Funded Project Final Survey Report

Principal Investigator: Prof Andrea Goldsmith

Project Title: Wireless Sensor Networks Technology for Smart Buildings

1. Project Description:

This project sets forth a research plan for developing enhanced energy usage models and solutions for home and office buildings based on modern sensing and wireless networking technologies. Availability of low-cost sensing and processing modules as well as recently developed efficient wireless communication protocols for building automation applications provide the basic enabling tools for the application domain of smart buildings. Network-centric application areas such as security and surveillance as well as novel user-centric technologies such as in-home patient and elderly monitoring have already been explored to some extent, but these are only the first of the plethora of possible applications for smart environments. Energy usage automation is a compelling application of sensor technology due to the universal need for energy usage optimization in homes and office buildings.

The proposed research plan employs tools and techniques of modern sensing, processing, and networking to develop optimized energy usage solutions. The plan consists of development efforts across three major topics:

1. Development of distributed sensor-based techniques and embedded algorithmic processes to measure, detect, estimate, and predict the constant and variable environmental factors as well as the user-centric conditions that determine the need for energy expenditure.

2. Development of local-area wireless communication and networking systems and adaptation of available protocols to enable the distributed sensing and processing devices to interact with each other, provide relevant information and receive commands from the users, obtain real-time energy pricing when available, log and report and develop history of the usage model, and offer scalable operation when more network devices are added to the environment for supporting this or other applications.

3. Development of energy usage models and optimization algorithms to minimize energy expenditure using the heterogeneous data provided by the networked sensors, user commands, and system settings, real-time pricing information when available, and feedback information available from the network.

Research Activities:

- We have developed algorithms for detection of occupancy and the user's location and activity in a smart home, methods for optimal light control settings based on user's location and activity and minimal use of

energy, and adaptive methods to adjust the service settings based on user behavior model and user feedback received over time.

- We have also developed protocols and network optimization techniques to meet the performance requirements of sensor networks designed for energy efficient buildings. These techniques optimize the resource allocation and routing of the wireless networks based on application requirements. The optimization framework for these techniques is quite general, and can be adapted to constraints on battery power, transmit power, delay requirements, and other communication constraints associated with low-cost radios embedded in sensors.

Major Findings:

It is feasible with today's sensing, processing, and networking technologies to realize a system of real-time detection and activity classification for a user in a smart home. It is also possible to adapt the service based on explicit or implicit feedback received from the user and adjust the settings to match the user's preferences.

At least an order of magnitude better performance and energy consumption can be obtained through optimization of networking protocols for sensor networks.

The cost for deploying a sensing, processing, and control system can be justified in the long-term by savings in the energy cost as well as the added user comfort offered by automation and adaptation. However, the proposition of installing a multi-sensor or a multi-camera system in a smart home needs to also be supported by two other factors: (1) proper handling of the sensed information and management of the data's security to ensure the privacy of the user and the establishment of a trust metric so the user can control the operation of the system and opt out at any time, and, (2) offering a multitude of applications beyond light control to further motivate the adoption of the technology. Such applications can include security (when the occupants are not home), baby monitoring and elderly care applications, and pervasive visual communication and tele-presence applications. Some of these applications are the subject of investigation at our lab.

2. **How have the results from this project contributed to the solution of energy efficiency challenges? How is it likely to contribute to solutions in the future?**

   - Energy efficiency challenges will require breakthroughs in control, communication, and sensing to monitor energy consumption on both a macro and micro scale, use this information to manage energy resources, and avoid catastrophic failures in the grid as well as energy shortages in time and geographical location. This project has developed some of the baseline sensing techniques and communication protocols for these sensing and control systems.

   - Sensing the occupancy in smart buildings enables adjustment of services such as light and temperature control in an energy-efficient fashion based on the number and location of the occupants as well as the type of event.

   - Optimization of heating and cooling systems will yield an efficiency benefit. In addition, it can also deliver coordinated demand response, with dynamically varying prices.

3. **What undergraduate or graduate students, as well as Post-Doctoral fellows, were involved this project. How were they involved?** ***Please list their name, classification and a short description of their involvement.***

   - Graduate students Sina Firouz and Boon Thian contributed to the development of the network optimization framework, as well as performance analysis of the resulting networks.
   - Itai Katz (MS/PhD student) developed an algorithm for human pose estimation, also installed a network of cameras in the Y2E2 iRoom for occupancy and event analysis applications.
   - Huang Lee (PhD student) developed methods for optimal light control based on the location and activity of a user in a smart home.
   - Chen Wu (PhD student) developed multi-camera computer vision algorithms for user activity classification in a smart home.
   - Yang Wang (PhD student) and Matt Kraning (PhD student). Each carried out basic research, as well as simulations to show that the methods work (in simulation).

4. **Will you be continuing work on this project? How and with whom? Please include any comments.**

Yes, we have set up a prototype smart home lab and are working on more advanced activity and event classification techniques, as well as new adaptive service provision schemes to adjust the services according to the user's behavior model and the feedback provided by the user. We also expect to continue our work on network optimization for sensing and control, and also expand our work into cross-layer design, taking into account the metrics and applications associated with energy efficiency in buildings as well as associated with the smart grid.

5. **Are you seeking or have you received additional funding as a result of this project, or for continued work on this project?** ***Please list the amount you are seeking/have received, source of the additional funding and a short description.***

We have received offers of funding from other sources for continuing this work. We were invited to apply for the ARPA-e funding. The allocated funding is for one graduate student and supervision for two years. We are seeking additional funding on "green" wireless networks, which reduce the energy consumption of wireless network infrastructures. We are also looking at participating in some smart grid funding, but have not pursued this yet.

6. **Has this project generated any other projects?** ***Please describe*****.**

We have developed a smart home lab, where we are studying user-centric service adaptation, behavior modeling, and more advanced activity classification methods. The project has also led to several other projects on optimization for the smart grid. In general, the project has contributed to our understanding of the needs and opportunities in energy efficiency research, which led to follow-on projects.

7. What patents, if any, have you received or applied for?

None.

8. Please list all academic and non-academic (Op-Eds, news magazines, etc) publications and conference presentations as well as articles in progress that came about as a result of this project. May we post these on the PEEC website? *If so, please list the URL or provide a pdf version*.

- S. Firouzabadi, D. ONeill and A.J. Goldsmith, "Optimal Power Line Communications Control Policies using Stochastic Optimization", International Conference on Power Line Communications, 2010. http://www.stanford.edu/~dconeill/bare4_ISPLC_AFinal.pdf

- D. ONeill, E. Akuiyibo, S.P. Boyd, and A.J. Goldsmith, "Optimizing Adaptive Modulation in Wireless Networks via Multi-Period Network Utility Maximization", IEEE Wireless Communications and Networking Conference, 2010. http://www.stanford.edu/~dconeill/icc10A_Final.pdf

- D. ONeill, Boon Sim Thian, A.J. Goldsmith, and S.P. Boyd, "Wireless NUM: Rate and Reliability Tradeoffs in Random Environments", IEEE Wireless Communications and Networking Conference, 2009. http://www.stanford.edu/~dconeill/WCNC.pdf

- D. ONeill, A.J. Goldsmith, and S.P. Boyd, "Optimizing adaptive modulation in wireless networks via utility maximization", *Best Paper Award* International Conference on Communications (ICC), 2008.
- http://www.stanford.edu/~dconeill/icc.pdf

- D. ONeill, A.J. Goldsmith, and S.P. Boyd, "Cross-Layer Design with Adaptive Modulation: Delay, Rate, Energy Tradeoffs", IEEE Global Communications Conference (Globecom), 2008. http://www.stanford.edu/~dconeill/globecom.pdf

- D. ONeill, A.J. Goldsmith, and S.P. Boyd, "Wireless Network Utility Maximization", Military Communications Conference (MILCOM), 2008. http://www.stanford.edu/~dconeill/milcomFinal.pdf

- I. Katz and H. Aghajan, "Multiple Camera Based Chamfer Matching for Pedestrian Detection", Workshop on Activity Monitoring by Multi-camera Surveillance Systems, International Conference on Distributed Smart Cameras (ICDSC), Sept. 2008. http://airlab.stanford.edu/WSNL/papers/icdsc08-ped.pdf

- C. Wu and H. Aghajan, "Human Pose Estimation in Vision Networks via Distributed Local Processing and Nonparametric Belief Propagation", Advanced Concepts for Intelligent Vision Systems (ACIVS), Oct. 2008. http://airlab.stanford.edu/WSNL/papers/acivs08pose.pdf

- A. Khalili, C. Wu, and H. Aghajan, "Autonomous Learning of User's Preference of Music and Light Services in Smart Home Applications", Behavior Monitoring and Interpretation Workshop at German AI Conf, Sept. 2009. http://airlab.stanford.edu/WSNL/papers/acivs08pose.pdf

- A. Khalili, C. Wu and H. Aghajan, "Hierarchical Preference Learning for Light Control from User Feedback", Workshop on Human Communicative Behavior Analysis, CVPR, June 2010. http://airlab.stanford.edu/WSNL/papers/cvpr10_HRLLighting.pdf

9. Provide a URL address for any websites that provide more information for interested parties on your research project, including photos and videos. We will add this information to your project summary on the PEEC website.

Our websites have links to all papers, books, courses, software and other materials that we have developed. Some project descriptions are provided at the following webpages:

http://airlab.stanford.edu/projects.html
http://airlab.stanford.edu/WSNL/smartenv.html#energy

10. Have you developed any specific products, (such as databases, physical collections, educational aids, software, etc), as a result of this project? *If so, please list along with a short description.*

No.

11. Were any undergraduate or graduate courses generated as a result of this project? *If so, please list the course title and a short description.*

No. The examples from the course EE364A are now based on energy management and smart grid problems.

12. Have you provided any information regarding your research to any public or private institutions (e.g., legislative briefing, government panel, congressional testimony, corporate presentation) or any public or private institution asked you for information regarding your research? *If so, please list the organization, date and a short description.*

No..

13. Have you partnered or worked with businesses, governmental agencies, NGOs, or other public or private organizations in connection with your project? If so, what role have they played? Please list the institutional name, type of institution and a short description of the partnership.

No.

14. What public education activities have you undertaken in conjunction with this project?

Our seminars and short courses contain brief overviews of all projects conducted in our labs. Our course materials are available online and very widely used. They include many examples developed during this project. Multiple plenary talks at international conferences were offered in which the potentials for improved energy efficiency via sensor networks were discussed.