# Supporting Location and Proximity-Based Studies in Natural Settings

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## *Abstract*

*Investigators who want to conduct long-term empirical studies in natural settings pertaining to the location of objects and people have limited options for an indoor positioning technology that is easy-to-deploy and cost-effective. For my dissertation work, I am conducting the development and evaluation of two technologies that try to address this need: PowerLine Positioning and BlueTrack. PowerLine Positioning is a novel, indoor localization system that uses the powerline infrastructure to provide the absolute tracking of people and objects in a home, while BlueTrack provides the tracking of relative proximity between people and objects in any space. I am researching how these technologies facilitate automatic and unobtrusive sensing and data collection for researchers interested in conducting location-based studies in the home or proximity-based studies anywhere. I also intend to show that these technologies are cost-effective and easy-to-deploy. Finally, I show that they can provide objective measures that researchers can use with interviews to produce richer and more detailed data than self-report alone.*



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## 1. Problem Statement and Research Question

Understanding the interaction between people and objects in their natural setting has been of great interest to researchers for many years. This desire has lead to the use of a variety of investigational techniques such as self-report, experience sampling, and ethnography. However, these techniques have limitations when used alone. Self-report is limited to how much information a person can recall in detail. Experience sampling mitigates this problem by probing at the time of the phenomenon, but user burden limits the number of samples researchers can obtain. In addition, individuals with physical or motor impairments have a harder time responding to these kinds of requests. Although ethnography provides rich data, it is often time-consuming and not practical for certain environments, such as in the home. Experience sampling and ethnography in certain situations are also prone to changes in the behavior being investigated (*i.e*. the Hawthorne effect).

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To address these challenges, technological solutions that employ automatic and unobtrusive sensing and data collection are appealing for a variety of reasons. First, they enable passive data gathering throughout an entire day for an extended period of time. Second, its ability to scale provides a means to generalize results. Finally, sensed data can be coupled with other investigational methods, such as interviews, to obtain more targeted questions.

Despite the appeal of automatic sensing, most researchers *today* who wish to automatically gather sensor information find it to be a difficult and costly endeavor. Often, investigators spend more time struggling with finding the proper technology than with conducting the study itself. As a result, past studies have been limited to laboratory settings, a single laboriously instrumented setting, or a compromise in the use of a lower quality sensing approach.

One important piece of sensed information is the knowledge of the location of people and objects in some setting. This can either be in the form of an absolute position in a space or a relative position between entities of interest. Despite some limitations, Global Positioning System (GPS) is currently the technology of choice for outdoor positioning. However, no single, easy-to-use and cost-effective solution exists for indoor environments, especially for the home. Although sensing platforms are beginning to emerge, they have largely been designed for specific behaviors or require the installation of many sensors in order to provide simple location information.

Thus, investigators who want to conduct long-term, in-home studies pertaining to the location of objects and people have limited options for an indoor positioning technology that is easy-to-deploy and cost-effective. This observation has motivated me to develop two pieces of technology, PowerLine Positioning and BlueTrack, which attempt to address this need. In addition, I am also conducting deployments of these technologies in actual studies that show their use and usefulness.

I believe there is great value in developing indoor positioning systems to support studies of people and objects in their natural setting. First, they can allow for the automatic collection of objective data to support empirical evaluations. Second, it becomes possible to collect data for longer periods of time and to scale to support many simultaneous studies. Next, technology can address quantitative questions when self-report is not appropriate or accurate. Finally, the collected data provides objective information against which researchers can probe for more details. A mixed-method approach where researchers can use the data to create prompts during an interview becomes an effective tool that provides additional descriptive, normative data for the study.

To facilitate this, it is important that the technology reduce the burden on the researchers. Thus, a system must be cost-effective and easy-to-deploy. This is especially important in the case of in-home studies where a participant’s time is valuable and any system must be easy to install and remove to make efficient use of time with the participant.

Having realized the burden of conducting in-home location-based studies and recognizing the limitations of current indoor positioning systems, my thesis work consists of the development of a novel technology to support the localization of people and objects in the home. In addition, I am also presenting a technology capable of determining the relative proximity between people and objects in any space, including outside the home.

The evaluation consists of two parts: a technical evaluation of both technologies to determine the performance and operational parameters and deployments of this technology to conduct studies relating to the absolute and/or relative locations of objects and people to show the value of these types of systems. I am using these studies to evaluate the technology's deployment issues (*e.g.*, time, cost, ease of use, *etc.*), the quality of the resulting data, and the effectiveness in answering the investigator's original questions.

With this thesis I address the following broad questions:

- How do we provide a practical indoor location system that requires minimal infrastructure, is easy to deploy, and is cost-effective?
- What are alternate ways to provide location information outside the home in unconstrained environments?
- What types of studies do these technologies enable and how does the limitation of the technology dictate the type of study that can be designed?
- What value does automatically collected data have, and how can it be coupled with existing investigation methods to produce a mixed-method approach?
- What advantages and disadvantages does this proposed mixed-method interview approach have?

## 2. Approach and Methodology

I am developing and evaluating two technologies, PowerLine Positioning and BlueTrack. PowerLine Positioning is a novel indoor localization system that supports the absolute tracking of people and objects in a home, while BlueTrack provides the tracking of relative proximity between people and objects in any space. PowerLine Positioning is an inexpensive system that uses the powerline infrastructure in a home. It requires only the addition of two plug-in modules to track simple location tags down to one meter. BlueTrack is a Bluetooth-based proximity tracking system that can determine three levels of proximity between custom Bluetooth tags and Bluetooth-enabled devices passively and without the need for active pairing between devices.

I have already conducted technical evaluations of both PowerLine Positioning and BlueTrack. This included gathering various performance measures of PowerLine Positioning from a number of in-home installations to gather its operational parameters. I evaluated the performance of BlueTrack in the laboratory for its proximity prediction accuracy. In addition, I used two diary studies to evaluate the accuracy of BlueTrack in a more natural setting.

I am also conducting two research studies that use PowerLine Positioning and BlueTrack. With these two deployment studies, I intend to show the type of studies these technologies enable, the deployment issues of the technologies, the quality of the automatically gathered quantitative data compared to traditional self-report methods, the improvement of the quality of data when applying the mixed-method approach using the tracking data.

The first study, which I have already conducted, is an in-depth, empirical investigation of the proximity of the mobile phone to its owner over several weeks of continual observation. The aim of this study is to determine if the mobile phone is a suitable proxy for its owner, understand the reasons behind separation between user and the mobile phone, and offer guidelines for building mobile phone applications. From this study, I showed that BlueTrack offered several key advantages. It allowed the continuous recording of the user's distance to their phone and the gathering of quantitative data not otherwise possible with other investigational means.

Additionally, the quantitative data I was able to collect allowed me to explore whether it was possible to apply machine learning techniques to the proximity behavior. Finally, there was little modification to the user's natural behavior during the investigation, and the resulting quantitative proximity traces proved valuable during the mixed-method interview process and the final analysis.

The second study, which is currently ongoing, is the deployment of PowerLine Positioning to study the activity of wheelchair users in their homes. In collaboration with researchers at The Center for Assistive Technology and Environmental Access (CATEA) at Georgia Tech, I am conducting a study of that looks at mobility patterns of wheelchair users in the home. My aims are to determine the in-home environmental factors that promote or hinder mobility, where users spend much of their time in the home, locations where users do not go, and when and where they transition between multiple ambulatory devices. Currently, the practice within the mobility disability research community is to employ self-report. However, self-report often does not give the researchers the level of detail necessary for their investigation. In the past, CATEA also struggled to find a practical indoor positioning system capable of meeting their accuracy and ease of deployment needs. I am using PowerLine Positioning to collect data of the usage of ambulatory and mobility devices in the home. My aim is use this data to obtain a more detailed and objective understanding of mobility patterns over a longer period of time and use the gathered location data to conduct more effective interviews with participants. I intend to show that the mixed-method approach results in finding more environment barriers and mobility issues in the home when compared to the current best practice of self-report. In addition, I also intend to use this study to evaluate the deployment issues of PowerLine Positioning in terms of installation and removal time and its ease of use for the researcher.

## 3. Related Work

Indoor positioning has been a very active area of research in ubicomp for the past decade, and many commercial systems are beginning to emerge. Several characteristics distinguish different solutions, such as the underlying signaling technology (*e.g.,* IR, RF, load sensing, computer vision or audition), line-of-sight requirements, accuracy, and cost of scaling the solution over space and over number of items. Hightower and Borriello provide a thorough overview of indoor positioning systems and techniques [5] . The earliest indoor solutions introduced new infrastructure to support localization. Despite some success, as indicated by commercialized products, the cost and effort of installation are a major drawback to wide-scale deployment, particularly in domestic settings. Thus, new projects in location-based systems research reuse existing infrastructure to ease the burden of deployment and lower the cost. The earliest demonstrations leveraged 802.11 access points, and more recent examples explore Bluetooth and wireless telephony infrastructure, such as GSM or FM transmission towers. A concern is that individuals may not be able to control the characteristics of this infrastructure and the operational parameters of the infrastructure may change without warning, resulting in the need to recalibrate. The desire to control the infrastructure and to scale inexpensively to track a large number of objects inspired the work on the Powerline Positioning system.

The design of the BlueTrack proximity detection system was partially inspired by the SPECs project at HP Labs [7] , which demonstrated how simple peer-to-peer wireless devices can be used to collect proximity information to recognize certain activities. In the case of SPECs, infrared technology was used to build applications that can take advantage of proximity knowledge of a collection of devices. The disadvantage to this approach is the sensors must be exposed and line of sight between devices. In my case, I use RF-based Bluetooth technology and take advantage of the Bluetooth on the phone and other Bluetooth-enabled devices to collect data on everyday phenomena, such as which portions of a day individuals are within arm's reach of their mobile phone. In addition, the BlueTrack system can provide information regarding the proximity measure (three levels) between devices.

With the advent of new, affordable technologies, there has been a trend in research to shift from building technology to supporting office life to supporting home life. Abowd and Mynatt point out a need for studying domestic settings to inform the design of new technologies [1] . Edwards and Grinter echo similar sentiments in that people are using technologies in new and interesting ways in the home [4] . Thus, a key research problem for designing for the home is first to study the everyday working of the home, such as how people live in the home, what they do, and the role that technologies play.

The initial foray in studying the home has been with ethnography. For example, Crabtree and Rodden present a series of ethnographic studies that aimed to uncover communication routines and how people use particular spaces in the home [3] . They provide guidelines for placing technology in appropriate locations in the home. More recent work has looked at collecting emprical evidence for studying the domestic space. For example, Intille *et al.* presents techniques for acquiring data about people, their behavior, and their use of technology in a natural setting [6] . One is a context-aware experience sampling method, which extends electronic experience sampling to proactively trigger data collection when certain phenomena. They use simple state-change sensors that can be quickly installed throughout nearly any environment to collect information about patterns of activity. They also describe a tool called image-based experience sampling that allows users to annotate particular video segments of a situation shortly after it has happened.

With the proliferation of portable electronic devices in the home, researchers are interested in studying the complex interactions between household residents and their devices. Aipperspach *et al*. have looked at using sensor-based visual records of the physical movement of people and devices to facilitate in-depth discussion during interviews [2] . I have been very much motivated with this later trend of building easy-to-deploy technologies in order to support studying people and objects in natural settings.

## 4. Preliminary Results

### 4.1 PowerLine Positioning Technology

Inspired by this strategy of leveraging existing infrastructure and recognizing that there are drawbacks to relying on public infrastructure or the deployment of many beacons, I was motivated to devise a solution for indoor localization that would work in nearly every household. With the significant insight being to use the residential power line as the signaling infrastructure, PowerLine Positioning is the first example of an affordable, whole-house indoor localization system that works in the vast majority of households, scales cost-effectively to support the tracking of multiple objects simultaneously, and does not require the installation of any new infrastructure. The solution requires the installation of two small, plug-in modules at the extreme ends of the home (see Figures 1 and 2). These modules inject a mid-frequency, attenuated signal throughout the electrical system of the home. Simple receivers, or positioning tags, listen for these signals and wirelessly transmit their positioning readings back to the environment (see Figure 3). PowerLine Positioning is capable of providing sub-room-level positioning for multiple regions of a room and has the ability to track multiple tags simultaneously.

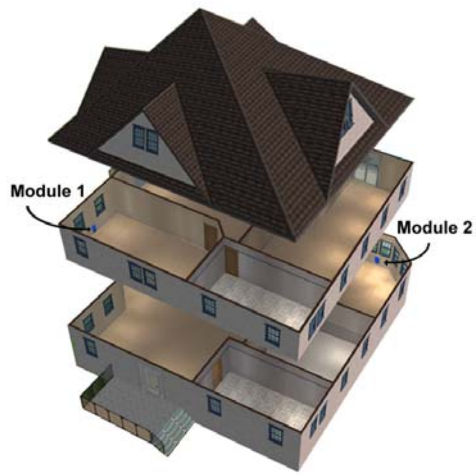


**Figure 1:** Placement of two signal-generating modules at extreme ends of a house. They are simply plugged into the wall.

**Figure 2:** Left: The signal generator plug-in modules are made to look like standard power outlet expanders to have them be aesthetically pleasing (the outlets are functional). Right: Inside back cover of the outlet expander housing the signal generating circuitry.

**Figure 3:** Left: Encasement that will be used to house the tag and the battery pack. Right: Prototype of the deployable PowerLine Positioning tags.

### 4.2 BlueTrack Technology

BlueTrack is a general purpose system capable of determining the proximity between tagged objects and people. BlueTrack uses Bluetooth technology for its implementation and has a number of advantages. The popularity of Bluetooth devices has greatly driven down the cost of its components, which makes it an affordable solution compared to proprietary radio systems. In addition, devices that already incorporate Bluetooth technology, such as mobile phones, laptops, Personal Digital Assistants (PDAs), and automobiles interoperate with the system, thus minimizing the number of objects that have to be instrumented. BlueTrack software can run on a variety of platforms including personal computers and mobile phone. Devices with the BlueTrack software (mobile phones, laptops, other BlueTrack tags, etc) can determine three levels of proximity to BlueTrack tags, which equate to roughly within arm's reach (within 1-2 meters of the tag), within the same room (within 3-6 meters of the tag), and unavailable beyond 6 meters from the tag. Unlike previous Bluetooth ranging attempts, devices running BlueTrack software do no have to pair with BlueTrack tags (see Figure 4). The ranging is accomplished using the Service Discovery Profile (SDP) layer, which also allows for substantially improved battery life.

**Figure 4:** Tag used in the BlueTrack proxmity system

### 4.3 Completed Deployment of BlueTrack for Mobile

The BlueTrack system was deployed to study the proximity of people and their mobile phones throughout the day. BlueTrack allowed me to obtain realistic proximity data for users that may not have otherwise been obtained with more low fidelity studies. Although a sampling of data points obtained through ESM can come up with similar proximity relationships, it runs the risk of altering the user's proximity relationship to the phone by continually reminding users about their phones' whereabouts. Based on interviews with all the participants and analysis of the proximity data, there was little modification to user's natural behavior during the study. They also reported no discomfort with the location tag and often reported "forgetting about it" soon after wearing it.

Additionally, resulting quantitative proximity traces proved valuable during the interview process. This resulted in much richer interviews that focus on more specific details than in generalities. As a result, it was possible to uncover various categories of separation that the users would not have remembered or thought to report. In addition, often participants could not recall the location of their phone. Thus, the proximity traces proved vital for the participants when they were explaining particular situations.

Finally, the objective proximity data showed that participants are not good at predicting their physical relationship to their mobile phone. Most participants grossly overestimated the mobile phone being close to them. The continual logging with BlueTrack also provided substantial data for creating a model to predict a user's proximity to their phone and helped discover contextual features off the phone that contributes to this prediction.

I believe this type of study is useful to obtain ground truth data about a user's proximity relationship to the phone. Perhaps more significantly, however, it can also result in baseline data to compare against similar proximity evidence that would result from the effects of new mobile phone applications, such as location-based services, continual health monitoring systems, or context-aware applications, will have on that proximity relationship. Finally, this same technique may be used to evaluate proximity relationships between collections of mobile phones and their owners as well as the proximity relationships between people and other technologies, mobile or stationary.

## 5. Conclusions and Future Steps

The BlueTrack technology has been developed and the laboratory evaluation and diary-study is complete. In addition, the in-depth mobile phone proximity study that used BlueTrack is also complete. The results form this study have already been analyzed and published at Ubicomp 2006 [8] . The PowerLine Positioning technology has been built and a substantial portion of the technical evaluation has also been conducted. The technology and its evaluation was published at Ubicomp 2006 [9] . I am currently in the midst of manufacturing the deployable tags that will be available mid-2007. As part of the testing of the new deployable tags, I will be conducting additional in-home performance tests. At the end of the manufacturing process, I will have a bill of materials that will contribute to the cost analysis of this system. Finally, the deployment of PowerLine Positioning to study the activity of wheelchair users in their homes still remains.

Though the advice from my thesis committee has been invaluable, I believe I would benefit from guidance from researchers who have experience in conducting long-term, empirical studies in domestic environments. In addition, advice from other researchers outside Georgia Tech who are not as familiar with my work will help me learn to better position my work amongst an international and more diverse audience. I am also interested in seeing who else outside computer science would be interested in the technology I am proposing for my thesis.

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