NSF Workshop on Information and Communication Technologies for Sustainability (WICS)

1. Sustainability and Information Communications Technology

A grand challenge of the twenty-first century is to foster a transition of societies worldwide to use resources such as water, air, land, food, and energy in ways that meet the present needs without compromising the ability of future generations to meet their own needs for these resources [UN Brundtland Report 1987]. "Sustainability" is broadly defined by National Academy of Sciences as "the interactions between natural and social systems and how these interactions affect the challenges of meeting the needs of present and future generations while conserving the planet's life support systems". Sustainability has three key aspects: environment, economy, and society, and "resolving the energy-economy-environment dilemma is the core of the sustainable well-being" [John Holdren 2008].

Information and Communication Technology (ICT) has had a tremendous impact in improving efficiencies from individuals to corporations. Going forward, we believe ICT has a great potential in facilitating the society's efforts to foster the envisioned transition toward *global* sustainability. ICT can play a key role in many aspects of sustainability, including, but not limited to, the management and efficient use of critical resources such as fuel, energy, water, materials, and agricultural land; biodiversity and eco-system management such as species survival/migration, invasive species, forest cover, and oceanic health; societal well-being such as health and disease management, water and energy availability and quality, and adaptation to climate change; disaster management such as fire, hurricane, flood, rescue and securing information infrastructure under disasters; and understanding climate change in terms of comprehensive monitoring, data management and analysis, and complex large-scale multi-level modeling and simulation.

Fortunately, latest technological advances in sensing, processing and communications provide a good starting point for their deployment in the sustainability efforts such as monitoring and data collection mechanisms, large-scale modeling and simulation tools, and algorithmic decision and optimization. Yet, the problems surrounding societal-scale resource planning and utilizations are far from being understood, much less solved. The goal of the workshop was to bring together researchers and practitioners with a broad vision and active interest in defining the path forward on how the computer science and engineering (CSE) research community can contribute in a significant way towards tackling challenging sustainability problems of our time.

2. Key ICT Mechanisms for Sustainability

NSF Science, Engineering and Education for Sustainability (SEES) is an NSF-Wide initiative with the objective to enable and facilitate the "discoveries needed to inform actions that lead to environmental, energy and societal sustainability" [NSF 2010]. NSF and other various federal agencies have held multiple workshops to understand and address these challenges from different perspectives. In a widely-cited report "Toward a Science of Sustainability," six grand research and development challenges are outlined that require the interplay from a broad spectrum of disciplines [National Science Foundation, 2009]. In a follow on DIMACS workshop, two additional areas are considered, namely, mathematical areas of emphasis (e.g., large data sets, statistical methods, dynamic models) and scientific/societal areas of emphasis (e.g., climate change and energy efficiency) [DIMACS, 2010, Cozzens and Roberts, 2011]. A more recent workshop, held jointly by NSF and CCC, focused on the role of Information Sciences and Engineering for sustainability [Computing Community Consortium, 2011]. Critical CISE (computer and information science and engineering) mechanisms for sustainability have been outlined, and key areas for CISE research for sustainability are identified including large-scale data management, modeling and simulation, optimization, intelligent systems, cyber-physical systems, human-centered and social computing, privacy and security, system engineering and integration, and green IT. Following the success of RISES workshop help in Delhi, India in April 2011, the current 'Salt-Lake City workshop' focuses on the role of Information Communication Technology (ICT) for sustainability. Therefore, in this report, we emphasize the issues extensively studied in the workshop.

There are key ICT mechanisms that are widely used in sustainability efforts. We summarize the key components discussed in this workshop. **Rich networked-sensors**, in all scales, have been widely used in a wide range of areas of sustainability domains for monitoring, controlling, and collecting, such as wildlife monitoring, weather condition monitor and forecasting, power grid monitoring and control, building monitoring and control, traffic and road condition monitoring, and data center monitoring. **Computational sustainability** is a new interdisciplinary field that aims to develop computational models, methods, and tools for sustainable development [Gomes 2009]. **Spatial computing** targets the computational structure of very large spatial computations (e.g. data analysis via spatial querying and spatial data mining) needed by social and physical sciences as well as engineering disciplines for sustainability efforts [Shekhar et al., 2003]. **Algorithmic decision theory** aims to exploit algorithmic methods to improve the performance of decision makers (human or automated) in the presence of concomitant challenges [Roberts, 2008, 2010]. These disciplines are closely related and often deeply coupled. We often refer to societal-scale applications of these disciplines as instances of "Cyber-Physical Systems" (CPS). CPS examples include smart grid and hazard weather monitoring system in the context of sustainability. There are several challenges common to CPS applications:

- Societal-scale systems must handle massive amounts of data that are often incomplete or unreliable or distributed;
- There is great uncertainty and non-stationarity in data. In the face of these uncertainties data from multiple sources of different temporal and spatial scales and different focuses often needs to be combined;
- Computations and decisions may need to be made in dynamic environments based on partial information and in short time;
- There is heightened risk due to extreme consequences of poor decisions.
- The real world sustainability problems are complex and dynamic with uncontrollable factors and without predefined discipline boundary; they must be tackled by highly multidisciplinary teams that understand each other's domain in a non-trivial manner.

Such research will not only provide important technological tools to address real-life challenges in sustainability, but also will be strengthened by such challenges, and thus advance the state of the art of computing and information science and related disciplines. The research encompasses balancing environmental, economic, and societal needs, with some examples listed as follows:

- Environment
  - How are we changing the physical environment of Earth's surface?
  - How can we best preserve biological diversity and protect endangered ecosystems? What are appropriate biodiversity metrics?
  - How are climate and other environmental changes affecting the vulnerabilities of coupled human–environment systems?
- Economic
  - How and where will 10 billion people live?
  - How will we sustainably feed everyone in the coming decade and beyond?
  - How does where we live affect our health? For example, what is the overall pattern of a certain type of cancer and where is it significantly elevated or changed? Are there hotspots and how to identify hotspots using non-traditional clustering algorithms?
  - How to achieve energy, water, food sustainability? For example, how to design and operate smart-grid systems?
- Social
  - How is the movement of people, goods, and ideas changing the world? For example, how to design ego-routing to minimize fuel consumption and GPG emission and what is the impact of historic and real-time data?
  - How is economic globalization affecting inequality? How do we map poverty, combining data from various sources, and design policies to combat poverty most effectively?
  - How to influence cascades in networks, both natural and man-made? For example, how to maximize the spread of technology and minimize the spread of diseases or invasive species?
- Methods
  - How might we better observe, gather, store, analyze, model, and visualize a changing world?
  - What are the societal implications of citizen science and how do we most effectively mobilize citizen for sustainability?
  - How can we achieve persistent surveillance in a sustainability manner that reduces cost and labor?
  - How to address new technical challenges in special computing such as eco-routing, emerging hotspot, auto-correlation, and non-stationarity?
  - How to gather, manage, and analyze large-scale data in the presence of stochasticity and uncertainty?

A few concrete examples are discussed as follows. For instance, a critical issue in preserving biodiversity is to maintain connectivity of wildlife reserves. It is a challenging computer science problem to design wildlife corridors that link biological areas and preserves genetic diversity for multiple species with different characteristics under various environmental, economic, and societal constraints. It can be formulated as a connection sub-graph problem, which is NP-hard. However, real-world problems possess hidden structure that can be exploited allowing scaling up of solutions [Dilkina et al., 2010; Lai et al., 2008]. Another example is evacuation route planning. Efficient tools are needed to identify routes and schedules to evacuate affected populations to safety in face of natural disasters or terrorist attacks. Challenges arise due to violation of key assumptions (e.g. stationary ranking of alternative routes, Wardrop equilibrium) behind popular shortest path algorithms and microscopic traffic simulators. To address the challenges, researchers have presented a new approach, namely Capacity Constrained Route Planner (CCRP), advancing ideas such as Time-Aggregated Graph (TAG) and an ATST function to provide earliest-Arrival-Time given any Start-Time [Shenkar, 2006]. These research projects are driven by real-world problems, which in turn advance the state of the art of computing and information science and related disciplines.

3. Key ICT Challenges for Sustainability

We have already seen the important role played by ICT in providing capabilities and functions that are essential to reducing costs, improving efficiency, and achieving scalability. These include cyber services replacing physical service that significantly reduces resource consumption; e.g., virtual meeting/collaboration instead of physical ones, online statements instead of those on paper; optimizing supply chains to provide and support what is needed and just-in-time; pervasive sensing of the environment to optimize energy user for home, work, and public places. Further, the ICT infrastructure itself can be made more sustainable. The workshop participants focused on a few of these key areas. The topics and discussions are summarized as follows.

Smart Grid

An emerging technology, smart grid predicts and intelligently responds to the behaviors and actions of electric power users and the generation of electricity, including unreliable and renewable energy sources to efficiently deliver reliable, economic, and sustainability electrical service. Many challenges exist in all aspects of the smart grid systems, including the design, standardization, architecture, and operation. Moving forward, 21st century grids are smart and diverse: 1) including distributed and centralized electricity supply; 2) existing bi-directional power flow at the meter and upstream; 3) the usage of pervasive "net" metering and "smart" meters; and 4) actionable real time price information plus automated response at the point of use. On the other hand, today's electric power systems are highly complex systems that a huge number of customers with uncontrolled demand, subject to unexpected disturbance and uncontrollable influences such as extreme weather. They operate close to the edge and thus vulnerable to failures. Power systems are high interdependent upon each other and subject to cascading failures that can have dramatic consequences. Renewable power sources introduce additional volatility and physical complexity in the power systems and it is challenging to fully utilize renewable sources, which is further complicated by micro-grids and networked micro-grids.

As an illustrating example of using ICT for sustainability, consider the case of phasor measurement. Phasor measurement will provide "MRI quality" visibility of the power system at the granularity of many times a second while the traditional measurement provides status updates every 2 to 4 seconds. New algorithmic methods are needed to understand, process, visualize data and to find anomalies rapidly and in early stage. Along the line, privacy and security issues need to be addressed [Roberts, 2010].

Renewal energy sources have attracted much attention for its sustainability. Currently, in US, 7.1% of electricity comes from hydroelectric and 2.4% comes from other renewable sources while coal and natural gas count for 48.9% and 20%, respectively. Many renewable sources are being considered, including solar PV (active), concentrated solar power (CSP), wind, fuel cells, tidal, biomass, and small hydro. These vary from small units to large farms (few KW to less than 10 MW) connected as a cluster in a farm or park and most of them are intermittent in nature. Some of them form microgrids. Challenges exist, including energy efficiency, storage planning and efficiency, voltage regulation, dynamic load modeling and forecasting, demand and supply matching, reliability, and power quality. Significant amount of research and experiments are needed to further the momentum of renewable energy.

Case Study: UC Davis West Village is a pioneering project on zero net energy community. It provides affordable living for 5000 UC Davis faculty and students. It targets Zero Net Energy from the electricity grid on an annual basis by leveraging hyper energy conservation measures, multiple integrated renewable resources at a community scale, and smart grid functionality. In particular, in addition to deep energy efficiency and solar thermal at West Village facilities, it has distributed solar PV in common areas, up to 5MW, and community energy park based on biodigester, fuel cell (300 kW), and battery (1 MW). Pioneering projects like the UC Davis West Village Energy Initiative provide venues to gain experience and validate new concepts. Other instances of smart building efforts including work at UCSD, Virginia, HP, and Stanford.

Building Energy and Water Efficiency

Building consumes a significant amount of energy. It counts for more than 70% of total US electricity consumption and more than 40% of total carbon emissions. To improve energy efficiency in buildings, multi-facets of efforts are needed. For example, to manage the energy footprint of a home or an office building, it needs approaches from data to analytics to recommendations to controls. To manage the interaction between smart buildings with grid/utilities, one can leverage dynamic pricing signals to match demand and supply. In the UCSD pilot project, two further steps are considered. The first step is to reduce energy consumption by IT equipment. Typically, in commercial and academic buildings, servers and PCs are left on to maintain network presence. One key technique is to “duty-cycle” computers aggressively while maintains seamless network presence [Agarwal et al., 2010a]. The second step is to manage energy consumption by the HVAC system where in the current system the energy use is not proportional to number of occupants [Agarwal et al., 2010b, Agarwal et al., 2011]. A key technical challenge is to use wireless sensors to detect occupancy and use real-time occupancy to drive HVAC. There is also a need to define performance metrics and to accommodate human being’s desire for comfort and for instantaneous response. The UCSD pilot project demonstrates a 40% potential energy saving in IT-heavy academic buildings. There are significant benefits and opportunities in the design and operation of more energy efficient buildings and net-zero buildings.

Energy and water are tightly coupled resources; it takes significant amount of water to make energy and it consumes vast amount of energy to provide water. Similar to the smart grid of energy, sustainability efforts require a smart grid of water [Kim et al., 2008]. Key challenges and opportunities are as follows:

- Smart water meters that provide leak alert, appropriate pressure and quality management, enforcement of water usage restrictions, and real-time and non-real-time feedback to users.
- Better management of water networks that detect theft, faulty meters, and leaks and reduce major breaks.
- Time-of-use and demand pricing that respond to energy prices and help reduce peak electric load, e.g., by using stored water, treated water, and heated water as energy storage and asset.

Green ICT

Cloud computing is becoming increasingly popular in enterprise and personal computing area. Eaas (Everything-as-a-Service) model has been increasingly popular fueled by the need to reduce CapEx and OpEx. According to Gartner, worldwide cloud services revenue is projected to reach $140B in 2014. It is estimated that 3% of the electricity consumption and 2% of the CO_2 emission are caused by ICT infrastructure. As we rely more and more on ICT to improve sustainability of the planet, it becomes imperative to optimize the ICT infrastructure itself to be sustainable. ICT sustainability spread across many areas/aspects, including the energy efficiency of datacenters, networks, and devices, and the design of hardware and software architecture of devices for sustainability [Mahadevan et al., 2010]. Green ICT sustainability challenges include:

- Making Network Devices Power Proportional
- Making Network Systems Power Proportional
- Understanding and realizing best operational and management practices
- Handling large proportion of legacy devices
- Combining network power management with location sensors, identity information from existing IT databases
- Establishing standard benchmarks
- Standardization and Interoperability

E-waste Management

The pervasive computing and sensing devices have on one hand significantly benefited our life and sustainability efforts, on the other hand, created sustainability problems themselves [Belvis 2007, Koehler et al., 2005]. E-waste has low recycling ratio, and represents 2% trash in landfills, and 70% of overall toxic waste. The extreme amount of lead in electronics alone causes damage in the central and peripheral nervous systems, the blood and the kidneys. In addition, while manufacturing consumes a significant amount of energy in an electronics device's life cycle, little research has been focused on it. Therefore, we call for more research in the following areas: 1) improved end-of-life treatments that are both environmental and health friendly; 2) better co-design of hardware-software architectures to prolong the lifetime of electronic devices; and 3) regulated policies for recycling of used devices (and their parts) that make manufacturers accountable.

4. Workshop Recommendations

Evaluation. The workshop calls for better evaluation methodologies and tools in sustainability research. A critical challenge that was identified and subject of intense discussion was related to the tremendous difficulty in providing and using data across the community of researchers, and the lack of accepted models and metrics, as well as data models and formats, to validate research results. Furthermore, in building such models and toolsets, it is worth noting that evaluation for physical systems is much different from that of cyber systems that the community is used to. For example, consider a micro-grid connected to the utility. While load-sharing is conceptually simple from a cyber perspective, it has great challenges in the physical world, including voltage control, phase control, safety, regulation, metering, and storage. The physics of connecting a micro-grid is much different from connecting a single house with solar panels because of the scale of the volatility involved. Therefore, understanding the physical system is critical to building meaningful evaluation tools. In addition, the test system is the production system, and thus its development faces challenges similar to other production systems, such as smart traffic control, medical, and water research. The existing (commercial) emulators are low-level, costly, slow, and not openly available. It is highly valuable to have PlanetLab-like testbeds, CRAWDAD-like trace repositories, and NS2-like (scalable and with high level abstract) simulation tools for better evaluations. Another critical challenge is to understand the research components as well as the engineering components in the system, and how they can be managed. NSF can play a central role in facilitating research and development in this key area.

Interdisciplinary Education. The success of the sustainability effort discussed in this report depends on the education of the next-generation workforce that embraces sustainability education in ICT and ICT education in sustainability. This, in particular, includes undergraduate and graduate student education. We call for innovative educational programs that inject sustainability issues into our curriculum in computer and information science and introduce our domain knowledge to students and workforce in other domains. Introducing sustainability issues into our colloquium allows students to understand the challenges and approaches and tackle real world problems. Methods to achieve these goals include introducing capstone courses and senior design projects tailored towards sustainability efforts. Another approach is to develop minors in computer science designed towards sustainability majors by focusing on ICT tools that are most relevant to sustainability, such as data mining, database management, and sensor and actuator network design and application. Furthermore, one could explore similar specialization at graduate level such as a M.S. degree tailored for sustainability. In addition, we also call for professional develop in the sustainability area. For example, it is essential for researchers on smart grid to really understand grid system, the physics, the operation, the safety regulations, etc. The NSF postdoc fellow program on sustainability is an excellent step in this direction. We would like to encourage mid-career faculty members to take an active role both in initiating interdisciplinary research and in developing education programs for sustainability efforts. We call for more programs to specifically support such challenging yet exciting career adventures.

Exciting Areas. The research areas that we discussed earlier are critical components in achieving sustainability. Some of the areas have received much attention from the research community, such as smart grid and green ICT. In addition to these efforts, we would like to draw attention to a few examples, in particular, water sustainability and disaster response system, which deserve more attention from the community in our opinion. Consider the example of water sustainability in commercial and residential buildings. Key ICT mechanisms can be used and further developed in water sustainability; e.g., sensor and actuator networks for leakage/contamination monitoring and control; real-time feedback to users, dynamic demand and supply management, co-management of water and energy, large data collection, management, and mining for river monitoring and climate change detection and modeling; and algorithm design and analysis for agriculture water allocation and reservation. The organizers also had an engaging discussion amongst themselves on the role of social networks on sustainability. Social networks have played a vital role in several organized efforts such as mass protests, event coordination, and building communities. Citizen science has migrated into the Internet leveraging the Web and social networks for sustainability efforts involving biodiversity, green energy, water conservation, and climate change. Much research is needed in this area for it to become a potent force multiplier for sustainability.

Collaboration. The workshop calls for better interagency and intersociety collaborations. Professional societies in power and communication as well as utilities are key players in smart grid and they should find ways to collaborate more and NSF should find ways to encourage such collaboration. Other possibilities of collaborations include academia with industry and government, academia with standards-setting agencies, and international collaborations for sustainability problems do not know national boundaries.

Standardization. The workshop calls for further involvement in standardization efforts, in particular, in smart grid. 80% of IEEE standards are power related. The state-of-the-art research is often 10-20 years ahead of the standards, due to the limited involvement of academia researchers, and due to the conservative nature of the field.

Interdisciplinary Collaboration. Interdisciplinary research is challenging. The most difficult part is to understand the other domain. We also need to help the other party understand our domain better and that CS is not just programming. There will be trials and errors on both sides before fruition. There are excellent examples and unlimited number of opportunities available! Interdisciplinary research has the great potential to advance the state of the art of computing and information science and related disciplines with unique societal benefits!

5. Workshop Organization and Participants

Monday, June 27, 2011	
7:30am-8:30am	**Registration and breakfast**
8:30am-9:00am	**Introduction by Workshop Chairs and NSF Officials**
9:00am – 10:40am **(Session I)**	Algorithmic Decision Theory and Sustainability, **Fred Roberts**, Rutgers University Smart Distribution Grid: Communications Perspective, **Mani Venkata**, Univ. of Washington 21st Century Energy Market Requirements for Information and Communications

	Technologies, **Gerold Braun**, UC Davis Sensor Networks in Sustainability, **Jim Kurose**, Univ. of Massachusetts
10:40am -11:00am	**Coffee break**
11:00am-12:30pm	**First Breakout Session**
12:30am – 1:30pm	**Lunch**
1:30pm – 3:10pm **(Session II)**	Addressing the Energy-Water Nexus in Sustainable Buildings and Communities, **Mani Srivastava,** UCLA Computational Sustainability, **Carla Gomes**, Cornell Sensing and Sensibility of Energy Use in Modern Buildings, **Rajesh Gupta**, UCSD IT For Sustainability: Challenges in Designing Smarter and Greener Systems, **Prashant Shenoy**, Univ. of Massachusetts
3:10pm – 3:20pm	**Coffee Break**
3:20pm – 4:35pm **(Session III)**	Sustainable Networks for Green Clouds, **Sujata Banerjee**, HP labs Pervasive Computing for Sustainability, **Mohan Kumar**, University of Texas, Arlington Spatial Computing and Sustainability, **Shashi Shekhar**, Univ. of Minnesota
4:35pm – 5:30pm	**Second Breakout Session (w/ coffee)**
5:30pm – 6:00pm	**Report and next step**
6:00pm – 8:00pm	**Dinner**
Tuesday June 28th 2011	
10:30am - 12:00pm	**Panel:** Information and Communication Technology for Sustainability Moderator: **Krishna Kant**, National Science Foundation Panelists: **Jim Kurose, Shashi Shekhar, Mani Venkata**, and **Mohan Kumar**. The panel is report-out and discussions following through the Workshop of Information and Communication Technology for Sustainability (WICS). The panelists discussed a broader range if sustainability impacts related to energy, water, food, environment, and bio-diversity.

Invited Speakers:

Sujata Banerjee, HP labs (sujata.banerjee@hp.com)
Gerold Braun, UC Davis (gwbraun@ucdavis.edu)
Carla Gomes, Cornell (gomes@cs.cornell.edu)
Mohan Kumar, University of Texas, Arlington (mkumar@uta.edu)
Jim Kurose, Univ. of Massachusetts (kurose@cs.umass.edu)
Fred Roberts, Rutgers University (froberts@dimacs.rutgers.edu)
Shashi Shekhar, Univ. of Minnesota (shekhar@cs.umn.edu)
Prashant Shenoy, Univ. of Massachusetts (shenoy@cs.umass.edu)
Mani Srivastava, UCLA (mbs@ucla.edu)
Mani Venkata, Univ. of Washington (mani.venkata@alstom.com)
Rajesh Gupta, UCSD (rgupta@ucsd.edu)

Workshop Organizing Committee:

Prasant Mohapatra, University of California, Davis
Xin Liu, University of California, Davis
Krishna Kant, NSF and Intel

The workshop website is http://www.cs.ucdavis.edu/~liu/WICS/WICS.htm .

References:

United Nation. (1987). Our Common Future, Report of the World Commission on Environment and Development, World Commission on Environment and Development, 1987.

Gomes, C.P. (2009). Computational sustainability: Computational methods for a sustainable environment, economy, and society. The Bridge 39(4): 5-13. Retrieved from http://www.nae.edu/File.aspx?id=17673 April 4, 2011.

Dilkina, B. and Gomes, C.P. (2010). Solving connected subgraph problems in wildlife conservation. In Proceedings of the 7th International Conference on Integration of AI and OR Techniques in Constraint Programming for Combinatorial Optimization Problems (CPAIOR-10), Bologna, Italy, pp. 102-116.

Lai, K.J., Gomes, C.P., Schwartz, M., McKelvey, K., Calkin, D. and Montgomery, C. (2011). 24 The Steiner Multigraph Problem: Wildlife corridor design for multiple species. Proceedings of the 25th Conference on Artificial Intelligence, Special Track on Computational Sustainability and AI (AAAI-11), to be held in San Francisco, California, Aug. 7-11.

Computing Community Consortium, (2011). Science, Engineering, and Education of Sustainability: The Role of Information Sciences and Engineering. http://cra.org/ccc/docs/RISES_Workshop_Final_Report-5-10-2011.pdf

John P. Holdren (2008), Science and Technology for Sustainable Well-Being, Science 25 January 2008: Vol. 319 no. 5862 pp. 424-434.

NSF 2010, Science, Engineering and Education for Sustainability (SEES) NSF-Wide Investment, http://www.nsf.gov/geo/sees/.

National Science Foundation, 2009, Towards a science of sustainability, http://www.nsf.gov/mps/dms/documents/SustainabilityWorkshop2009Report.pdf

DIMACS, 2010, Workshop on Mathematical Challenges for Sustainability http://dimacs.rutgers.edu/Workshops/Sustainability/program.html

Fred Roberts, 2010, Algorithmic Decision Theory for the Smart Grid, Workshop on Algorithmic Decision Theory for the Smart Grid, DIMACS, October 2010.

Margaret B. Cozzens and Fred S. Roberts (eds.), Mathematical and Statistical Challenges for Sustainability, American Mathematical Society, Providence, RI, 2011. (Available online at http: http://dimacs.rutgers.edu/SustainabilityReport/SustainabilityReport_Final08-02.pdf)

Fred S. Roberts, Computer Science and Decision Theory, Annals of Operations Research, 163 (2008), 209-253.

Shashi Shekhar and Sanjay Chawla, 2003, Spatial Databases: A Tour, Prentice Hall, 2003.

Shashi Shekhar, 2006, A scientific approach to evacuation planning, The Sensor Newsletter, Volume 6, Number 3, Intelligent Transportation Systems Institute, University of Minnesota, Winter 2006.

Yuvraj Agarwal, Stefan Savage, Rajesh Gupta (2010a), "SleepServer: A Software-Only Approach for Reducing the Energy Consumption of PCs within Enterprise Environments" , USENIX ATC, 2010.

Yuvraj Agarwal, Bharathan Balaji, Seemanta Dutta, Rajesh K. Gupta, Thomas Weng, (2011) "Duty-Cycling Buildings Aggressively: The Next Frontier in HVAC Control", ACM/IEEE IPSN/SPOTS, 2011.

Yuvraj Agarwal, Bharathan Balaji, Rajesh Gupta, Jacob Lyles, Michael Wei, Thomas Weng, (2010b) "Occupancy-Driven Energy Management for Smart Building Automation", ACM BuildSys 2010.

Younghun Kim, Thomas Schmid, Zainul M Charbiwala, Jonathan Friedman, Mani B Srivastava, (2008), "NAWMS: Nonintrusive Autonomous Water Monitoring System," The 6th ACM Conference on Embedded Networked Sensor Systems (SenSys 2008)

Priya Mahadevan, Sujata Banerjee and Puneet Sharma, (2010), "Energy Proportionality of an Enterprise Network," First ACM SIGCOMM Workshop on Green Networking, August 2010.

Eli Blevis (2007), Sustainable Interaction Design: Invention & Disposal, Renewal and Reuse, CHI 2007 Proceedings.

A. Koehler and C. Som (2005), Effects of Pervasive Computing on Sustainable Development, IEEE Technology and Society magazine, Spring 2005.

Navin Sharma, Pranshu Sharma, David Irwin, and Prashant Shenoy (2011). "Predicting Solar Generation from Weather Forecasts Using Machine Learning," Proceedings of the Second IEEE International Conference on Smart Grid Communications (SmartGridComm), Brussels, Belgium, October, 2011.