

URB 07 Putting a Spotlight on Personal Resource Consumption

URB 07.1 People

- Principal Investigator: Mani Srivastava
- Faculty: Mani Srivastava, Electrical Engineering, UCLA; Jeff Burke, School of Theater, Film and Television, UCLA
- Graduate Students: Younghun Kim, Electrical Engineering, UCLA; Thomas Schmid, Electrical Engineering, UCLA; Zainul Charbiwala, Electrical Engineering, UCLA

URB 07.2 Overview

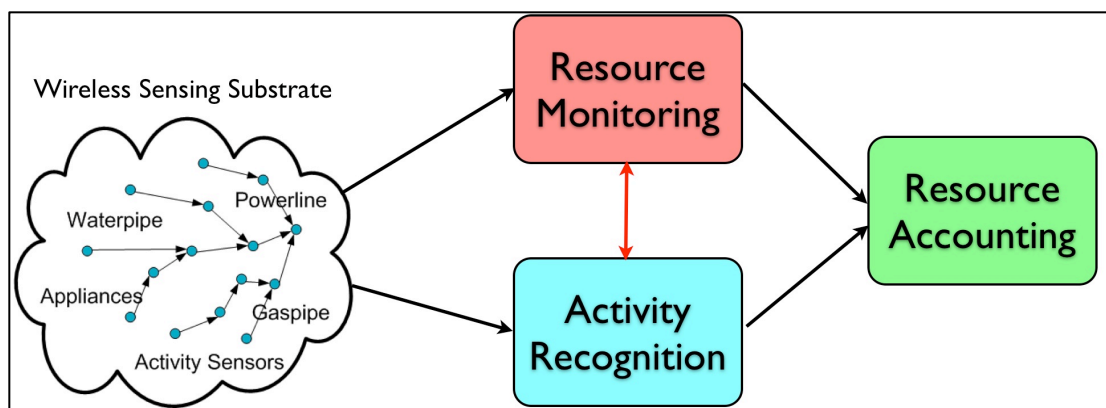
Spotlight is a system that aims to profile real-time information about energy and resource consumption by particular end-use to occupants in residential spaces. We develop technologies for an economical and easy-to-deploy monitoring system that is able to provide personalized, real-time, and activity-annotated energy and resource consumption reports. The reports essentially visualize how much resource each individual consumed, at what time (or during what activity), in what form (electric, water, natural gas, or heating oil), and through what appliance or device. The Spotlight system, we expect, would effectively encourage individuals to modify specific energy-wasting habits, compare usage trends within their peer group and neighbors, support behavior modification through auditory and visual feedback, and track that progress over time.

URB 07.3 Approach

Providing personalized consumption reports to individuals requires solving several technical challenges: (i) economical measurement of the energy and resource being used by various end-points (appliance, faucet, heating unit, etc.) in a household, (ii) identification of the individual(s) using an end-point at a particular time and the activities they were engaged in, and (iii) associating energy and resource consumption at end-points to specific individuals and their activities.

Monitoring end-point level resource consumption is difficult in current technology without expensive or professionally installed sensors for directly metering energy and resource usage at each energy or resource consuming end-point or circuit. Also most of them are not designed for real-time data collection to a central server, thus are not suitable for this application. To develop an economically feasible monitoring system, we develop an architecture that combines *pre-existing resource monitoring systems* and *noninvasive indirect resource sensing mechanisms* in a tiered wireless sensing architecture. The key is to develop smart inference and learning algorithms for end-point level resource monitoring and personalized activity inference.

In this architecture, we want to avoid the traditional approach of using complex and carefully trained and calibrated sensing hardware for monitoring resource consumption and occupant. Instead, simple hardware for opportunistic sensing of information about resource consumption and resident activity is used with smart algorithms and models



Spotlight System Architecture

to train and calibrate the hardware and to make inferences with minimum user intervention, which is essential for an economically scalable and easily installable system.

To tackle these challenges, we propose several architectural elements. The first element is an **auto-calibrating tiered sensing** approach to measuring resource consumption at every end-point in the building. High cost, installation and retrofitting difficulty, and aesthetic or ergonomic intrusiveness are inherent in in-line sensors that directly monitor resource usage at every resource-consuming end-point. Our approach is to use a number of cheap *less intrusive* sensors that detect signals, such as sound, light and/or vibration, emitted by resource-consuming end-points and related to the resource consumption rate, together with a single *direct* sensor measuring the total consumption of that resource type for the whole building at the main metering point. The key to making this idea work is an *autonomous calibration framework* that learns the calibration functions that map the readings from cheap *indirect* sensors into precise resource consumption estimates.

The two other elements of the architecture are **occupant activity recognition** and **resource accounting**. To correctly associate resource consumption with specific occupants and their activities is vital to providing personalized resource consumption information. The challenge is to be able to do so without the occupants to continually wear or carry special sensors.

We explore a distributed wireless sensing subsystem using a activity inference engine together with personalized activity models to opportunistically fuse uncertain cues from simple ambient sensors into robust inferences about identity and activity state of users of resource-consuming end-points. By combining this information together with the end-point resource consumption, the accounting subsystem associates resource consumption data with occupant activity.

By creating technology that generates fine-grained personalized energy and resource accounting to be an integral part of all built environments, we hope to engender significant socioeconomic benefits. For example, encouraging conservation among individuals and families; demand side management and assessment of the efficacy of conservation in buildings; resources and waste inventory reporting in organizations; targeting of incentives by utilities; and, auditing for compliance with regulations by government agencies.

URB 07.4 System(s) Description and/or Experiments

System Description: to show its overall concept, we developed two prototype systems: a personal power monitoring system and a pipe-level real-time water monitoring system

Spotlight Prototype (SPOTLIGHT):

To show its proof of concept design, we have implemented and deployed a prototypical system in a 2-person apartment. The design of the system is centered around instrumentation of participating appliances. In the prototype, four appliances (a television, a coffee machine, and two standing lights) are powered through commercially-off-the-shelf power meters that directly measure the power consumption of the appliances. This power meter provides a serial interface for external logging. The serial interface connects to a MicaZ 'appliance' mote that forms the sensing and communication hub for the appliance. The sampling and reporting rate of the power meter is set at 1 Hz. On receiving power measurements, the appliance mote forwards these messages to the Spotlight server through its radio.

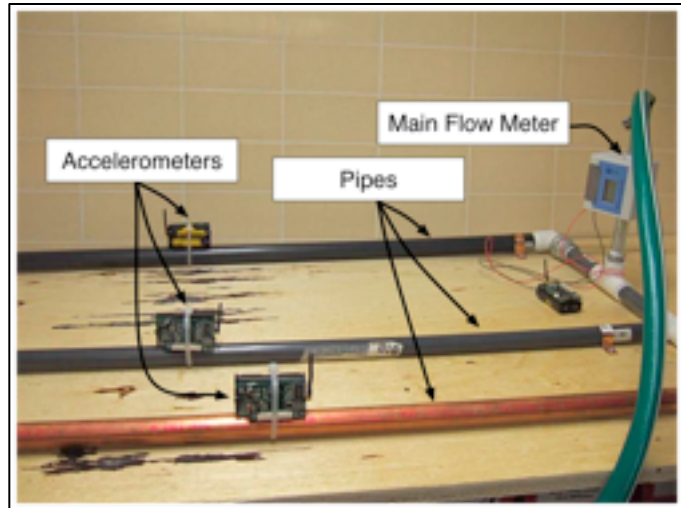
The MicaZ mote is equipped with a 2.4 GHz Zigbee compliant radio that is used for sensing the proximity of participating users and for communicating with the Spotlight server. Users carry MicaZ 'tag' motes that broadcast periodic beacon messages advertising their presence. The appliance motes listen to the beacons and record the radio signal strength (RSSI) for tag beacons. These RSSI values are also forwarded to the Spotlight server for further data processing.

The Spotlight server is a system that receives beacon strengths and power measurements from the various appliance motes and processes them together to identify user proximity and eventually per user appliance energy consumption. The Spotlight server is connected to the appliance motes through a 'base station' MicaZ mote

attached to the server's serial port. The Spotlight server uses the SensorBase to record, maintain and retrieve the measurements from the appliance motes.

Nonintrusive Autonomous Water Monitoring System (NAWMS):

In order to test and validate our proposed two tiered sensing system architecture, we constructed a plumbing testbed with three pipes of different materials and diameters (copper ¾", PVC ¾", PVC 1"). The main water pipe is equipped with a *direct* water flow meter that meters the flow rate. We used a MicaZ mote for the interfacing medium that provides the fusion center with real-time flow rate measurements. Each branch pipe of the testbed is equipped with an acceleration sensor. In this setup, we use a MicaZ mote with the MTS310 sensor board. The MTS310 sensor board contains a 2-D Analog Device ADXL202 accelerometer that has a range of +/- 2g. The node samples the axis perpendicular to the pipe at 100Hz and calculates the variance of acceleration every 50 samples. This variance is then sent to the fusion center for further processing.



Testbed for Nonintrusive Autonomous Water Monitoring System

In addition to the sensors, each branch has a ball type valve at the end in order to control the flow rate within each pipe. To get the per-pipe ground truth, we added another flow rate meter to the end of each pipe.

URB 07.5 Accomplishments

SPOTLIGHT

Our prototypical implementation views appliances providing a service to a user and the energy consumption associated with the appliance as a cost for the service. Each participating appliance is defined a service range within which the user can benefit from the service. By using radio receive strength (RSSI) from user-wearable mote tags an appliance can determine the users in its service range. While analyzing energy consumption pattern of users, we found that the system can profile two interesting aspects of energy profiles: first, total energy consumption, which gives us how much energy is consumed by an individual whether it's useful or not, and second, total wasted energy, which implies the energy wasted by an individual unintentionally. Users may consult with the total amount of energy users consume, when they want to reduce their energy consumption. We assume that if occupants are continuously aware of their consumption and their need for energy, users could optimize theirs. Since the system can also give the occupants the information on wasted energy, they also could reduce their unintentional energy waste.

NAWMS

In this work, we tried to tackle the first challenge: designing a resource monitoring subsystem that provides the same resolution at a cost and effort that is reasonable for household use. Exploiting the fact that the vibration measure has monotonic relation with water flow rate in a pipe, NAWMS uses inexpensive vibration sensors attached externally to individual pipes, which reduces both cost and effort of installation. Those sensors and their un-controlled installation, however, require to have sophisticated calibration procedure, which may result in typically laborious sensor calibration steps. By developing an autonomous calibration scheme that continuously recalibrates the sensors, we showed that an economical monitoring with reasonable accuracy is possible without labor-intensive sensor calibration and installation.

Under idealized setting where we neither have external noise nor vibration propagation among pipes, we considered various pipe topologies and formulated a numerical optimization problem that yield the system

calibration coefficients at once. It turns out that the autonomous calibration is happening by solving a linear programming problem. In that, the system extensively uses the two-tiered architecture and exploits pre-installed main.

Since branch pipes are physically connected to the others, vibration from various pipes may propagate through their connection. Such phenomena either renders the simple linear programming problem a NP-hard problem, when we explicitly account for this, or increases estimation error, when we do not account for this. To solve this, we have derived two types of optimization problems: Two Phase Linear Programming Model and Mixed Linear Geometric Programming Model. Both of them are known to be solvable in known polynomial time. Although both of them relax the original NP-hard problem, they reasonably improve the estimation accuracy.

To be able to regulate system performance, a sensor system needs to recalibrate sensors upon performance degradation, which may increase maintenance cost. To address this challenge, we introduced a well-defined performance metric that helps evaluate the system performance in real-time. We have shown through a case study that it enables the system to adaptively calibrate the calibration functions.

Exploiting the two-tiered sensing architecture, we were able to develop a nonintrusive autonomous water monitoring system that neither requires expensive sensor calibration nor invasive sensor installation. It is possible to have a less intrusive, auto-calibrated, per pipe water monitoring system that provides pipe-level real-time water flow rate which was previously not possible without extensive installation of inline sensors. In our experimental set-up shown in the figure, we showed that vibration based water flow rate estimation is possible. The reported estimation error is less than 10% on average.

URB 07.6 Future Directions

We see two main directions, which we want to pursue: (i) generalizing the autonomous calibration method for finer grained resource monitoring system in residential spaces and (ii) developing activity/identity inference mechanisms for resource accounting.

To make the resource monitoring system economically feasible, an autonomous and noninvasive sensing subsystem is essential. With a modification from the NAWMS work, we envision that our proposed framework for water monitoring could be applied to other resource monitoring systems. For example, the power line in a household has a similar architecture, it has one main meter, and magnetic sensors, which can sense electrical power consumption related signals, need to be calibrated in order to estimate the power consumption of an appliance. We expect that the same is true for natural gas and oil for heating and cooking.

We see this problem is a particular case of sensor calibration problems which has one property, that is, one sensor is calibrated and monitors the sum of the resource consumption whereas the other sensors are monitoring resource consumption related signal. Now the main challenge is to find a unique set of calibration functions given a set of measured data. We anticipate, similar to the NAWMS case, that a class of optimization problems yield a unique solution that describes a monotonic input-to-output relationship thus is the unique calibration function, which primarily suggests us that without any human intervention, a system can obtain a complete set of calibration functions by minimizing the class of optimization problems.

In addition, we plan to develop an activity and identity inference technique based on the finer grained resource monitoring subsystem. Correlating resource consumption per occupant is a very essential step for solving the problems associated with detecting and identifying people and their activities. In doing this, we will revisit the problem of human detection and identification in the context of energy and resource consumption by exploiting existing sensing. We seek to find a higher-level algorithm that will decide how to associate end-point resource usage with the occupants and their activities so that they can draw concrete conclusions on their consumption.