APPLICATION-LED RESEARCH IN UBIQUITOUS COMPUTING: A WIRELESS SENSOR NETWORK PERSPECTIVE

Joshua Lifton and Mathew Laibowitz

Responsive Environments Group
MIT Media Lab
Cambridge, MA 02139

1. INTRODUCTION

The broad vision of ubiquitous/pervasive computing has inspired several fields of more narrowly defined research, among them wireless sensor networks. Although more narrowly defined, the field of wireless sensor networks is nonetheless stuck in a similar application limbo. In what follows, we discuss this problem in more detail, suggest possible routes of escape, and relate the lessons learned back to the more general ubiquitous/pervasive computing community.

2. STATE OF THE APPLICATION SPACE IN WIRELESS SENSOR NETWORKS

Wireless sensor network research as a whole suffers a dearth of viable application scenarios for which wireless sensor networks are the best solution. For example, more than a few authors mention forest fire detection as an application of wireless sensor networks. In this scenario, sensor nodes are dropped from an airplane into a forest and then route temperature information back to civilization. This is untenable for a number of reasons.

Firstly, by the time a change in temperature can be detected, the fire is most likely well under way. Secondly, even with today's most environmentally friendly technology, it is unacceptable to litter forests with sensor nodes containing heavy metals, solvents, and other toxins. Finally, a single low-cost graduate student or forest ranger stationed at a fire watch tower can monitor hundreds of square miles of forest much more effectively than any sensor network thus far proposed. To our knowledge, the forest fire detection application has never been deployed, but is rather touted solely as an easily understood application with which to motivate simulation or theory.

This and other similar situations exemplify several obstacles to application-led wireless sensor network research. For example, researchers are generally unfamiliar with the application domains they are trying to address and therefore cannot accurately assess the efficacy of a wireless sensor network solution relative to a more traditional solution. In addition, most researchers do not have the resources to design, build, deploy, and maintain a wireless sensor network application. This lack of hands-on experience has contributed to the commonly accepted assumption that there is a sea of applications waiting to make use of the results of simulation and theory, thus leading many researchers to only minimally motivate their work.

This is not to say there aren't applications, simply that more effort should be focussed on fleshing them out. The remainder of this paper is a (necessarily limited) starting point for doing just that. We discuss the role applications can and should play in wireless sensor network research, suggest some simply guidelines for evaluating potential applications, examine application identification, outline four concrete categories of wireless sensor network applications, and finally summarize some high-level obstacles to application-led research.

3. ROLE OF APPLICATIONS

The role of applications is four-fold.

3.1. Validate Theory and Simulation

The ultimate test of any theory or simulation is experiment, and building real applications is a clear path toward experimentation. These type of applications are not particularly prevalent in wireless sensor network research since the scale (e.g., node count and physical size) and complexity of readily built wireless sensor network applications pale in comparison to the scale and complexity called for by most of the theories and simulations in need of testing. For example, given it is currently quite challenging to build, deploy, maintain, and monitor an application with only 100 nodes, it is not reasonable to expect to test a theory whose main result is arrived at only as the number of nodes in the network goes to infinity.

3.2. Motivate Theory and Simulation

Theory and simulation require motivation. In the context of wireless sensor networks, this often comes in the form of a specific application or class of applications. Unfortunately, more often than not, the specifics of the application are not discussed. Furthermore, the same set of example applications (e.g., forest fire detection) seem to be repeatedly cited without a critique of their plausibility or usefulness.

3.3. Sample User Needs

In the end, the killer applications of a technology are decided by the users, not researchers or developers of technology. Creating and deploying applications is a very direct way to gain insight into what users want and need (as opposed to, for example, focus groups or statistics gathered from similar domains). Very few wireless sensor network applications exist, let alone are designed for non-expert users.

3.4. Build a Base for Future Applications

One of the dominant, if understated visions of wireless sensor networks is that their utility is derived from their versatility. Accordingly, no single application has been identified that would alone warrant the widespread deployment of wireless sensor networks. Rather, the synergy between multiple diverse applications is supposedly what will motivate their deployment. Thus, every application developed has the potential to incrementally bring closer the day when it is worth the cost of building and deploying wireless sensor networks for widespread use. In this sense, there is a parallel with desktop computers; few people are willing to buy a desktop computer only for the utility a word processor program provides, but many people are willing to buy desktop computers for the aggregate utility provided by all the programs available to them.

4. METRICS FOR SELECTION, ANALYSIS AND EVALUATION OF APPLICATIONS

In the context of wireless sensor networks, there are several ways to select, analyze and evaluate applications. Here is a non-comprehensive list of points to keep in mind:

- Can the problem be solved better by centralized approaches? If there is no benefit to implementing a wireless sensor network solution, then don't.
- Interesting problems do not imply interesting applications. It may take more effort to find an interesting application than to solve an interesting problem.
- Useful algorithms and tools are not themselves applications. For example, data aggregation is useful, but not itself an application.
- Favor interesting applications over optimal applications. Interesting applications will further the field more than optimal applications at this point. Scalability, energy consumption, speed, bandwidth, etc. can be optimized afterward.

5. APPLICATION IDENTIFICATION

This is certainly the most difficult problem facing wireless sensor network application developers. In part, this is because there is still a sizable gap between what technologies are available with which to develop and envisioned applications. More seriously, however, is the problem of finding compelling applications at all. Time will hopefully take care of the former problem, but only imagination and ingenuity can cure the latter. To that end, it behooves researchers to expand their definition of a wireless sensor network to include, for example, a great diversity of physical scales. Why not microns (e.g., super dense artificial skin) or parsecs (e.g., interplanetary navigation networks)? The definition could also be expanded by considering actuators on each node, closed-loop versus interactive systems, and tiered networks.

6. EXAMPLE APPLICATION DOMAINS

We present here four broad categories of applications with examples of each category.

6.1. Augmented Sensing

The structural similarity between wireless sensor networks and biological sensor networks suggests that wireless sensor networks may be well-suited to augment biological sensor networks. For example, an extremely dense, skin-like sensor network might be embedded in a body suit in order to process incoming tactile data and then route high-level features to an off-body receiver for use in a telepresence application. Such a sensor network could also be applied as skin for robots, aiding in kinesthesis. Sensor networks distributed on a larger physical scale could also augment our natural senses. For example, a sensor network distributed throughout a building or construction site might augment a building manager or site foreman's perception of what is happening in the building.

6.2. Instant Infrastructure

Wireless sensor networks are often touted as having the potential to provide infrastructure on short notice in uncertain environments. Localization, tracking and communication services are examples of applications of use in situations arising in military operations, space exploration, and disaster relief.

6.3. Distributed Infrastructure

Situations currently employing centralized permanent infrastructure may benefit from a distributed solution enabled by wireless sensor networks. Power generation and distribution is a prime example. At present, power supplied by large generators is centrally controlled to carefully match power demanded by end users. This precludes widespread adoption of household power generators (e.g., solar panels, flywheels, and wind turbines) connecting directly to the power grid and deciding as a network when to generate or store power. On one level, the power generators and storage devices could be considered as nodes in a sensor network. On another level, each household's power generation and storage unit might have access to information culled from a wireless sensor network distributed throughout the household in order to monitor, mitigate and predict electricity use by the inhabitants and therefore make more informed decisions as to how much power to request or offer the rest of the grid.

6.4. Physically Situated Information

Embedding digitally accessible information into the physical environment (e.g., RFID tags and IR beacons) has long been a goal of the ubiquitous computing community. At the most basic level, such information could be used to support localization services. Information may also only have meaning or use in the context of a particular physical location. Graffiti is an analog example of physically situated information. A digital example might be movie posters that digitally store feedback about the advertised movie entered by passersby and/or collected from remote sources. In essence, this is an example of physically situating the viral consumer and social networks already prevalent on the Internet, thus magnifying their effect by making information available at the time and place users most want access to it.

7. OBSTACLES TO APPLICATION-LED RESEARCH

By far the most formidable obstacle to application-led research is the host of limitations imposed by using a real hardware platform. Either the researcher can develop her own platform at considerable time and financial expense, or she can use one of the very few available experimental platforms at the expense of being constrained by hardware not designed for her application and also at considerable financial expense.

Another obstacle to application-led research is the extreme emphasis on communication protocols and energy conservation. Clearly, these will be the limiting factors in the end, but applications should be pushing the bounds of the state-of-the-art in communication protocols and energy conservation, not lagging far behind. For example, sensing problems (e.g., calibration) are just as important to most potential applications, but command relatively little research focus.

Usability is another obstacle of our own making. Wireless sensor networks will not become widespread until average people can use them. We already have an idea of the applications Big Brother would like, but which applications exist that an average person would find compelling?

8. CONCLUSION

In many ways, wireless sensor networks are positioned to become the machinery on top of which ubiquitous/pervasive computing operates. Thus, the issues surrounding wireless sensor networks outlined here apply equally well to ubiquitous/pervasive computing.

We've given a brief outline from the perspective of wireless sensor networks research as to the role of applications in research, heuristics for evaluating possible applications and research directions, promising categories of applications, and obstacles to application-led research.

In addition to technological limitations, application-led research also suffers from an over-emphasis on optimization. On the other hand, pulling real users into the equation can only further the field and should be encouraged.

The potential for wireless sensor networks and ubiquitous/pervasive computing is greater than it has ever been. When all is said and done, developing compelling applications is the only way to realize this potential.