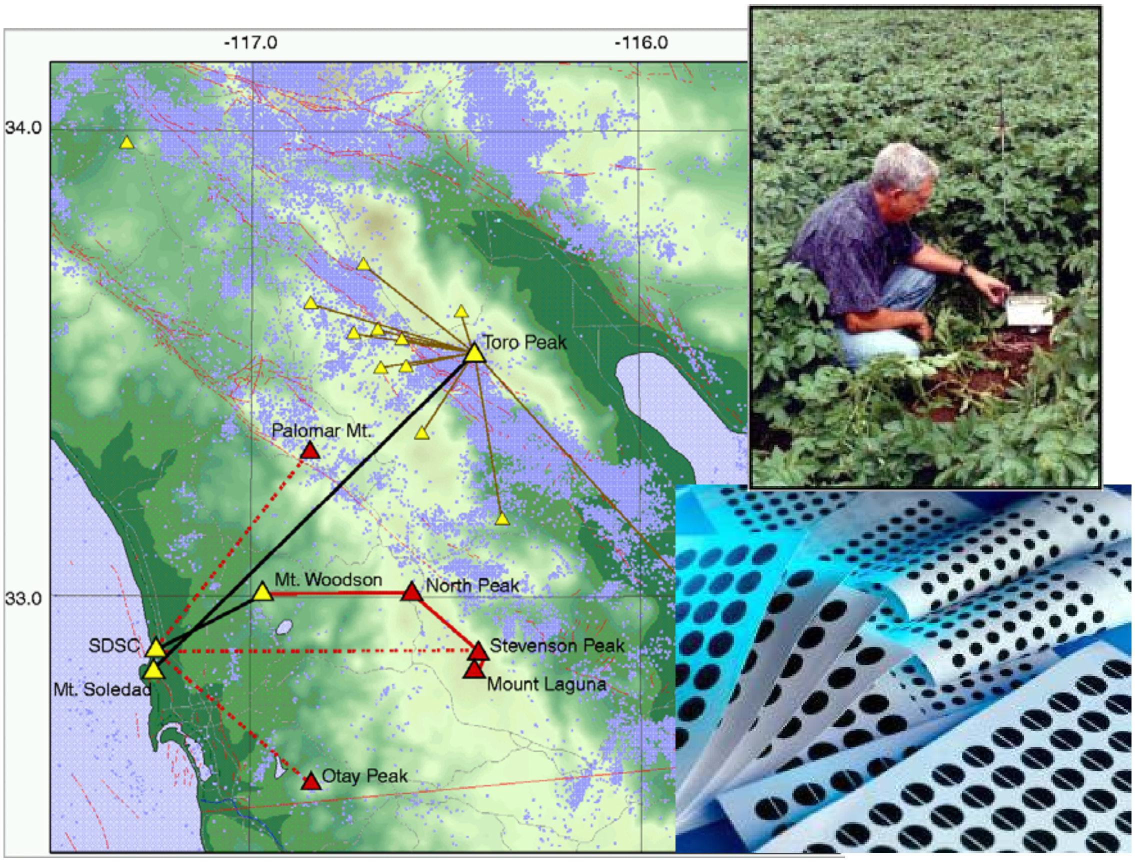
WIRELESS SENSOR NETWORKS
TECHNOLOGIES AND CAPABILITIES



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I. INTRODUCTION

The use of electronic instruments for data-acquisition and monitoring is not a new concept: for years technicians and engineers have relied on digital measurements of characteristics as simple as temperature and as complex as pH or radioactivity. Gradual refinements in the measuring techniques, the sensing equipment, and the computer processing support for electronic sensors have led to more widespread use of monitoring technologies. Yet, the technologies represented by today's electronic transducers are fundamentally the same as those developed throughout the twentieth century, which intake and output electronic voltages, the difference between which can be interpreted to describe the physical phenomenon being monitored.

For a number of reasons, this style of data transducers has been limited to small, centralized applications. Foremost, the presence of wires connecting each sensor to its power supply and data processor has limited each sensor's versatility. But other factors have provided limitations as well, such as the cost of computing equipment and technical knowledge required to assemble even a simple system of sensors. In short, the large numbers of variables in a traditional sensor system, when combined with the numerous points where error can be introduced, have made large monitoring systems impossible to construct.

Furthermore, the difficulty of constantly monitoring every point in a complex system with traditional technologies has contributed to a specific underlying attitude among researchers. In many cases where a complex system is being studied, researchers place sensors at a few critical points throughout a system, collect data at several critical points in time, and interpolate between the resulting data to describe other points in the system. The uncertainty in the properties of un-monitored points can be deduced by the use of statistics, but the point remains that these points are described by assumptions and not measurements, and could therefore be wrong. The assumption that many systems are homogenous, that they have the same properties throughout, is a defense mechanism science has developed because of the difficulty of monitoring every point in a system.

A family of emerging technologies, in the form of distributed wireless sensor networks, offers relief to the gross uncertainties of traditional monitoring technologies. Wireless sensors are a recent development in computing technology that allows for continuous monitoring of all the physical and temporal points that describe a system. Commercially available sensor packages combine the newest technology in transducers with self-contained power supplies and with wireless communication systems, a combination that eliminates the need for the wired connection of a sensor to its control system. Each sensor platform, or "mote", is further equipped with its own micro-processor and memory, so it can run simple computer programs to conserve power and maintain a data connection to its control system.

The advent of monitoring technologies that require neither extensive support equipment, nor technical knowledge by the user, offers no less than a fundamental change in the way scientific research is done. Already, the results of several trials with these sensors have led to revisions of current beliefs on several scientific issues. As wireless sensors continue to become commercially available, this paper seeks to outline the state of the art in wireless monitoring, and likely growth areas for this technology in the next several years. As with the introduction of any new technology, the use of wireless networks has created a growing number of questions its creators and users must answer. The need for a dialogue exists where these questions can be answered, lest the technology or the public be harmed by the failure to make policy regarding this new arena of technology.

II. CURRENT STATE OF THE TECHNOLOGY

Recent advances in wireless sensor networks can be reduced to two radical innovations: improvements in sensing and data processing, and innovations in the field of wireless data transfer. We will discuss these two areas separately before detailing their integration into pervasive monitoring systems.

Smart Sensors

As mentioned earlier, many of the electronic sensors developed during the twentieth century are electronic transducers, which intake a constant supply voltage, and output a varying voltage that can be converted into data. A simple example of such a sensor is a thermometer, usually comprised of an electronic resistor whose resistance changes with temperature, allowing more or less voltage to pass through it. Simple physical sensors can detect moisture, tilt angle, magnetic field and acceleration by using simple physical properties of their construction material. Other examples of simple sensors include light bulbs and light detectors, and beepers and sound-detecting microphones.

At the other end of the spectrum, a number of higher-level sensors exist as well. These sensors include radiation detectors and global positioning systems. Advanced sensing systems like these must carry out a number of complex processes before an output voltage can be generated. A movement to integrate silicon microprocessors into sensors began with these complex sensors, but has recently begun to spread toward simple sensors as well. Perhaps the driving force behind this movement is the increasing physical capacity and decreasing size of micro-processors. If some of these simple sensors could be written into a silicon wafer rather than attached later on, the cost and reliability of manufacturing these items would increase dramatically.

The drive to pioneer next-generation sensor technologies is led by a single company, Crossbow Technology, Inc., of San Jose, California, which works closely with the Intel Research Lab at Berkeley, and the UC-Berkeley Computer Science Department for research and development. Crossbow currently makes three models of wireless motes, which are commercially available through their website. Crossbow is also one of the first companies to combine sensing technologies with data processing abilities, by placing a microprocessor inside each of their motes.

The reason previous sensor systems have relied on a single, central computer to reduce data is because of the difficulty of programming the computer. Converting raw sensor voltages into useful data requires the user to write a program that will receive the information from a sensor, carry out the necessary calculations, and store the data for later use. Therefore, by installing microprocessors on individual motes, each mote needs to be programmed by a user. The programs must also be stored in a memory chip on the mote, whose physical size and data capacities are heavily constrained.

For this reason, Crossbow's motes employ the "TinyOS" operating system, developed as open-source software by the University of California at Berkeley. The programming language of TinyOS was established for the sole purpose of writing full programs with the fewest number of characters necessary – because data characters each require a small amount of space in a computer's memory, and a mote's tiny memory chip can fill up fast. Users of TinyOS compose programs in a shell system that runs inside a standard Mac or PC operating system, and programs can then be download directly or wirelessly into each mote. Once a mote is equipped with a sensor board and a programmed micro-processor, it can begin retrieving the requested data and transmitting back at given intervals.

Crossbow has made various kinds of sensors commercially available to the public. In various combinations, the available technologies include accelerometers, inertial positioning systems, magnetometers, tilt sensors, and GPS systems. These can be combined with simple technologies such as thermometers, barometers, light sensors, moisture sensors, pressure sensors, sound detectors, LED lights and beepers. One of Crossbow's simplest sensor packages, the MTS-300 CA, is shown in Figure 1 with its included sensors.

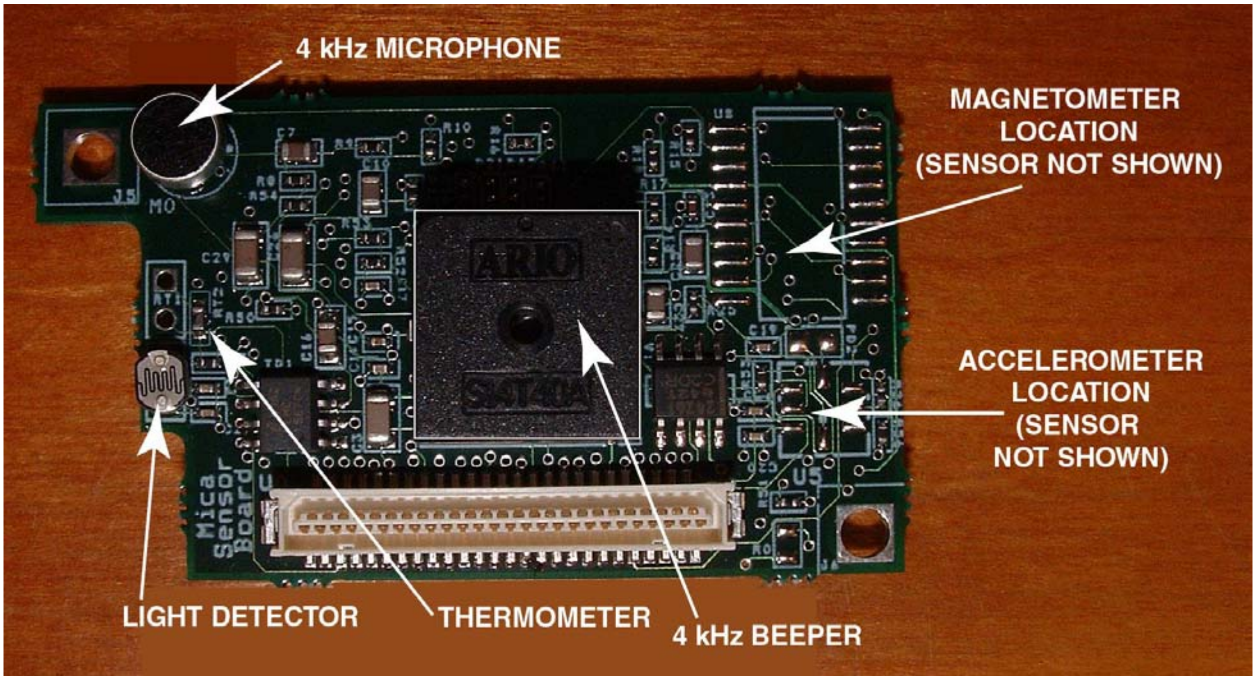


Figure 1 – Photograph of Crossbow MTS-300 CA Sensor Board with each individual sensor labeled. The vertical dimension of the board is about 1½ inches.

Mesh Networking

Accompanying the improvement in sensor technology is the concept of retrieving data and re-programming motes wirelessly. To accomplish this task, a new concept of connectivity called "mesh networking" has been implemented by Crossbow in some of their sensor designs. This technique for routing wireless data packets allows dynamic, short-term connections that will change with the environment being monitored. In this system, motes are allowed to enter or exit the network without an interruption in the overall system.

Mesh networking is fundamentally different from the wireless technology used today. For example, cellular phones and wireless internet connections, which require each wireless device to connect directly to a hub, will not function if a receiver is out of range, or if the connection is obstructed. Hence, in many buildings, or in mountainous terrain, these devices will not work. A visual analogy for hub networking is the spokes of a wheel, where each individual spoke must connect directly to the single center hub.

In mesh networking, most wireless devices connect directly to a central hub as well. However, a device that is out of the hub's range is capable of locating and establishing connection with another device instead. By forming a relay connection through a device that is already in range of the hub, the data can be transmitted as faithfully as if coverage existed in that given area. Figure 2 depicts a schematic diagram of hub- and mesh-networking systems.

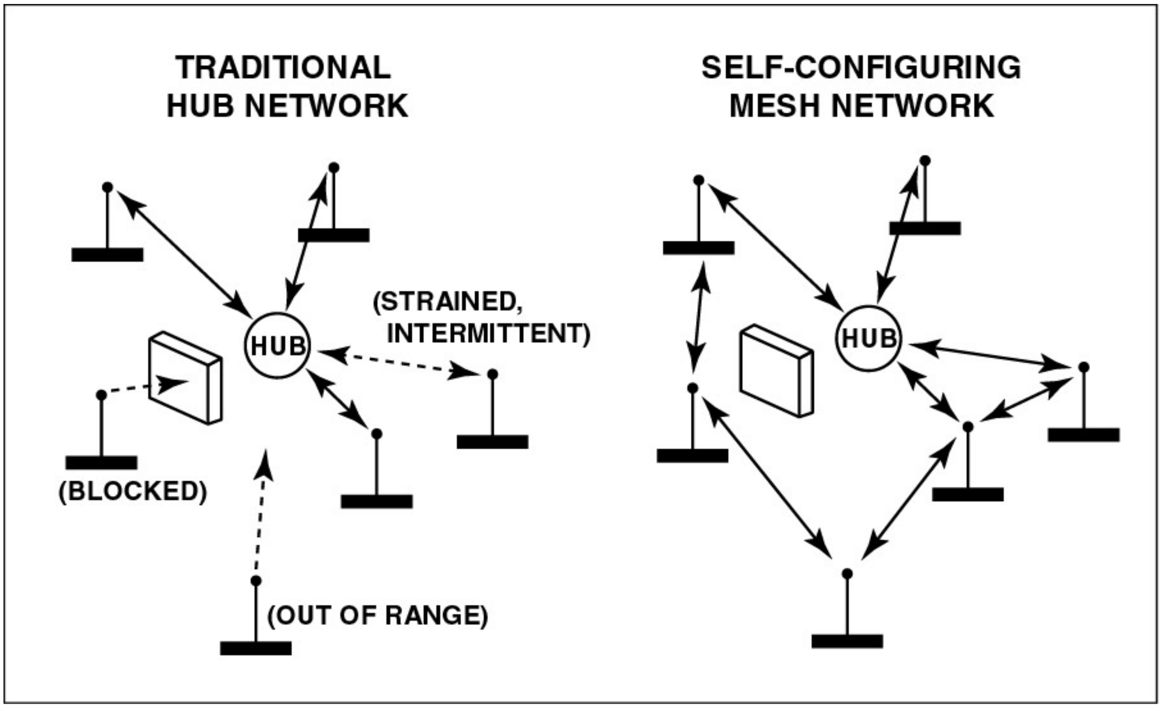


Figure 2 – A schematic drawing showing the superior connection capabilities of a mesh network.

One of the most obvious advantages to a mesh network system involves the monitoring of moving objects. A GPS position sensor moving through a grid of wireless relay points can have its position constantly known, even though it doesn't maintain a consistent connection with any single sensor. An analogy would be a car driving through a city where each street corner is equipped with a wireless mote. The car's position is constantly known because each sensor sends a signal when the car passes through its intersection, leaving a history of chronological position measurements.

Although wireless sensor networks are the first place to employ mesh networking technology, this new method of connectivity shows promise for other wireless communication as well. Experts feel that mesh networking may be a future growth area for telephone and wireless internet sectors. Configuring in this fashion would allow a greater coverage area with today's infrastructure; similar coverage could also be achieved with less infrastructure, thereby lowering costs for companies and reducing impact on the surrounding area. Similar to how cellular phones became widespread in developing nations without telephone infrastructure, the reduced need for infrastructure may make mesh networking an attractive method for spreading wireless internet technology to developing nations.

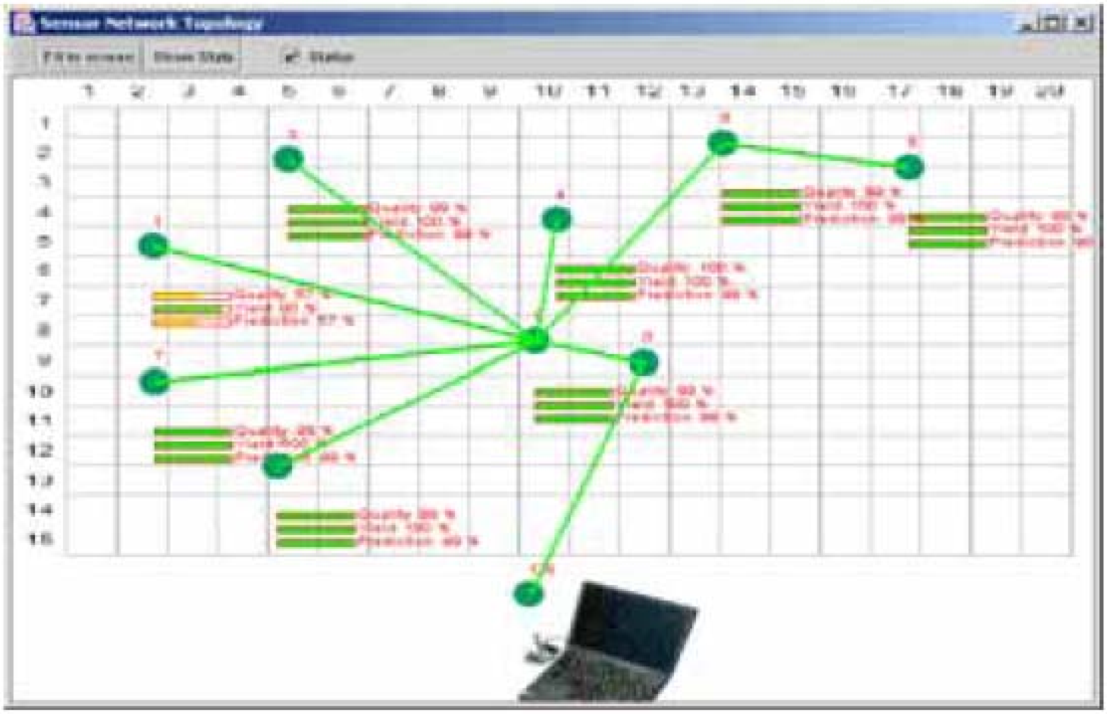


Figure 3 – A Crossbow program shows a map of the active connections between eight motes, their hub, and the host computer. Photo courtesy of Crossbow Technologies.

Integrated Wireless Sensors

The powerful combination of cutting-edge electronic sensors and an efficient, self-adapting network is valuable, but like any technology, this system faces limitations. Since each sensing mote is self-contained, a power source such as a battery must be included. One of the simplest TinyOS programs that can be run on motes is designed to leave the mote's electronic components turned off until they are needed. Power-intensive processes such as running the sensor board are not affected by this loss. When TinyOS then prompts for the board to collect a data sample, the sensors are switched on for a period of several milliseconds, then switched back off once the data is recorded. In this fashion, with most of the electronic components turned off 99 percent of the time, battery life can be prolonged considerably.

Even with a power conservation system that only activates a mote for milliseconds at time, the gradual degrading of the battery voltage is the most limiting factor for current mote designs. Although software systems can be designed so data integrity is not compromised by decreasing battery power, each sensor will have a finite battery life from the date it is deployed. Based on the difficulty of locating the sensor, replacing the batteries after a time span may be difficult. Crossbow estimates that a mote, when outfitted with a temperature sensor that takes a reading every fifteen minutes, will last about two years with two AA-size batteries. If this same sensor is switched into always-on mode, it will last about two weeks.

As a battery approaches the end of its finite lifetime, its supply voltage gradually decreases to zero. Before the point of complete power loss, a battery is still useful, but compensation must be made for the changing battery voltage. The method used by Crossbow sensors to prevent data skewing by a fluctuating power source is a self-calibration system. Because the motes contain a processor to convert raw transducer voltages to data points, each mote can easily keep track of its own power supply and ensure that the correct voltage is used when calculating data values. The limitation of such a system, of course, is that when a battery runs too low, a sensor stops working.

Another novel way to prolong the battery life of a mote is to institute a system of selective monitoring. The numerous sensors can be employed in combination to activate only when certain phenomena take place. For instance, in an experiment described later on, researchers monitoring nesting birds programmed their sensors to record data only when they detected a certain temperature, such as would occur when the bird was in the nest. By combining the efforts of several sensors in this fashion, researchers can obtain their data with greater power efficiency.

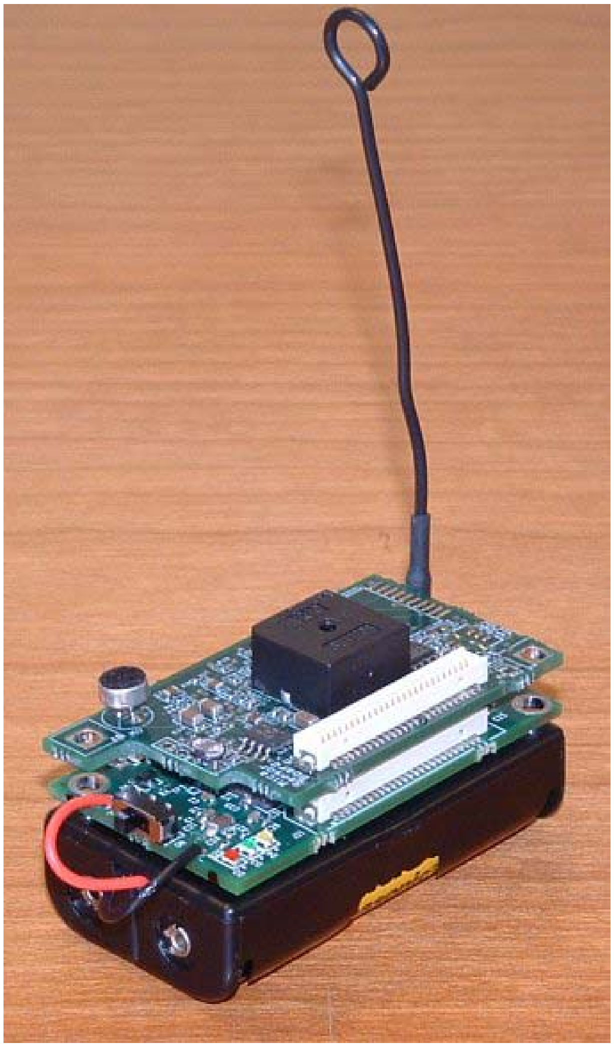


Figure 4 – A complete Crossbow mote uses the sensor board (upper green board), processor board (lower green board), and battery pack (black bottom portion). An antenna is needed for wireless transmission.

Aside from technologies to prolong battery life, several ideas currently exist for recharging the power supply for each mote. Because the electricity demands of each mote are very small, a photovoltaic cell would actually be quite useful in the right environment. Photovoltaic cells are not very efficient, but as long as they several hours of direct sunlight, they would supply enough power to meet the needs of a low sample-frequency mote. Another idea for harnessing external power is the vibration-generating technology currently employed on some wrist watches today. If a mote were to be installed on a device that would experience movement, this concept would be similar to a solar cell in its ability to supply a small amount of power.

Apart from size, storage, and power limitations, the ability of many users to implement wireless sensor networks may be hampered by their cost. The most rudimentary sensors, such as the one shown in Figure 4, have temperature, humidity and light sensors built into them. Crossbow estimates that these sensors cost about $20 each for the sensor board $100 each for the processing and wireless network components. In large enough quantities, these figures can be driven to less than $100 per mote. Within a period of several years, however, this figure could decrease by a factor of 5 to 10. Currently the most limiting factor is the cost of the wireless networking components, and it is hoped that the anticipated widespread growth of this technology can drive the cost of each processing board into single-digit figures.

III. CURRENT APPLICATIONS OF THE TECHNOLOGY

Unlike previous wired systems, wireless sensor technology will allow for data collection at many points in a given study area. The small size of wireless motes will minimize their impact on the study subject, while a unique power-management scheme will allow sensors to operate for years without maintenance. Additionally, data is processed in the mote's own microprocessor, which automatically accounts for the effect of battery degradation on data. A number of experimental applications have taken place, each using a small wireless sensor network.

Perhaps the most famous of these trial applications is the habitat monitoring of the Leach's storm petrel that took place in Great Duck Island, Maine in the summer of 2002. Researchers from Intel's Berkeley research laboratory worked with the UC-Berkeley computer science division to develop a small mesh network and install it on the island. Designed to collect simple temperature and humidity data, the system was installed in the petrels' underground burrows to monitor how much time the birds spent in the nest during the egg-laying period. The system also used temperature sensors to monitor the weather on Great Duck Island, and infrared sensors to verify that birds were actually present in the monitored burrows. Perhaps the most interesting aspect of the Great Duck Island trial was the data-retrieval system devised by researchers. As the island is uninhabited by humans, the data hub in this case was a solar-powered telephone connection, which would collect the aggregated data from the sensor network and relay it by satellite connection to the researchers in Berkeley. The petrel experiment was declared a success after one million data points were collected; the data has now been supplied to biologists to assist in their research. As a proving ground for both sensors and mesh networks, the Great Duck Island trial is very important to note, because the first generation of both technologies performed above expectations in a non-laboratory environment.

In the wake of Great Duck Island, a number of more practical trials have been started to accompany the technology's commercial release. The Center for Embedded Network Sensing (CENS) at UCLA is the first facility to use sensors for chemical monitoring. By burying motes in a 1-meter grid pattern over an alfalfa field in Palmdale, California, the CENS trial is working with the Los Angeles County Sanitation District, to verify patterns of ground water runoff in the area. Due to water shortages in the region, the county has proposed that farmers use treated wastewater for irrigation, rather than drawing from the water supply. The problem with this proposal is that treated wastewater contains high nitrate levels, and excessive irrigation use of this water could cause nitrates to leak into the ground water supply. By placing motes at regular intervals in the field, researchers can identify nitrate concentrations while they are still in the topsoil; the only other way to monitor is by digging wells, which will detect problems only after the ground water has been contaminated. Furthermore, a greater number of monitoring points allows researchers to identify areas with particularly high concentrations, and to identify why the circumstances differ across the study area. Data showed that different patterns of depletion were occurring in various zones, and that these depletion models were consistently interacting and changing.

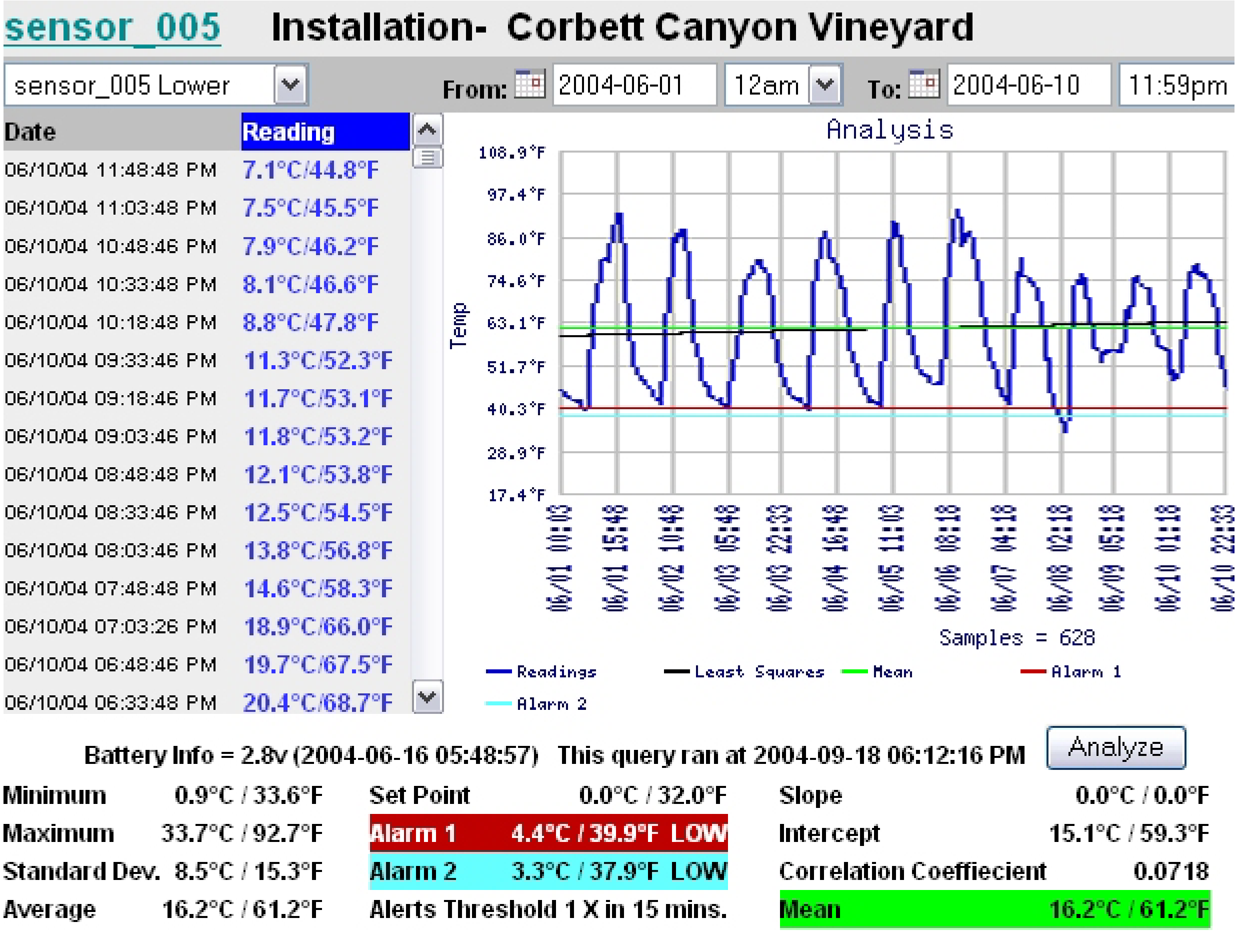
Just as the distribution of sensors in Palmdale allows Los Angeles County to monitor nitrates before they enter the groundwater, similar systems are possible for chemical monitoring across the country. Chemical sensors are currently the sensing industry's highest priority for research and development, so technology is quickly improving. For groundwater monitoring, two approaches are possible: either through development of a generic sensor that can be deployed anywhere and monitors the three or four most common water contaminants, or by developing customized sensors that monitor only the attributes of interest in a certain area. The cost of acquiring customized sensors will likely be higher for such agencies as the Los Angeles

Sanitation District or the EPA, but the payoff will be greater as well. As seen in Palmdale, the source of a pollutant can be tracked very precisely, allowing authorities to deal with problems in their point-source phase, before the ground water has been affected.

If the advent of wireless sensor networks shows promise for groundwater monitoring, air quality is not far behind. UCLA's CENS recently used a network of motes to test the theory that a forest canopy will act as a sink for carbon dioxide, breaking down the gas during the plants' natural respiration process. In a patch of forest in Carson, Washington, researchers placed motes near tree tops to monitor carbon dioxide levels from nearby factories; while the sensors and networks were effective, results were inconclusive because the air above the forest couldn't be easily monitored. Researchers hope to try again soon, this time using machines that will crawl along cables strung between treetops, extending and lowering sensors into the surrounding air. Advocates hope to make the point that a manufacturing plant's carbon dioxide output should be scaled to the surrounding environment's ability to break the gas down.

Similar to water monitoring, trials of carbon dioxide sensing in remote areas hold promise for the spread of sensing into more complex systems. In a city, where few trees exist to break carbon dioxide down, emissions of carbon monoxide and dioxide can endanger city inhabitants as well as the environment. A small trial conducted by University College London, UK, has concluded that although the carbon dioxide level may be consistent throughout an urban area, high concentrations of carbon monoxide may be localized to a busy intersection or road, while levels are normal only fifty feet away. In this case, wireless air quality sensors would be able to alert pedestrians of hazardous areas, and they can choose an alternate walking route. Such air quality sensors will not only lead to greater knowledge of urban pollution problems on the long term, but will protect city inhabitants on their daily commute as well.

Other trials of wireless monitoring technology have focused on commercial applications as well, as in the case of the Corbett Canyon Vineyard in California. Sensors embedded in the grape vines and the surrounding soil take measurements of temperature and moisture every fifteen minutes, and once surrounding hubs collect and relay the data, irrigation systems can be automatically activated to water the plants, or the vintner can be alerted of low temperatures that would degrade the quality of the wine. Corbett Canyon has also built a web-page interface for retrieving data on its vines, and the information is transmitted in real-time. Other wineries have begun to use the technology as well, including the King Family Farms in British Columbia, Canada. Using wireless monitoring for agriculture is by no means limited to wineries: any crop has its optimum levels of temperature and moisture, and better knowledge of each plant's status will in turn lead to more responsible agriculture, allowing irrigation systems to water only the crops that require sustenance. Figure 5 shows a sample of the data collected from a single sensor at Corbett Canyon.



sensor_005 **Installation- Corbett Canyon Vineyard**

sensor_005 Lower From: 2004-06-01 12am To: 2004-06-10 11:59pm

Date	Reading
06/10/04 11:48:48 PM	7.1°C/44.8°F
06/10/04 11:03:48 PM	7.5°C/45.5°F
06/10/04 10:48:46 PM	7.9°C/46.2°F
06/10/04 10:33:48 PM	8.1°C/46.6°F
06/10/04 10:18:48 PM	8.8°C/47.8°F
06/10/04 09:33:46 PM	11.3°C/52.3°F
06/10/04 09:18:46 PM	11.7°C/53.1°F
06/10/04 09:03:46 PM	11.8°C/53.2°F
06/10/04 08:48:48 PM	12.1°C/53.8°F
06/10/04 08:33:46 PM	12.5°C/54.5°F
06/10/04 08:03:46 PM	13.8°C/56.8°F
06/10/04 07:48:48 PM	14.6°C/58.3°F
06/10/04 07:03:26 PM	18.9°C/66.0°F
06/10/04 06:48:46 PM	19.7°C/67.5°F
06/10/04 06:33:48 PM	20.4°C/68.7°F

Battery Info = 2.8v (2004-06-16 05:48:57) This query ran at 2004-09-18 06:12:16 PM

Minimum	0.9°C / 33.6°F	Set Point	0.0°C / 32.0°F	Slope	0.0°C / 0.0°F
Maximum	33.7°C / 92.7°F	Alarm 1	4.4°C / 39.9°F LOW	Intercept	15.1°C / 59.3°F
Standard Dev.	8.5°C / 15.3°F	Alarm 2	3.3°C / 37.9°F LOW	Correlation Coeffiecient	0.0718
Average	16.2°C / 61.2°F	Alerts Threshold 1 X in 15 mins.		Mean	16.2°C / 61.2°F

Figure 5 – Temperature data from single mote at Corbett Canyon Vineyard, California. This sensor collected data every 15 minutes over a ten-day period in June 2004. The oscillations denote dayime high- and overnight low-temperatures.

Several trials of wireless sensor technology have focused on degradation of large infrastructure systems as well. In a collaborative effort between UC-Irvine and the University of Southern California's Information Sciences Laboratory for Embedded Network Sensor Experimentation (I-LENSE), vibration sensors have been installed on several pedestrian bridges and highway overpasses in Southern California. The sensors test for the presence of each structure's "natural frequency," or a rate of vibration that is harmful to the bridge's structural integrity. The Intel Research Lab at Berkeley has taken this experiment to the next step, and hopes to place about 200 motes on the Golden Gate Bridge. These sensors will monitor the bridge's movement during strong wind, and will immediately trigger alarms if a parameter seems to be irregular. An even larger application by the CENS and UCLA's Department of Earth and Space Sciences has placed about fifty sensors in various places along the San Andreas fault, hoping to develop an early-warning mechanism for large earthquakes.

Wireless sensors are not limited to vehicle infrastructure, however. A trial between USC's I-LENSE and UC-Irvine has involved the monitoring of the water-supply system in Memphis, Tennessee. By placing a number of wireless motes throughout the pipes that bring drinking water to residents, researchers can monitor changes in the water quality in real-time. If a break in one of the system's pipes was to occur, city officials would know immediately because of the pressure drop sensed at different motes, whose positions throughout the system are documented. Similarly, if a contamination were to take place, researchers would be able to track the agent as it pervaded the system, shutting down the necessary portions. They would also be able to track the plume backward to find the contamination source.

A number of other smaller trials for wireless monitoring have taken place as well. These cases have focused on monitoring of the electric grid, structural integrity of buildings, and a number of other plant and animal habitats. One of the most wide-ranging of these is a large scale experiment by California Institute of Technology and NASA's Jet Propulsion Laboratory. By monitoring a certain species of plant, the creosote bush, researchers hope to develop a system for anticipating desertification worldwide. Researchers are hoping to gauge the extent to which increasing desertification is a result of long-term climate change, rather than variations in local microclimates.

Overall, although wireless sensor networks have seen a large number of trials to prove the technology, the sensors have gone largely unrealized in commercial applications. Still in their novelty phase, the cost of these networks has been prohibitive, as has the fact that few potential users know of the technology, and even fewer are willing to acquire the technical expertise needed to assemble and operate current systems. Although the technology is far simpler and easier than any previous attempts at pervasive monitoring, assembling and programming a network of wireless motes is immensely complicated.

IV. FUTURE GROWTH AREAS FOR THIS TECHNOLOGY

Perhaps the foremost trend in pervasive monitoring will be a dramatic decrease in physical size. A movement toward continued miniaturization already exists, and as the technology of sensing, data processing and mesh networking is improved, the factors that dictate a mote's size will undergo changes. In the largest and least expensive of currently-available sensors, the size of the AA batteries that power the package determine the dimensions of the mote. The smallest commercially available sensors today are about the size of a quarter, and are still powered by a wristwatch battery.

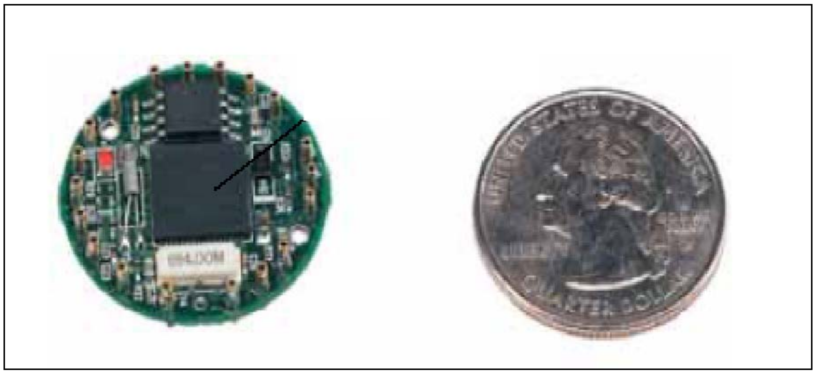


Figure 6 – Crossbow's Mica2Dot mote shown next to a quarter. One-quarter of an inch thick, the Mica2Dot is currently the smallest commercially-available mote. Photo Courtesy of Crossbow Technologies.

The goal toward which many companies are striving is the creation of "smart dust," or motes about one cubic millimeter in size, so small that they can hardly be seen or identified. Most smart dust motes would be equipped only with basic sensors such as temperature and light, but the true value of these sensors lies in their networking ability. By simply scattering a handful of smart-dust motes across a field, one would be able to use the mesh-networking system to track a higher-level sensor as it moved through the field. Alternately, if some emergency such as a chemical spill were to occur, response teams could spread smart-dust motes through the evacuated zone, thus monitoring the spread of the spill in real-time without the health risks of humans entering the spill zone blindly.

Because of the immense potential that smart-dust motes hold for defense and emergency response applications, the Department of Defense's Defense Advanced Research Projects Agency (DARPA) has earmarked funding for not only the largest mesh-networking test to date, but for a wide range of monitoring possibilities, from crack monitoring in jet-engine turbine blades, to "battlefield control" technologies, or capabilities that would allow monitoring of uninhabited combat areas. The extent of today's unmanned battlefield-control capabilities is limited to land mines, to which smart dust would undoubtedly prove to be superior alternative.

Aside from the rapid-deployment potential wireless motes hold for emergency response teams, a large family of other homeland-security applications exist that can serve as dual-use for environmental monitoring and emergency response. For instance, a system of water quality sensors placed throughout a city's supply system would return constant data on water pressure and chemical concentrations; if a rapid change took place in the system, authorities would be able to react quickly with extensive knowledge of the problem. Similar designs are possible for air quality monitoring, background radiation monitoring, and many other sources. The best part about such systems is their universality – a system that is constantly monitoring weather conditions or environmental properties could be quickly adapted to detect and monitor disasters as they unfold.

In all of these potential future applications, it is important to distinguish between outcomes that are possible and those that are feasible. Even in large-scale systems that are funded by government, cost and other factors concerning wireless networks are prohibitive. One of these factors is the technical difficulty of assembling current systems. Despite claims stating that wireless systems can be used right out of the box, in fact the assembly of components and the installation of TinyOS programs requires a strong computer programming ability. Another worrisome consideration involves the scattering of smart-dust motes for pervasive monitoring: the small size of such motes makes them nearly impossible to recover once they are finished being used, and a large number un-retrieved motes with batteries could cause a worse environmental disaster than was initially being monitored.

Nonetheless, a number of companies continue to push the sensing capabilities of wireless motes forward into new areas. The next generation of sensor-boards is expected to feature capabilities such as sound-recording and digital photography. Networking improvements that would precede these advances are a high bandwidth capability between motes, so that more bits of data can be transmitted more quickly. Further, the power requirements of photography and recording, or even possibly video recording, are far greater than those of simple temperature and humidity sensors. Because the size and performance capabilities of batteries are near their maximum today, it is likely that small fuel-cell power supplies – which may be available in laptop computers as early as 2006 – could be the next power source to drive wireless motes.

V. PROBLEMS AND CONSIDERATIONS

The growth of a new commercial field for wireless sensors clearly raises questions about the fallibility of the technology, as well as the effects it will have on the subjects being monitored. The greatest weakness of a wireless sensor net is likely to be its vulnerability; we often see how susceptible the internet and personal computers can be to viruses and computer glitches, and the danger for wireless motes is even greater due to their remoteness.

Two types of security challenges faced by wireless sensors will be external sources, including malfunction or destruction of individual motes, or internal sources such as viruses or hackers. The structure of a mesh network of sensors is specifically designed to counteract external attacks on the system. The use of redundant, dynamic connections allows individual motes to enter and leave the network without undermining the integrity of the whole system. If anything, this robust capability will be a liability: the same capability that keeps the system operating through adverse conditions could make it very difficult for the user to disable if the need should arise. The structure of wireless mesh networks is specifically designed to overcome external challenges to the system.

On the other hand, wireless networks could be very sensitive to internal attack because of their data routing structure. In order to accommodate a system of dynamic, intermittent connections, motes are designed to automatically update their programming commands by forwarding the new commands through each other. If a virus or an illegitimate command were to enter the system, it could propagate in much the same way, and no defense mechanism exists to prevent each mote in the network from becoming infected very quickly.

Aside from the security of a network, perhaps the greatest concern about pervasive monitoring is the extent to which it will intrude into people's everyday, private lives. While some intrusions can be easily prevented, such as the placement of cameras into private areas, many other applications represent dual-use of the technology. On one hand, placing sensors in public areas with the intent of enforcing safety and stopping terrorism is done for the public good, but the same sensors can be used to "spy" on individuals, to obtain personal information, or to observe them in their personal lives. Even if promises are made to only use sensors for constructive purposes, how can one be sure they are not susceptible to the aforementioned viruses and intrusions, which divert the original purpose of the sensors?

VI. CONCLUSIONS

The role of public policy exists in technological fields to ensure that positive results of an emerging technology are realized, while minimizing the adverse effects and abuses of the same capabilities. Particularly in scenarios involving emerging technologies – whose capabilities are hardly known, to say nothing of the liabilities – it is tempting to favor policy that is too heavy-handed in one direction. However, neither prohibition of wireless sensing networks nor entirely unchecked deployment is a realistic or responsible option.

Instead, there is a role for scientists and developers to consider the liabilities of their work at every step in a technology's design and development. The same technical knowledge that makes new technologies possible also serves as the best resource for preventing misuse of the capabilities. A need for interaction exists so that technical concerns can considered in policy decisions, and so that public limitations are known to developers of a technology.

Finally, a forum needs to exist where public opinion can be consulted regarding new technologies. Ultimately, the public will be the recipient of better environmental quality monitoring and emergency response, as well as the subject of scrutiny under tighter security measures. Nonetheless, the public must feel that it is a part of the technology's development, because in almost every government and non-government program, the public is the reason the technology exists.

Wireless sensor networks represent a radical innovation in computing, and hold immense promise for supplying better, faster, and quicker information about the world we live in. Only by embracing the technology will we be able to reap the benefits, and only by responsible development will we be able to fully embrace the technology.

APPENDIX A
PEOPLE INVOLVED WITH WIRELESS SENSORS AND MESH NETWORKS

INTEL RESEARCH LABORATORIES – Four divisions exist: in Berkeley (UCB), Cambridge, UK (Cambridge Univ.), Pittsburgh (Carnegie Mellon), and Seattle (UW). Much of the Smart-Dust and ubiquitous computing stuff is done in Berkeley. Centers are listed under universities below. *See www.intel-research.net.*

CROSSBOW TECHNOLOGIES

41 Daggett Drive, San Jose, CA, 95134
Phone 408-965-3300
www.xbow.com

CENTER FOR EMBEDDED NETWORK SENSING (CENS), UCLA

Deborah Estrin, Director and Professor of Computer Science.
Ramesh Govindan, Computer Science Professor.
William Kaiser, Electrical Engineering Professor.
Gregory Pottie, Electrical Engineering Prof.
Michael Hamilton, UCLA Biology Professor, also of the San Jacinto Mountains Reserve.
Partnered with Agilent Techs, Crossbow, Intel, and Sun Microsystems.
Includes a division for Social, Ethical, Legal Implications.
UCLA 3563 Boelter Hall, Los Angeles, CA, 90095. Phone 310-206-2476.
www.cens.ucla.edu

INTEL RESEARCH LABORATORY AT BERKELEY

Kurt Brown, Director, Intel Employee.
Joe Hellerstein, Director, Intel Employee.
David Culler, Researcher and UC-Berkeley Professor.
Deborah Estrin, Researcher, also see UCLA's CENS above.
2150 Shattuck Ave, Ste 1300, Berkeley, CA, 94704. Phone 510-495-3000.
www.intel-research.net/berkeley

BERKELEY SENSOR AND ACTUATOR CENTER (BSAC), UC-BERKELEY AND UC-DAVIS

John Huggins, Director, Electrical Engineering and Computer Science (EECS) Professor.
497 Cory Hall #1774, Berkeley, CA, 94720. Phone 510-643-6690.
www-bsac.eecs.berkeley,edu

BERKELEY WIRELESS RESEARCH CENTER (BWRC), UC-BERKELEY

Jan M. Rabaey, Director, EECS Professor, also from PicoRadio.
Bob Broderson, Co-Director, EECS Prof.
Partnered with Intel, STMicroelectronics, Infineon Technologies, Hitachi, HP.
2108 Allston Way, Ste 200, Berkeley, CA, 94704. Phone 510-666-3102 (Rabaey).
bwrc.eecs.berkeley.edu
Has a spin-off called PicoRadio, see
http://bwrc.eecs.berkeley.edu/Research/Pico_Radio/Default.htm.

USC – INFORMATION SCIENCES INSTITUTE (ISI) – I-LENSE RESEARCH GROUP

John Heidemann, Director.
Phone 310-448-8708 *Email johnh@isi.edu*

Closely-allied with the UCLA CENS.
http://www.isi.edu/~johnh/

USC – AUTONOMOUS NETWORKS RESEARCH GROUP (ANRG)
Bhaskar Krishnamachari, EE and CS prof. Phone 213-821-2528.
Works Closely with CENS above.
http://ceng.usc.edu/~anrg/

USC – BIOLOGICAL SCIENCES DEPARTMENT
David A. Caron, Chair and Prof. Phone 213-740-0203
A Number of Environmental Applications.
http://www.usc.edu/dept/LAS/biosci/Caron_lab/index.html

VIRGINIA TECH
Sandeep K. Shukla, EE Prof. *341 Durham Hall, Blacksburg, VA, 24061. Phone 540-231-2133. There's no center at VT – he's it.*

PURDUE UNIVERSITY – CENTER FOR WIRELESS SYSTEMS AND APPLICATIONS (CWSA)
Catherine Rosenberg, CWSA Director, EE and CS prof.
Jan P. Allebach, Co-Director, EE and CS Prof.
This center is brand new.
Phone 765-494-0034 (Rosenberg), 765-494-2698 (Allebach).
http://dynamo.ecn.purdue.edu/~cath/CWSA/

MIT – COMPUTER SCIENCE AND ARTIFICIAL INTELLIGENCE LABORATORY, NETWORKS AND MOBILE SYSTEMS GROUP (NMS)
Hari Balakrishnan, EECS Professor
Their SLAM (Scalable Location-Aware Monitoring) system looks promising.
32 Vassar Street, Cambridge, MA, 02139. Phone 617-253-8713 (Balakrishnan).
http://nms.csail.mit.edu/

MIT – CENTER FOR BITS AND ATOMS (CBA)
Neil Gershenfeld, Director.
Research on Social Aspects of Technology
http://cba.mit.edu

CARNEGIE-MELLON UNIVERSITY (CMU) – INTEL RESEARCH LAB AT PITTSBURGH
Not really focused on this topic

CMU – DEPARTMENT OF COMPUTER SCIENCE AND ENGINEERING
Todd C. Mowry, Professor, Director of Intel Research Lab, Pittsburgh.

CMU – CENTER FOR WIRELESS AND BROADBAND NETWORKING
http://broadband.web.cmu.edu/

CMU – HUMAN COMPUTER INTERACTION INSTITUTE
http://www.hcii.cmu.edu/

UNIVERSITY OF WASHINGTON (UW) – DEPARTMENT OF COMPUTER SCIENCE AND ENGINEERING

http://www.cs.washington.edu/

UW – EMBEDDED COMPUTATION GROUP

Gaetano Boriello – Computer Science Professor, Intel Research Employee.
Phone 206-685-9432 *Email gaetano@cs.washington.edu*
Large Number of publications, spinoffs.
http://www.cs.washington.edu/research/embedded.intro.html

UW – INTEL RESEARCH LAB AT SEATTLE.

James Landay, Lab Director.
Phone 206-633-6555 *Email james.a.landay@intel.com*
Focus on embedded sensors and ubiquitous computing; not as specific to wireless networks as Berkeley.