collisions can be overcome.

In order to show that the number of collisions is indeed low for activity recognition applications using low SR sensors, we measured the number of collisions over two weeks of real activity sensor data collected in [1-4] from two subjects, each living alone. During this data collection, 77 and 88 sensor boards (not MITes) equipped with EEPROM memories and external reed switches were installed in two single person apartments. The percentage of collisions was 3.2% (77 sensors) and 0.71%

(88 sensors) respectively. These numbers are relatively high because (1) the time resolution of the sensors was ±2 secs after linearly interpolating the timestamps and (2) some of the collisions were caused due to the activation/motion of adjacent sensors. Even if the percentage of collisions is 3.2% in a typical home setting, for the MITes two retransmissions would be enough to increase P_{Rx} to 99.9%.

We also performed a software simulation as in [1-4] to find the probability of collision when the number of nodes is increased from 1 to 500 and each sensor is assumed to fire randomly over time windows of 10, 5, 1, and 0.5 seconds. The simulation results over 10,000 windows are shown in Figure 1b. The graph shows that even when all the sensors are fired randomly every 5 secs, P_{Rx} is better than 97% for 500 sensors. Even in a worse-case scenario where all 500 sensors are fired every 0.5 seconds (as in a period of extremely high activity with multiple people), P_{Rx} is 0.6 and can be increased to 1 by retransmitting 6 times. The simulation was run using a message length of 256µs (as used by the MITes).

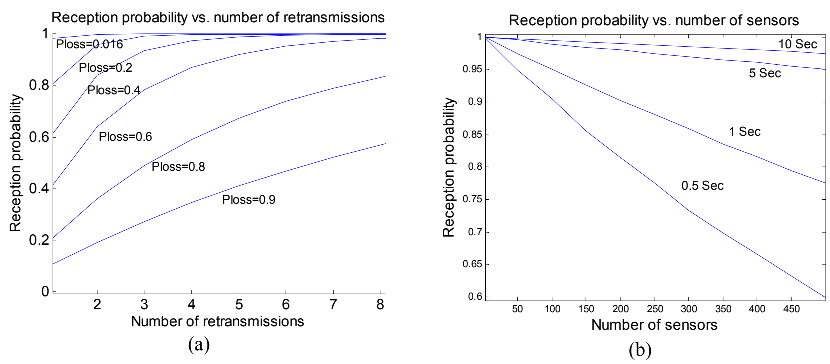

Figure 1. (a) Plot of P_{Rx} vs. number of retransmissions and (b). Plot of P_{Rx} vs. number of sensors in the system.

5.4 Multi-modal sensor types

Using the design and protocols described above, we have been able to create a system of multi-modal sensors where a single receiver can collect 10 types of data from a home setting. Table 3 presents a summary of the different types of MITes sensors we have built and evaluated as well as well as some of their most important parameters. For battery life computation we assume a 0dB Tx output power, six retransmissions per sensor activation, and a CR2032 battery, if not otherwise noted. The cost listed in Table 3 is the production cost (administration and NRE cost not included) and was calculated assuming a production quantity of 50 and a two-month lead time, as quoted by a U.S company (including PWB tooling, masks, stencils, soldering, and no electrical testing). Finally, an asterisk in the price column indicates that the hand labor cost of soldering the external sensor was not included.

The MITes kit has been designed so that it can be easily expanded to include a few additional node types. Any sensor with RS232, I2C, or SPI output can be easily attached to the nodes with minor firmware modifications. Adding sensors with analog output is also possible, however, external circuitry would be required to condition the signal to the ADC input voltage range of 1.5V. A low SR location tracking node useful for much pervasive computing research, and a high SR audio node that could

MITES Type	Measures	Sensor	Range	Res	Battery life (days)	Cost ($)
Object usage	Object manipulation	Accelerometer. ADXL202	±2g 2-axis	0.005	46, 10Hz	28.43
Mobile	Onbody Acceleration (Acc)	Accelerometer. ADXL202/10	±2g or ±10g 3-axis	0.005	1.5, 200Hz	44.3
Temperature	Temperature	MAX6677	–40C to 125C	±1.5	1309, 1Hz	20.3*
Light	Ambient light intensity	Digital TSL235R	0.003-1ku W/cm2 at 320-1050nm	16bit	620, 1Hz	21.0*
Current sensing	Current consumption	Split-core current transformer	30mA to 28A	10bit	14, 1Hz	75.5*
Heart rate	Beats per minute	WearLink Polar chest strap/receiver	30-240 bmp	1	2.5 @1-255bmp 9Vbattery	95.5*
Ultraviolet exposure	Onbody UV exposure	UV Photodiode Eryf by Sglux	0-28UV	0.027	2.58, 1Hz	93.5*
Location beacons	Rough location with respect to a receiver node	Tx beacon and Rx node counting packets received	2.5, 3.8, 4.8, and 9.4m outdoors 0.7, 3, 4.5, and 6m indoors	-	5, 12Hz	48.5*
Proximity	Proximity to area (binary output)	PIR motion KC7783R	Circle with 0-2.6m varying radius (by replacing lid)	1	47.5, 2Hz 9Vbattery	33.1*
RFID wristband	Acc + RFID tagged objects	ADXL202/10 M1 Mini SkyTek	10cm	-	0.2, 5Hz 4.7 Li-Po.	181*

Table 3. Summary of MITes types available and performance parameters.

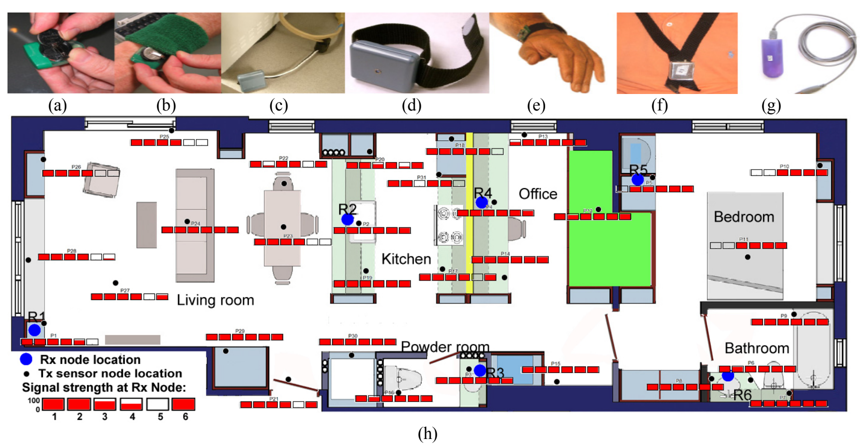

Figure 2. Images of MITes (left to right): (a,b)mobile, (c)current sensing, (d) UV, (e) RFID, (f) location, (g) USB receiver, and (h) PlaceLab Tx/Rx range at 31 test points.

transmit raw audio would be valuable additions to our kit. These additions could be made in future work without impacting the performance characteristics of the other sensor types. Figure 2 shows some images of existing MITes.

Finally, MITes can be extended to cover areas larger than an individual receiver node's Tx/Rx range by simply adding more receivers. Each receiver must be attached to a PC or small microcomputer (such as the Maxim-Dallas TINI board) that broadcasts the data through a UDP connection to a central computer. The central computer timestamps, stores, and processes the data. Delays introduced by the UDP network communication can be compensated for by time stamping the data at each receiver node and synchronizing the computers. This architecture has been implemented in a live-in laboratory that uses six receivers.

6 Evaluation

As each MITes type is used in ongoing work (see Section 10), researchers are validating their performance in use in natural environments. Here we focus on evaluation of data transmission that applies to *all* the MITes types and demonstrates that the protocols described in Section 4 provide good performance in a real home for both low and high sampling nodes when multiple node types are used simultaneously.

6.1 Wireless link

The transmission reception line of sight (LOS) range was first measured experimentally outdoors in an open athletic field free of obstructions. The Tx/Rx range was measured by broadcasting 180 [8B] packets per second on channel 0 (2.4GHz), counting the number of intact received packets per second (PPS) at the receiver node (2B CRC error checking), and computing the mean over a 100s window. The plot shown in Figure 3a was generated by changing the distance between the Tx and Rx nodes in increments of 7.6m while keeping the antennas parallel to each other. The plot in Figure 3b was generated by additionally rotating the transmitter antenna randomly by hand trying to cover as many antenna orientations as possible; this plot shows the antenna directionality or robustness to changes in antenna disposition in applications such as wearable computing. The final range was computed as the distance at which the average number of packets received drops to 90%. The experiment was performed on a sunny day with 56% RH, 8.9°C, 0dB Tx output power, and nodes placed 1.2m from the ground.

Table 4 shows the resulting Tx/Rx ranges for multiple commercially available antennas. Given the size of the microstrip antenna, this compares well with other bulkier or more expensive options.

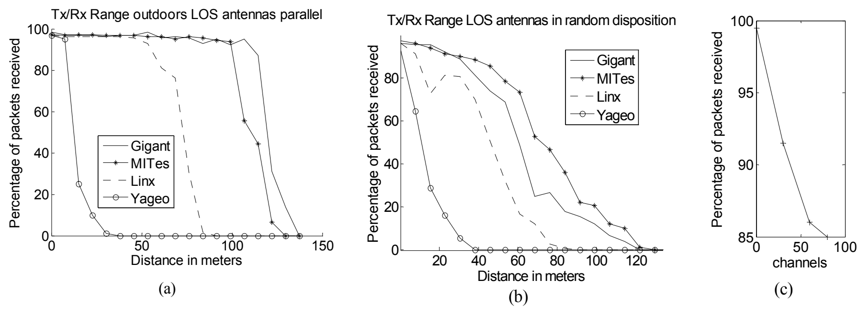

Figure 3. (a) LOS range outdoors with antennas parallel. (b) LOS range with the Tx antenna in a random disposition. (c) %Packets received(y) vs. Tx/Rx channel(x) 0-81.

	MITes microstrip ($0.01)	**Linx Chip($1.5) ANT2.45CHP**	**Yageo chip ($3)**	**Monopole Gigant ($35)**
Parallel orient.	106.6 m	60.96 m	15.24 m	114.3 m
Random disp.	38.1 m	15.24 m	7.62 m	30.48 m

Table 4. Tx/Rx LOS range outdoors with different antennas on the same MITes.

A more useful test for many pervasive computing applications than an open field LOS test is a test in a typical home environment. We therefore tested the wireless signal indoors in an instrumented residential home (PlaceLab).[3] The Tx/Rx range was again measured by broadcasting 180 PPS, counting the number of received PPS at the receiver node, and computing the mean over a 100s window. We first measured the percentage of packets received at each of the six receivers roughly located in every room while installing a Tx sensor node at 31 *worse case* locations throughout the apartment. Figure 2h shows the location of the receivers as blue dots and the location of the test points as black dots. The Tx sensor node was installed with random antenna orientation, and varying heights from the floor while all room doors were shut and one person was present in the apartment. Some of these locations consisted of installing the Tx node inside closed drawers and cabinets (places where object motion sensors might be placed). We found that the average percentage of packets received at each receiver R1…R6 was 88.6, 88.4, 93.5, 98.4, 70.9, and 75% respectively. Figure 2h shows the packet reception probability at each receiver with respect to each of the 31 test points as bars. The tests show that it is possible to receive 98.4% of the packets correctly using only one receiver node located at the center of the apartment. In this setting, we can further increase the reception probability at every receiver to 100% by retransmitting each packet two times (see plot 1a). This result strongly suggests that MITes are suitable for simple data collection in natural settings. It is important to note that the range described in the previous experiment results when using a high 16-bit error correction to assure the quality of the packets received.

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[3] This is a 16.5x5.2m condominium in a modern building. Interior walls use steel frame construction with drywall. The environment has several kilometers of digital and electrical wiring embedded in the walls, which may provide far more wireless interference than in a typical stand-alone, single family home.

6.2 MITes environmental noise, number of wireless broadcasts, and installation time

In order to characterize the MITes performance in the presence of environmental noise, we measured the maximum increment in the percentage of packets dropped while the WLAN was on at the PlaceLab (as a worse case of environmental noise) and when the following devices were also turned on: (a) a vacuum cleaner 3.7% (drop), (b), the microwave 4.3% (drop), and (c) a cordless telephone at 2.4GHz 1.2% (drop). The drop just by turning on the WLAN is 0.006%. To maximize the wireless Tx/Rx performance, we also found the channel with best Tx/Rx reception performance experimentally by measuring the percentage of packets dropped at each channel. The plot is shown in Figure 3c, and the channel with best performance is channel 0. This channel was chosen as the shared channel for the low SR sensor nodes in our system.

To provide a more intuitive characterization of the battery life of MITes, we measured the total number of wireless broadcasts supported using a CR2032 coin cell battery. This was measured by programming three MITes sensor nodes to transmit packets continuously until they ran out of battery. The average number of total broadcasts is 20.85 million. Finally, we measured the average installation time per sensor experimentally by asking two subjects to install sensors in their own homes by themselves. Subject one installed 75 sensors in 45min and second subject installed 100 sensors in approximately one hour. These gives an average installation time per sensor of 36 seconds in both experiments.

7 MITes deployment and summary of contributions

Because MITes meet our usability criteria in Table 1, we have been able to deploy them in a variety of research projects both by the authors and others. Of particular interest to medical researchers is that they allow the simultaneous measurement of two or more states. For example, medical researchers are using MITes to study the relationship between physical activity and other states, such as heart rate and use of objects in the home (e.g. television). The mobile MITes are being validated by researchers at Stanford Medical School who are reporting excellent performance relative to the state of the art actigraphs used in that field, and they have been used in projects on detecting convenient times to interrupt, the correction of human balance, feedback systems for rehabilitation, as well as context-awareness and activity recognition. They are being used in two external medical projects where the sensors are worn for days or weeks at a time so medical researchers can study the behavior of people in naturalistic settings, and in both cases the mobile MITes are being used in combination with other node types such as heart rate, current flow, and light. The UV MITes were developed for cancer researchers interested in the relationship between sun exposure and physical activity. The proximity MITes [13] were developed in collaboration with Mitsubishi Electric Research Laboratories (MERL) and are being installed by MERL in an office to study behavior in office spaces and to develop real-time recognition of meeting, visiting, and chatting events. Finally, 125 object usage MITes have been used in four different research studies in the PlaceLab.

In summary, we have designed a sensor kit that is affordable and robust and optimized for longitudinal, non-laboratory deployments. This kit can be used by researchers who want to deploy large numbers of sensors simultaneously in settings such as homes.

A website with MITes hardware and software specifications provides more detail [32]. Researchers interested in using MITes in their own work should contact the authors. In practice, the greatest barrier to using MITes is ordering the MITes hardware, attaching the specialized sensors, and programming the EEPROM, since the devices are not commercial products.

Acknowledgements

This work was supported, in part, by National Science Foundation ITR grant #0313065 and the MIT House_n Consortium. The proximity MITes were developed in collaboration with Mitsubishi Electric Research Laboratories (MERL).

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