FINAL REPORT

NSF WORKSHOP ON SMART CITIES

December 3-4, 2015

Arlington, VA



National Science Foundation WHERE DISCOVERIES BEGIN

Organizer:

Christos G. Cassandras, Boston University

Organizing Committee: Andreas Malikopoulos, Oak Ridge National Laboratory Ioannis Paschalidis, Boston University Daniel Work, University of Illinois

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EXECUTIVE SUMMARY

The NSF **Workshop on Smart Cities** was held on December 3-4, 2015 in Arlington, VA. Its objective was to bring together researchers and technical leaders from academia, industry, and municipal government in order to set a short and long-term research agenda for emerging issues in Smart and Connected Communities. Such issues span a variety of fields and specialized disciplines including: transportation, environment, energy, building design and management, urban planning, sensor and actuator networks, social science, economics, software platform design and data management. Thus, one of the goals of the Workshop was to find common themes pertaining to Smart Cities which bring together Engineering, Computer Science, and Social Science.

The workshop was motivated by the continuing growth of urban areas, making their management one of the critical challenges our society faces today. The emergence of mobile wireless sensor and actuation network technologies, along with broader developments in Cyber-Physical Systems (CPS), have created unprecedented opportunities through innovative services for transportation, energy distribution, health care, environmental monitoring, business, commerce, emergency response, and social activities. The Workshop was structured to include presentations and discussions focused on what is possible for Smart Cities and, more broadly, Smart and Connected Communities, and what foundational research is necessary over the next decade to enable these new opportunities and bring them to fruition while mitigating unexpected consequences that may adversely affect urban dwellers. Its outcome is a state-of-the-art vision for Smart Cities whose realization will have significant impact on the design, management, and overall sustainability of urban environments and, more broadly, connected communities.

• MAIN OUTCOMES

The detailed Workshop Program is provided in Section 2 and may also be found at <u>http://www.bu.edu/systems/nsf-conference-december-3-4-2015/nsf-agenda/</u> All presentations that were made available by the speakers can be accessed from this web site.

The major outcome of the Workshop is the current report which is based on individual breakout session reports coordinated and edited by the organizing committee members. It is clear that a comprehensive vision for Smart Cities encompasses multiple aspects of fundamental research and applied research in Engineering, Computer Science, and the Social Sciences. The report focuses on the five topics corresponding to the five breakout sessions and on the common themes that have emerged from the plenary sessions in which breakout session outcomes were presented and discussed. These outcomes are summarized in the recommendations that follow.

RECOMMENDATIONS

An overarching recommendation is for the National Science Foundation to support fundamental and applied research in new areas and research directions that directly affect Smart Cities and, more broadly, Smart and Connected Communities. It is important to recognize the multi-disciplinary nature of this research and the need to promote and facilitate the collaboration of researchers from all relevant disciplines. At the same time, it is important to realize that such research activities must take place in an environment that brings together all the Smart City stakeholders, including community governments and leaders; academic researchers who can develop and test new technologies, economic mechanisms, and policies; and private industry which is best suited for the deployment of specific technology-based solutions. It is a major challenge to define the types of partnerships needed and the resources necessary to accomplish this goal.

Individual breakout session reports in Section 3 include specific conclusions and recommendations pertaining to each session's topic. Common themes, however, have clearly emerged; these are presented here, organized in two categories: strategic principles and specific research directions that need to be pursued.

STRATEGIC PRINCIPLES

- Recognize that the Smart and Connected Communities research and development landscape is different compared to more traditional areas of research. Therefore, encourage and reward successful and sustainable partnerships among local and regional stakeholders (e.g., universities, local government, health systems, community organizations and residents, foundations).
- There is a need to develop new funding models based on the realization that cities themselves do not possess the necessary resources to support research projects. At the same time, such models need to enable researchers from multiple disciplines to come together and effectively collaborate.
- Interdisciplinary research should be encouraged and efforts should be undertaken to discourage tactics that, sometimes, communities and programs engage in to preserve a comfortable status quo. Change will not come from entrenched communities operating in silos but from welcoming new ideas into a field.
- The availability of data is at the heart of any successful research related to Smart and Connected Communities. It is important to facilitate the creation of widely accessible datasets for researchers to use, test, and compare new ideas and methodologies. Along the same lines, incentives need to be in place so that both private and public organizations can make data available on a continuing basis.
- It is important to identify effective and sustainable means of data sharing among community service providers for both population health management and to address individual health needs.

- On the education front, it is imperative to produce data-literate undergraduates regardless of the discipline they pursue. At the undergraduate level, Smart City concepts could be woven throughout the curriculum through hands-on projects. Shared datasets and modular teaching components could be an enabler. At the graduate level, it is important to craft degrees where students can learn appropriate skillsets that involve what can be broadly termed "data science".
- Public discussion, education, and transparency about the technologies, implications and tradeoffs in Smart and Connected Communities will be essential. Education is a potential area for such collaboration. It is of interest to move beyond traditional education and think about joint educational activities with city government (e.g., through certificates, short courses, and educational retreats).

RESEARCH DIRECTIONS

- Given that the majority of the population lives in old, well-developed, and dense cities, the emphasis of research should shift from design and solutions that require the building of new infrastructure and towards the re-purposing, optimization, and better control of existing infrastructure, driven by the ability to collect data so as to be both proactive/preventative, as well as reactive in real-time.
- The availability of data motivates data-driven approaches for resource allocation at all levels of the Smart City infrastructure. Therefore, research is necessary to develop such data-driven resource allocation mechanisms.
- It is important to study the opportunities provided for co-optimizing over different resource allocation mechanisms throughout Smart City infrastructures. In energy management, for example, data from other infrastructures will enable better decision-making and control of electricity supply, and vice-versa.
- New research is needed in machine learning and data analytics emphasizing dynamic system aspects and the need to move beyond static optimization towards effective and tractable dynamic optimization under uncertainty. This is a direct consequence of the fact that sensing is now ubiquitous and a commodity, so that the need shifts towards understanding, estimating, and inferring from the data in order to optimize and control. To that end, "sparsity" is key, i.e., cluster, classify and distill from the data what is useful for every particular question one wants to answer.
- Research is necessary to develop distributed/massively parallel algorithmic and information architectures which can result in computation and information exchange tractability.
- Research is necessary on the processing of multiscale information from massive data which are becoming widely available. In the transportation domain, these data

originate from travelers, vehicles, and the transportation infrastructure. What was traditionally modeled as "uncertainty" (noise or disturbance) is rapidly becoming additional input or extra state information with the potential to more rapidly account for changes that cannot be predicted by deterministic models.

- It is important to study and account for the privacy issues that emerge in the collection and processing of data. This issue cuts through all aspects of Smart City research, from health care to monitoring and load disaggregation in energy management.
- New fundamental research is needed in sensing/estimation theory, information theory, communications, optimization, control, and game theory applied to specific applications related to Smart and Connected Communities.
- Research is necessary to enhance the understanding of interdependencies in complex dynamic systems and to explicitly incorporate human behavior in the operationalization of Smart Cities. Driverless vehicles, for example, could decrease global fuel usage; if, however, they make journeys easier to undertake, fuel usage could increase if populations decide to take advantage of this fact. Understanding paradigm shifts in human behavior as a result of automation will require new insight into human-technology interactions.
- New research is necessary to understand the impact of Connected Automated Vehicles (CAVs), including means to quantify the improvement in transportation efficiency resulting from CAVs which can exchange information with each other and with the infrastructure.
- Research is needed for integrating algorithmic solutions in health care that aim at predicting and preventing rather than acute treatment. Algorithmic solutions are scalable and offer personalized attention to each patient's record, which the health care system does not have the means and the bandwidth to provide.

1. WORKSHOP PARTICIPANTS

Invited Participants

- 1. Amy Aussieker (aaussieker@envisioncharlotte.org)
- 2. Azer Bestavros (best@bu.edu)
- 3. Michael Caramanis (mcaraman@bu.edu)
- 4. Christos Cassandras (cgc@bu.edu)
- 5. Charlie Catlett (cec@anl.gov)
- 6. [#] Daniel Correa (Daniel_K_Correa@ostp.eop.gov)
- 7. Patricia Culligan (culligan@civil.columbia.edu)
- 8. Santiago Garces (sgarces@southbendin.gov)
- 9. Ian Hiskens (hiskens@umich.edu)
- 10. Dan Hoffman (Daniel.Hoffman@montgomerycountymd.gov)
- 11. Nigel Jacob (nigel.jacob@boston.gov)
- 12. Karl Johansson (kallej@kth.se)
- 13. Branko Kerkez (bkerkez@umich.edu)
- 14. Steven Koonin (steven.koonin@nyu.edu)
- 15. * Debra Lam (debra.lam@pittsburghpa.gov)
- 16. Cedric Langbort (langbort@illinois.edu)
- 17. Jonathan Levine (jnthnlvn@umich.edu)
- 18. Andreas Mai (andmai@cisco.com)
- 19. Andreas Malikopoulos (andreas@ornl.gov)
- 20. * Amen Ra Mashariki (AMashariki@cityhall.nyc.gov)
- 21. Chris Osgood (chris.osgood@boston.gov)
- 22. Ioannis Paschalidis (yannisp@bu.edu)
- 23. Marcia Pincus (marcia.pincus@dot.gov)
- 24. Farhad Pooran (Farhad.Pooran@schneider-electric.com)
- 25. Sokwoo Rhee (sokwoo.rhee@nist.gov)
- 26. Kurt Roth (kroth@cse.fraunhofer.org)
- 27. Constantine Samaras (csamaras@cmu.edu)
- 28. * Saskia Sassen (sjs2@columbia.edu)
- 29. Andrew Smyth (aws16@columbia.edu)
- 30. Walter Stewart (StewarWF@sutterhealth.org)
- 31. Dan Work (dbwork@illinois.edu)
- 32. Ruthbea Yesner Clarke (RClarke@idc.com)

Envision Charlotte Boston University Boston University Boston University Argonne National Lab., University of Chicago White House OSTP Columbia University South Bend, IN University Michigan Montgomery County, MD

City of Boston KTH Royal Institute of Technology, Sweden University of Michigan New York University City of Pittsburgh U. Illinois, Urbana-Champaign University of Michigan Cisco Oak Ridge National Lab. Mayor's Office of Data Analytics, New York City City of Boston **Boston University** US Dept of Transportation Schneider Electric NIST Fraunhofer Center for Sustainable Energy Systems Carnegie Mellon University Columbia University Columbia University Sutter Health U. Illinois, Urbana-Champaign International Data Corporation

* Unable to Attend

[#] Keynote Speaker

National Science Foundation Participants

- 1. Eyad Abed (eabed@nsf.gov)
- 2. Nicholas Anderson (nanderso@nsf.gov)
- 3. Peter Arzberger (parzberg@nsf.gov)
- 4. Radakishan Baheti (rbaheti@nsf.gov)
- 5. Madeline Beal (mbeal@nsf.gov)
- 6. Margaret Cavanaugh (mcavanau@nsf.gov)
- 7. Fay Cook (fcook@nsf.gov)
- 8. David Corman (dcorman@nsf.gov)
- 9. Cheryl Eavey (<u>ceavey@nsf.gov</u>)
- 10. Joan Ferriri-Mundy (jferrini@nsf.gov)
- 11. Samir El-Ghazaly (selghaza@nsf.gov)
- 12. Deborah Goodings (dgooding@nsf.gov)
- 13. Bruce Hamilton (bhamilto@nsf.gov)
- 14. Zack Hayden (zhayden@nsf.gov)
- 15. Anthony Kelly (akelly@nsf.gov)
- 16. James Kurose (jkurose@nsf.gov)
- 17. Thi Le (tle@nsf.gov)
- 18. Mimi McClure (mmcclure@nsf.gov)
- 19. Stephen Meachan (smeacham@nsf.gov)
- 20. Alexander Medina-Borja (amedinab@nsf.gov)
- 21. David Mendonca (mendonca@nsf.gov)
- 22. Elise Miller-Hooks (Elisemh@nsf.gov)
- 23. Sunil Narumalani (snarumal@nsf.gov)
- 24. Sara Nerlove (snerlove@nsf.gov)
- 25. Leah Nichols (lenichol@nsf.gov)
- 26. Gabe Penez-Giz (gperez@nsf.gov)
- 27. Yuri Podpaly (ypodpaly@nsf.gov)
- 28. Sushil Prasad (Sprasad@nsf.gov)
- 29. Rajiv Ramnath (rramnath@nsf.gov)
- 30. Mike Rook (mrook@nsf.gov)
- 31. Massimo Ruzzene (mruzzene@nsf.gov)
- 32. Gurdip Singh (gsingh@nsf.gov)
- 33. Usha Varshney (uvarshne@nsf.gov)
- 34. Grace Wang (jiwang@nsf.gov)
- 35. Chengshan Xiao (cxiao@nsf.gov)
- 36. Heng Xu (hxu@nsf.gov)
- 37. John Zavada (jzavada@nsf.gov)

Guests

- 1. Panos Antsaklis (antsaklis.1@nd.edu)
- 2. Brenda Bannan (bbannan@gmu.edu)
- 3. Michelle Cullen (mlcullen@us.ibm.com)
- 4. Ann Drobnis (adrobnis@cra.org)

University of Notre Dame George Mason University IBM Computing Community Consortium 5. Patricia Foland (pfoland@scienceus.org) WTEC Mark Franz (mfranz1@umd.edu) University of Maryland 6. Kyle Johnson (kyle.johnson@nist.gov) 7. NIST Aditya Johri (johri@gmu.edu) 8. George Mason University Ben Levine (brlevine@andrew.cmu.edu) MetroLab Network 9. 10. Zeyi Lin (Zeyi_Lin@ostp.eop.gov) White House OSTP 11. Richard Marciano (marciano@umd.edu) University of Maryland 12. Tho Nguyen (tho.nguyen@fulbrightmail.org) University of Virginia 13. Diana Pankevich (Diana_Pankevich@ostp.eop.gov) White House OSTP 14. Radha Poovendran (RP3@uw.edu) University of Washington, Seattle 15. Ali Reza-Khaligh (khaligh@ece.umd.edu) University of Maryland 16. Robert Shelton (shelton@wtec.org) WTEC 17. Jelena Srebric (jsrebric@umd.edu) University of Maryland Virginia Tech 18. Susan Sterett (ssterett@vt.edu) 19. Shuangbao (Paul) Wang (paul.wang@umuc.edu) University of Maryland

2. WORKSHOP ORGANIZATION

The Workshop was organized in terms of six plenary and five breakout sessions (the complete program is given below). Plenary sessions 1, 2, and 4 were designed for overview presentations by academic researchers and by representatives from industrial organizations and municipal governments describing ongoing activities. The five breakout sessions were designed to focus on different critical aspects of Smart Cities: Infrastructure and technology; data collection and management; transportation; sustainability; and health and social factors.

Recognizing the multifaceted nature of the issues related to Smart Cities, the organizers chose the five themes above as key research and development components in the evolution of Smart and Connected Communities. Clearly, this coverage is inevitably incomplete, but we believe it captures many common elements reflected in the recommendations found in the Executive Summary, as well as in the detailed breakout session reports.

7:30-8:00AM	BREAKFAST
Time	
8:00-9:15AM	Introduction: Chairs: R. Baheti, Program Director, Division of Electrical, Communications and Cyber Systems D. Corman, Program Director, Division of Computer and Network Systems
8:00-8:50AM	Opening Remarks by: James Kurose, Assistant Director of NSF, Computer and Information Science and Engineering (CISE/NSF) Fay Cook, Assistant Director, Social, Behavioral and Economic Sciences (SBE/NSF)
	Samir El-Ghazaly, Division Director, Division of Electrical, Communications and Cyber Systems (ECCS/ENG/NSF)
	Deborah Goodings, Division Director, Civil, Mechanical and Manufacturing Innovations (CMMI/ENG/NSF)
	Christos Cassandras, 🔎 Workshop Chair
8:50-9:15AM	Keynote: Dan Correa, Senior Advisor for Innovation Policy, White House Office of Science and Technology Policy <u>"Smart and Connected Communities"</u>
9:15-10:45AM	Plenary 1: Smart Cities – City, Industry and Government Perspectives Chair: M. Ruzzene, Program Director, ENG/NSF Co-chair: I. Paschalidis

Workshop Program

9:15-9:30AM	A. Mashariki (NYC)	Title TBA
9:30-9:45AM	D. Hoffman (Montgomery County)	Pilot – Prototype – Proof of Concept: Making Smart Cities Real for Residents 🔎
9:45-10:00AM	M. Pincus (DOT)	Connected Cities Research Program
10:00-10:15AM	A. Mai (CISCO)	Digitization of Transportation – Value at Stake
10:15-10:30AM	S. Garces, (S. Bend)	From Data to Decisions: How South Bend Redefines Itself as a Smart City 🍋
10:30-10:45AM	C. Osgood (Boston)	Go Boston 2030 – Improving Mobility In The City of Boston
10:45-11:15AM	BREAK	
11:15-12:15PM	Plenary 2: Smart Cities – Academic P Chair: D. Corman, CISE/ENG Co-C	erspective Shair: D. Work
11:15-11:30AM	A. Smyth (Columbia U.)	Smart Cities: Meeting Urban Challenges through Sensing and Data-Driven Modeling
11:30-11:45AM	S. Koonin (NYU)	Lessons Learned from Three Years of CUSP
11:45-12:00PM	C. Catlett (Argonne National Laboratory, U. of Chicago)	The Quantified City: Understanding Cities Through Instrumentation and Integrated Data
12:00-12:15PM	C. Cassandras (Boston U.)	Smart Cities as Cyber-Physical Systems 🔎
12:15-1:15PM	LUNCH	
1:15-2:45PM	Breakout 1: Infrastructure and Technol Chair: D. Work Location: Ernest Hemingway Salon 1	logies for Smart Cities
	Participants: M. Caramanis, C. Cassan Kerkez, A. Mai, C. Osgood, F. Pooran, S	dras, P. Culligan, I. Hiskens, D. Hoffman, K. Johansson, B. S. Rhee, K. Roth, C. Samaras, A. Smyth, D. Work
1:15-1:25PM	P. Culligan (Columbia U.)	The Role of Distributed Infrastructure and the Internet of Things
1:25-1:35PM	C. Samaras (Carnegie Mellon U.)	Automated Vehicles in Smart Cities: Energy and Environmental Impacts 🔎
1:35-1:45PM	K. Johansson (KTH)	Freight Transport and Logistics for Smart Cities 🔎
1:45-2:45PM	Discussion (notes will be taken)	

1:15-2:45PM	Breakout 2: Data Collection and Mana Chair: I. Paschalidis Location: Ernest Hemingway Salon 2 Participants: A. Aussieker, A. Bestavro Langbort, J. Levine, A. Malikopoulos, A	ngement in Smart Cities s, C. Catlett, R. Clarke, S. Garces, N. Jacob, S. Koonin, C. A. Mashariki, I. Paschalidis, M. Pincus, S. Sassen, W. Stewart
1:15-1:25PM	A. Bestavros (Boston U.)	A Smart-City Needs an Open Cloud 🔎
1:25-1:35PM	C. Langbort (U. Illinois)	Challenges and Opportunities of People-Centric Data-Driven Systems in the Smart City 🍋
1:35-1:45PM	I. Paschalidis (Boston U.)	Show Me the Data! Smart Analytics Enabling Inference and Predictions
1:45-2:45PM	Discussion (notes will be taken)	
2:45 – 3:00PM	BREAK	
3:00-4:30PM	 Breakout 3: Transportation Chair: A. Malikopoulos Location: F. Scott Fitzgerald DE (Main Workshop Room) Participants: C. Cassandras, K. Johansson, C. Langbort, J. Levine, A. Mai, A. Malikopoulos, C. Osgood, M. Pincus, F. Pooran, D. Work 	
3:00-3:10PM	J. Levine (U. Michigan)	Smart Policies, Smart Transportation 🔎
3:10-3:20PM	D. Work (U. Illinois)	Building Smarter Transportation Systems 🔎
3:20-3:30PM	A. Malikopoulos (ORNL.)	Coordination of Connected and Automated Vehicles at Urban Traffic Intersections 🔎
3:30-4:30PM	Discussion (notes will be taken)	

3:00-4:30PM	Breakout 4: Sustainability Chair: M. Caramanis Location: Ernest Hemingway Salon 1 Participants: M. Caramanis, C. Catlett C. Samaras, A. Smyth	, P. Culligan, I. Hiskens, B. Kerkez, S. Koonin, S. Rhee, K. Roth,
3:00-3:10PM	I. Hiskens (U. Michigan)	Sustainable Electricity Supply
3:10-3:20PM	M. Caramanis (Boston U.)	Smart Power Distribution Networks: Adaptive Flexible Loads and Resources
3:20-3:30PM	B. Kerkez (U. Michigan)	Building the Internet of Water
3:30-4:30PM	Discussion (notes will be taken)	
3:00-4:30PM	Breakout 5: Health, Social Factors Chair: I. Paschalidis Location: Ernest Hemingway Salon 2 Participants: A. Aussieker, A. Bestavro Paschalidis, S. Sassen, W. Stewart	s, R. Clarke, S. Garces, D. Hoffman, N. Jacob, A. Mashariki, I.
3:00-3:10PM	S. Sassen (Columbia U.)	Title TBA
3:10-3:20PM	N. Jacob (Boston)	Building <i>Learning</i> Cities: Enabling Experimentation in Local Government
3:20-3:30PM	W. Stewart (Sutter Health)	Building Sustainable Models of Care for the Underserved 🔎
3:30-4:30PM	Discussion (notes will be taken)	
4:30-5:00PM	Plenary 3: Wrap-Up for Day 1 Chair: R. Baheti, ENG/NSF Co-chair	: C. Cassandras

DAY 2		
8:30-9:00AM	BREAKFAST	
9:00-10:30AM	Plenary 4: Smart Cities – City, Industr Chair: H. Xu, Program Director, SBE/N	y and Government Perspectives ISF Co-chair: A. Malikopouplos
9:00-9:15AM	D. Lam (Pittsburgh)	Pittsburgh Inclusive Innovation Roadmap
9:15-9:30AM	A. Aussieker (Charlotte)	Transforming Charlotte into a Smart City by Using the Public Private Plus Partnership Foundation 🍋
9:30-9:45AM	F. Pooran (Schneider Electric)	Smart Mobility for Arterial IT 🔎
9:45-10:00AM	K. Roth (Fraunhofer)	Smart Buildings: Opportunities and Challenges 🔎
10:00-10:15AM	S. Rhee (NIST)	Cyber-Physical Systems and Global City Teams Challenge 2016 🔎
10:15-10:30 AM	R. Clarke (IDC)	A Process for Successful Projects: How to Keep the City at the Center of the IoT Partner Ecosystem
10:30-11:00AM	BREAK	
11:00-12:00PM	Plenary 5: Breakout Reports 1-2 Chairs: I. Paschalidis, D. Work	
12:00-1:00PM	LUNCH	
1:00-2:30PM	Plenary 6: Breakout Reports 3-5 Chairs: M. Caramanis, A. Malikopoulos, I. Paschalidis	
2:30-3:00PM	BREAK	
3:00-4:00PM	Wrap-Up and Future Perspectives Chair: C. Cassandras NSF Program Directors	

DIRECT ACCESS TO WORKSHOP PRESENTATIONS

Christos Cassandras (Opening Remarks) – <u>http://www.bu.edu/systems/files/2015/12/Cassandras-Overview.pdf</u>

Dan Correa (Keynote) - <u>http://www.bu.edu/systems/files/2015/12/Correa.pdf</u>

Plenary 1: Smart Cities - City, Industry and Government Perspectives

Dan Hoffman -	http://www.bu.edu/systems/files/2015/12/Hoffman.pdf
Marcia Pincus -	http://www.bu.edu/systems/files/2015/12/Pincus.pdf
Santiago Garces -	http://www.bu.edu/systems/files/2015/12/Garces.pdf
Chris Osgood -	http://www.bu.edu/systems/files/2015/12/Osgood1.pdf

Plenary 2: Smart Cities – Academic Perspective

Steven Koonin -	http://www.bu.edu/systems/files/2015/12/Koonin.pdf
Christos Cassandras -	http://www.bu.edu/systems/files/2015/12/Cassandraspdf

Breakout 1: Infrastructure and Technologies for Smart Cities

Patricia Culligan -	http://www.bu.edu/systems/files/2015/12/Culligan.pdf
Costa Samaras -	http://www.bu.edu/systems/files/2015/12/Samaras.pdf
Karl Johansson -	http://www.bu.edu/systems/files/2015/12/Johansson.pdf

Breakout 2: Data Collection and Management in Smart Cities

Azer Bestavros -	http://www.bu.edu/systems/files/2015/12/Bestavros.pdf
Cedric Langbort -	http://www.bu.edu/systems/files/2015/12/NSF_smart_2.pdf
Ioannis Paschalidis -	http://www.bu.edu/systems/files/2015/12/Paschalidis.pdf

Breakout 3: Transportation

Jonathan Levine -	http://www.bu.edu/systems/files/2015/12/Levine.pdf
Dan Work -	http://www.bu.edu/systems/files/2015/12/Work.pdf
Andreas Malikopoulos -	http://www.bu.edu/systems/files/2015/12/NSF_Andreas.pdf

Breakout 4: Sustainability

Ian Hiskens -	http://www.bu.edu/systems/files/2015/12/Hiskens.pdf
Michael Caramanis -	http://www.bu.edu/systems/files/2015/12/Caramanis.pdf
Branko Kerkez -	http://www.bu.edu/systems/files/2015/12/Kerkez_Smart_Cities.pdf

Breakout 5: Health, Social Factors

Walter Stewart - <u>http://www.bu.edu/systems/files/2015/12/Stewart.pdf</u>

Amy Aussieker -	http://www.bu.edu/systems/files/2015/12/Aussieker.pdf
Farhad Pooran -	http://www.bu.edu/systems/files/2015/12/Pooran.pdf
Kurt Roth -	http://www.bu.edu/systems/files/2015/12/Roth.pdf
Sokwoo Rhee -	http://www.bu.edu/systems/files/2015/12/Rhee.pdf
Ruthbea Yesner-Clarke -	http://www.bu.edu/systems/files/2015/12/Clarke.pdf

Plenary 4: Smart Cities – City, Industry and Government Perspectives

3. BREAKOUT SESSION REPORTS

3.1. INFRASTRUCTURE AND TECHNOLOGY FOR SMART CITIES

Contributors: Patricia Culligan, Karl Johansson, Constantine Samaras, Daniel Work

3.1.1. Significance, Obstacles, and Opportunities

At the center of a Smart City lies its infrastructure. It is, therefore, natural to try and identify the fundamental requirements for such an infrastructure with the goal of delivering **data-driven real-time services**. These services are geared toward achieving the sustainability and resilience goals of individual communities. Ultimately, this will result in **intelligent resource allocation** mechanisms.

Four key-elements will need to be considered in the development of technologies and infrastructure for Smart and Connected Communities (Figure 1). One key element is the long- and short-term **goals of the community stakeholders** themselves. These goals might include improved public and environmental health, enhanced safety, better access

to education and other services, fiscal efficiency, climate resilience, and many more. Any strategy for real-time, dataenabled operation of services should be geared toward meeting these goals. Another key-element is the **social ecosystem** of the communities themselves, which includes how individuals and groups interact with each other as well as their community's infrastructure. Understanding how people connect with others and use the cities/communities in which they live is important to tailoring technology and infrastructure solutions to meet a specific community's goals. A third key-element is the community's **physical networks** and the resources that they supply, including water, energy, food, waste removal as well as the transportation of people and goods. Understanding how, as well as to whom, these networks provide resources is essential to improve resource



Figure 1: Key elements for Smart and Connected Communities

efficiency, sustainability and/or resilience. The final element to be considered is **network cyber intelligence**, which is envisioned to be a combination of sensing, modeling, monitoring, control and communications between the cyber-network components, physical systems and people that can aid in learning about how cities and communities function as well as implementation of strategies to meet community goals.

Enabling the role of technologies and infrastructure in Smart and Connected Communities will require understanding, monitoring and modeling connections between people, the built environment, the natural environment and community-based social systems. In seeking to achieve this goal, the following are major obstacles:

• We have a limited understanding of how people interact with built, natural, and social infrastructure. As an example, we may understand the use of energy as a whole, but not

what motivates individuals to change their own energy use. This suggests that when data are collected and organized, we need to consider different data scales: at the aggregate, as well as at a personalized level.

- We have a limited understanding of infrastructure interdependencies which are further complicated by the fact that these dependencies change over time.
- We have a limited understanding of the socio-technical components that make up the city.
- We lack effective ways to put people/communities in the loop and reason about such systems.
- It is difficult to differentiate between operational objectives (e.g., decisions to make today) and longer-term planning objectives.

The complexities and associated tradeoffs involved in integrating technological and physical systems with humans and the social structures they form are illustrated in Figure 2. For instance, we can manage extremely complex social systems (e.g., Facebook) with very limited physical complexity. At the other end of the spectrum we can manage extremely complex physical and cyber systems (e.g., SCADA water grids), but with very limited social complexity. The challenge is to merge the complex social systems and the complex infrastructure systems, then reason about both. A good example is on-demand mobility where we need to control the traffic signal infrastructure (top left), and serve the personalized travel demands (i.e., Uber; bottom right). How to link the personalized routing level control and the impersonal infrastructure (signal) level control is a particularly hard problem.



Figure 2: Complexity tradeoffs in smart and connected Communities (courtesy, K. Johansson, KTH)

The most significant opportunity for overcoming the obstacles outlined above is **data availability**. Extensive datasets are now available that enable us to answer questions such as "What could one do with an hourly census of the city?" It may also be possible to utilize data so as to explore societal response to technological changes, which remains

largely unpredictable. For example, in what way will demand for energy be affected by demand for autonomous travel?

An impediment to broad data availability is that many of the information-rich datasets required by researchers are often privately owned and may not be widely accessible (e.g., smart meters, Amazon delivery data). Another potential impediment is that of ethical and privacy issues that emerge in data collection. This raises the interesting possibility of incorporating ethical rules into data collection software.

There are significant opportunities that **decentralization** of the infrastructure may offer, and a challenge is to recognize that a decentralized *physical* infrastructure may still require a centralized *cyber* infrastructure. It is also important to distinguish between the complexity of the physical infrastructure (e.g., SCADA systems for managing resources such as water) and the complexity of the *social system* which benefits from this infrastructure (e.g., the complexity of Facebook).

Another opportunity for developing effective Smart City infrastructures is the emerging development of **standardized platforms**. It is important, however, to distinguish between platforms at a concrete application level (e.g., using cloud technologies) and abstract platforms used to reason across disciplines through a common intellectual framework, e.g., a systems thinking approach.

Finally, enabling transformative advances in our understanding of the community ecosystem requires **new funding models** to support basic and applied research. On the basic research level, one potential funding model is a set of Urban and Community Observatories that undertake 5 or 10-year missions to continuously characterize the community ecosystem. These could be similar to National Laboratories or other Federally Funded Research and Development Centers, or take on the form of Engineering Research Centers anchored in local research universities. The multi-year place-based support is a critical element of these observatories, enabling characterization of changes across a time-series and multiple sets of natural experiments driven by natural phenomena and exogenous factors. The observatories would be a hub for researchers from multiple disciplines to come together and employ emerging analytic data collection and analysis techniques in the community ecosystem.

On the applied research level, unique challenges of communities can be analyzed and addressed by interdisciplinary research teams. True co-production of knowledge will require fully engaged civic stakeholders, and creative funding models will be required that go beyond traditional single principal investigator-led university research. New funding models formed as a partnership between universities, communities, firms, and non-profit institutions are required to leverage the often-tacit institutional knowledge of community stakeholders. Funding models for specific projects could take the form of public-private partnerships, cooperative agreements, or grantmaking directly to communities. Support could also be in human capital, through sponsored inter-personnel agreements into community agencies for researchers and post-doctoral fellows, similar to the AAAS Science and Technology Fellowships.

3.1.2. Recommendations

- The availability of data is at the heart of any successful research related to infrastructures for Smart Cities. It is important to facilitate the creation of widely accessible datasets for researchers to use, test, and compare new ideas and methodologies. Along the same lines, incentives need to be in place so that both private and public organizations can make data available on a continuing basis.
- The availability of data also motivates data-driven approaches for resource allocation at all levels of the Smart City infrastructure. Therefore, research is necessary to develop such data-driven resource allocation mechanisms.
- Research is needed for the development of cyber-resilient architectures. Such architectures should not necessarily focus on the prevention of an attack, but rather on the prevention of "unacceptable" failures.
- Research is necessary to enhance the understanding of interdependencies in complex dynamic systems and incorporate human behavior in the operationalization of Smart Cities. Driverless vehicles, for example, could decrease global fuel usage; if, however, they make journeys easier to undertake, fuel usage could increase if populations decide to take advantage of this fact. Understanding paradigm shifts in human behavior as a result of automation will require new insight into human-technology interactions.
- It is important to develop tools to aid short- and long-term decision making. This will advance the predictive and modeling capacity than can encompass the full-complexity of the multiple scenarios of interest (similar to climate-based decision tools, which provide support for short- and long-term decision making for scenarios influenced by climate variability).
- Identify the critical services that must be protected, in the event that we cannot compartmentalize the damage due to an attack.
- Explore tradeoffs between the suboptimality of a system design and the level of redundancy that such a design can guarantee (e.g., physical and local control, reverting back to a safe mode).
- On the education front, it is imperative to produce data-literate undergraduates regardless of the discipline they pursue. At the undergraduate level, Smart City concepts could be woven throughout the curriculum through hands-on projects. Shared datasets and modular teaching components could be an enabler. At the graduate level, it is important to craft degrees where students can learn appropriate skillsets that involve what can be broadly termed "data science". Finally, public

discussion, education, and transparency about the technologies, implications and tradeoffs in Smart and Connected Communities will be is essential.

• There is a need to develop new funding models based on the realization that cities themselves do not usually possess the necessary resources to support research projects. At the same time, such models need to enable researchers from multiple disciplines to come together and effectively collaborate.

3.2. DATA COLLECTION AND MANAGEMENT IN SMART CITIES

Contributors: Azer Bestavros, Cedric Langbort, Yannis Paschalidis

3.2.1. Significance, Obstacles, and Opportunities

Smart cities increasingly rely on a variety of data sources to capture the "state of the city" and drive important policy decisions including planning, resource allocation, optimization of city services and operations, but also dynamic control of a variety of interconnected systems the city relies upon, from public transit and the road network to infrastructure maintenance and emergency response.

These data come from many diverse channels including (a) private entities such as vendors with equipment in the city, cell phone and road network traffic data (e.g., Mobile Millennium deployed in the San Francisco Bay Area to estimate travel times on surface roads and highways; similar data from private firm INRIX), and (b) data collected with the consent and participation of individual users such as data from Waze, Google maps, OpenStreetMap or other applications. In this category also belong data collected from apps cities themselves develop (e.g., Street Bump developed by the City of Boston to detect potholes and other road issues) or from other information the various city departments collect about the use of city services and resources.

It is evident, that data play an increasingly dominant role in making cities smarter. It is important to underline that challenges emerge not only from the *volume* of the data generated and collected, but also from the high generation/collection rate (*velocity*) of continuously collected data, the heterogeneity of the data (*variety*), and the need to ensure data *veracity* and accommodate the inevitability of missing/non-accurate data.

An important challenge in a data-driven city is how to acquire, collect, manage, store, and utilize the data described above. What is needed are **scalable and flexible computational platforms** that facilitate the interactions through data between disparate agents (private vendors, the city, citizens) that may not necessarily want to share "raw" data for privacy, security, and other business concerns. Such platforms need to be sustainable and economically viable, consistent with agile software and best business practices.

Data, on its own, is not particularly useful since the ultimate goal is to "close the loop" and inform decision making, policy decisions, optimization and control. To that end, developing the appropriate analytics to process data and distil useful information is an important objective. It becomes critical to sort out what features are relevant for each decision and induce sparsity of the factors driving decisions; this appears necessary to avoid drowning in the data deluge. It is also important for the analytics to be robust in the inherent uncertainty and errors associated with real data.

Security of a city and the **privacy** of its citizens can be impacted if, for example, the underlying data-driven cyber physical systems can be hacked or compromised. The

trustworthiness of the data is also an important issue not only because of external attacks, but also because system participants themselves, be they users or third party data providers, may have an incentive to misreport, either to preserve their privacy or to try and manipulate the outcome of the sensing process to their advantage. Finally, **fairness** may be jeopardized if "data becomes law", and decisions in the City are solely based on the output of data-mining systems whose data collection and analysis processes are not impartial (even if inadvertently so) or transparent. For instance, reliance on digital technology and smartphones may result in discrimination against groups currently underrepresented in the digital world (e.g., elderly, minorities, and the poor).

Given the value of data, and the potential privacy and security implications data sharing can have, it is understandable that there is often reluctance by providers and individual users to consent to access. It becomes critical to effectively communicate the benefits of data availability to a city and its citizens but also to provide mechanisms of privacypreserving sharing either through trusted intermediaries or through restrictions on the types of permissible function evaluations on the data (e.g., averages). It is also important to think about incentives and ways to monetize data access.

While data, technology, and data-driven decision making and control can have a huge impact in making cities "smarter" and more efficient, it is useful to remember that systems we develop are there to serve people - a society of citizens - and their effectiveness heavily depends on **citizen engagement**, participation, and willingness to follow recommendations whose aim is to "nudge" a city towards more socially optimal equilibria.

3.2.2. Recommendations

- Support new work in fundamental science including sensing/estimation theory, information theory, communications, machine learning, optimization, control, and game theory applied to specific applications related to smart and connected communities.
- Interdisciplinary research should be encouraged and efforts should be undertaken to discourage tactics that, sometimes, communities and programs engage in to preserve a comfortable status quo. Change will not come from entrenched communities operating in silos but from welcoming new ideas into a field.
- Given that the majority of the population lives in old, well-developed, and dense cities, the emphasis of research should shift from design and solutions that require the building of new infrastructure and towards the re-purposing, optimization, and better control of existing infrastructure, driven by the ability to collect data so as to be both proactive/preventative as well as reactive in real-time.
- New research is needed in machine learning and data analytics emphasizing dynamic system aspects and the need to move beyond static optimization towards effective and

tractable dynamic optimization under uncertainty. This is a direct consequence of the fact that sensing is now ubiquitous and a commodity, so that the need shifts towards understanding, estimating, and inferring from the data in order to optimize and control. To that end, "sparsity" is key, i.e., cluster, classify and distill from the data what is useful for every particular question one wants to answer.

- There is a need to develop robust learning, optimization, and control techniques so as to handle "noise" and uncertainty that will always be present in data-driven models.
- Cities involve many "social" actors who operate without significant coordination and in a selfish manner. Moreover, policies, objectives, and utilities of these actors are typically unobservable. To affect their behavior, one needs to learn behavior from data and devise controls and recommendations that take into account social/human factors. Likewise, research (in Engineering, but also in the Social Sciences) aimed at understanding the possible role of algorithmic discrimination in urban systems and infrastructures is also needed.
- It is important to arrive at a refined understanding of how existing data fusion and data mining algorithms perform in the presence of strategic self-interested sensors and data sets, as well as to help in the design of new tools and protocols that can withstand them. Recent developments in fields such as Adversarial Machine Learning should be relevant, even though their emphasis has heretofore not been on infrastructures, smart cities or, more generally, controlled systems.
- Support work in Information Economics aimed at characterizing the exact value of data in the Smart City (with appropriate account of sunk costs and externalities).
- Recognize that the Smart City research and development landscape is different compared to more traditional areas of research. Therefore, encourage and reward successful and sustainable partnerships between academia and important stakeholders (e.g., city governments). Education is a potential area for such collaboration. It is of interest to move beyond traditional education and think about joint educational activities with city government (e.g., through certificates, short courses, and educational retreats).

3.3. TRANSPORTATION

Contributors: Cedric Langbort, Jonathan Levine, Andreas Malikopoulos, Daniel Work

3.3.1. Significance, Obstacles, and Opportunities

The challenges involved in managing transportation systems have been well documented. For example, two-thirds of the oil used around the world currently goes to power transportation vehicles, of which half goes to passenger cars and light trucks¹; transportation will contribute about 25% of incremental carbon emissions over the next two decades as the total number of vehicles on the roads increases²; and in 2014, congestion caused people in urban areas to spend 6.9 billion hours more on the road and to purchase an extra 3.1 billion gallons of fuel, resulting in a total cost estimated at \$160 billion³. Furthermore, according to the US National Highway Traffic Safety Administration (NHTSA) in 2012 there were 5.615 million crashes in the United States leading to 33,561 deaths.

The goals of an "efficient" transportation system are to **alleviate congestion**, **reduce energy use** and **emissions**, and **improve safety**. The deep integration of technology in the transportation sector is providing fundamentally new methods to manage the flow of goods and people in our next generation transportation systems. Core disruptive technologies include **vehicle connectivity**, **vehicle automation**, and the notion of shared personalized transportation infrastructure enabled by **mobility on demand** systems. The central challenge is to develop smarter transportation systems to connect communities and increase access, without also increasing the negative consequences of transportation (e.g., emissions, energy consumption, and congestion).

Connected and automated vehicles (CAVs) provide the most intriguing opportunity for



Figure 3: A transportation system with connected and automated vehicles

enabling users (including individual vehicles and traffic control centers) to better monitor transportation network conditions and make better operating decisions to improve safety and reduce pollution, energy consumption, and travel delays. Recognition of the necessity of CAVs is gaining momentum. Many stakeholders intuitively see the benefits of multiscale vehicle control systems and have started to develop business cases for their respective domains, including the automotive and insurance industries, government and service providers. It seems clear that the availability of

vehicle-to-vehicle communication has the potential to reduce traffic accidents and ease congestion by enabling vehicles to more rapidly account for changes

¹ Federal Trade Commission, http://www.ftc.gov/.

² MIT Energy Initiative, http://web.mit.edu/mitei/index.html

³ B. Schrank, B. Eisele, T. Lomax, and J. Bak, "2015 Urban Mobility Scorecard," Texas A& M Transportation Institute, Tech. Rep., 2015.

in their mutual environment. Likewise, vehicle-to-infrastructure communication, e.g., communication with traffic structures, nearby buildings, and traffic lights, should allow for individual vehicle control systems to account for unpredictable changes in local infrastructure.

In a rapidly urbanizing world, we need to make fundamental transformations in how we use and access transportation. This starts with the observation that the purpose of a transportation system is not **mobility** but rather **accessibility** to goods, services, and activities. Mobility is only an unintended outcome of our accessibility needs and may be viewed as an intermediate service (the means) on the way to what we really want: access. Today's private vehicle mobility paradigm often requires dedicated parking, a need which may fade in **shared mobility** systems such as car share or ride share. Such systems also become more viable in dense, high demand regions, because the downtime between trips is small and overlapping trips can be shared. Distinguishing between mobility and accessibility is essential in determining the policy issues that need to be resolved and which are closely related to **land-use decisions**.

Safety is typically considered a major potential advantage when we think of connected and self-driving vehicles. However, there are additional benefits such as saving time for other activities, e.g., work, rest, along with avoidance of the economic costs and health costs of congestion (in terms of pollution or even anxiety). With the emergence of CAVs, the concept of "mobility on demand" has attracted considerable attention. Such systems have the potential to allow accessibility through all stages of life, improving the quality of life even if operating a personal vehicle is no longer option.

We are currently witnessing an increasing integration of our energy, transportation, and cyber networks, which, coupled with the human, or communication network, is giving rise to a new level of complexity in **connected communities**. Progress in pervasive sensing brings an unprecedented volume of data allowing us to observe, measure, and evaluate the transactions, performance, and efficiency of the critical infrastructures. Recent emergence and explosion of data from citizen sensors via social media and other cyber platforms provides a unique opportunity to understand and anticipate accessibility needs in future connected communities.

A fundamental obstacle in seizing this opportunity is our present lack of understanding of the interactions between vehicles, people, and infrastructure. Developing a novel science and technology is necessary to observe, measure, analyze, and model transportation, using a data-driven understanding of complex connected communities that are governed by both physical and behavioral sciences.

3.2.2. Recommendations

 Support fundamental research on the processing of multiscale information from massive data originating from travelers, vehicles, and transportation infrastructure. What was traditionally modeled as "uncertainty" (noise or disturbance) is rapidly becoming additional input or extra state information with the potential to more rapidly account for changes that cannot be predicted by deterministic models.

- Enhance our understanding of complex transportation systems and establish a holistic, multifaceted approach using scalable data and informatics. Such understanding can be used to develop rigorous mathematical models and decentralized control algorithms to enable transportation systems to improve their performance over time while interacting with their environment.
- Support the development of mathematical models to characterize emergence, leading to the design of rules for the interactions of the individual vehicles and travelers so that desired emergent phenomena occur.
- Support research to quantify the improvement in transportation efficiency resulting from connected vehicles which can exchange information with each other and with the infrastructure.
- Investigate transportation network optimization aimed at identifying the right policies and providing appropriate incentives to reduce vehicles miles traveled and maximize sustainability impact. This will help us answer questions such as "What is the minimum number of travelers that need to be incentivized or vehicles that need to be connected in order realize the potential benefits?" and "What are the implications in the transportation network if a certain number of drivers just ignore these instructions?"
- Support research to study the relative impact and potential benefits to Smart Cities of alternative transportation modes and type of vehicles, e.g., hybrid electric vehicles, electric vehicles.

3.4. SUSTAINABILITY

Contributors: Michael Caramanis, Ian Hiskins, Branko Kerkez

3.4.1. Significance, Obstacles, and Opportunities

Sustainability in the urban built environment is critically dependent on key infrastructures. Notable amongst these infrastructures with a substantial physical component are the networks that deliver energy (electric power, natural gas, and district heating to name a few) and water.

With the resurgence of urbanization, the sustainability of existing infrastructures is challenged by the expected electric energy consumption growth driven by **Electric Vehicles** (EVs), and the rapidly increasing integration of **Distributed Energy Resources** (**DERs**) (including roof top PV and the accompanying power electronics, combined heat and power micro-generators, distributed storage and flexible time-shiftable loads), along with a dwindling water supply. In the presence of increasing demand for their services, aggressive network-based service infrastructure expansion is not only costly but also immensely disruptive to city life. To complicate matters, the stability/predictability of electrical supply systems that are dominated by distributed generation and load control is not well understood.

It is therefore imperative to investigate opportunities for mitigating costs and disruption through control approaches for Cyber-Physical Systems (CPS).

The Electric Power Transmission and Distribution networks and the Water Supply and Collection (sewer) networks are by definition archetypical systems that may be investigated with and benefit from dynamic systems theory, optimization and control. In particular, the Electric Power System is a crucial system that can benefit from CPS Science and Engineering breakthroughs. More specifically, Alternating Current (AC) power system integrity and economic/technical sustainability rely on both (*i*) Hybrid -- continuous and discrete dynamic physical system analysis and design – even if there is extensive reliance on off-line studies of such systems – that provide the foundation to stability analysis and (*ii*) cyber/performance-operating-system decisions that occur at the market/performance time scale of hours to 5-minute periods.

More importantly, a major opportunity arises from the complementarity/synergy of new **flexible loads** and DERs on the one hand and non-dispatchable and volatile renewable generation on the other. In fact, turning the old-fashioned generation follows load paradigm to the new paradigm of *flexible loads and DERs follow non-dispatchable generation* (wind farms in particular) is a major untapped opportunity.

Specific opportunities for enhancing the sustainability of energy and water service infrastructures through CPS science-based research and implementation in cities include:

- Increased efficiency of energy and water use by matching zero variable cost albeit non-dispatchable supply (renewable generation, natural precipitation) with usage. Storage, demand scheduling, and waste avoidance can benefit from tools addressed by CPS Science and Engineering.
- Demand response which is (*i*) acceptable to users and (*ii*) can be driven by either direct network operator/utility control or price signals involving reasonable investment and operation/transaction cost and uncertainty.
- Stability control and system reliability though (not an exhaustive list)
 - Provision of reserves not only by centralized, but also by distributed flexible loads and DERs in power systems.
 - Effective flood control by use of sensor networks enabling active/dynamic system identification and control of distributed water storage and treatment facilities.
- Interaction and coordination of energy and water networks. For example:
 - Water pumping into drinking water reservoirs is a reschedulable electricity load that may account for 2-5% of electricity consumption.
 - Optimal use of local drinking water storage facilities may decrease costs of network delivered water supply stations and enhance the associated network sustainability.
- The Smart City setting provides opportunities for co-optimizing electricity supply with other city infrastructures. Data from other infrastructures will enable better decision-making and control of electricity supply, and vice-versa

Some common themes that emerge from this discussion are summarized below:

- **Model choice and complexity**: The availability of more data may reduce the need to explicitly model detailed dynamics. This suggests adopting an increasingly data-driven modeling approach.
- **Role of uncertainty**: Many systems within a city are driven by highly uncertain inputs (power demands, rainfall, etc.). How do we develop analytical tools and robust control algorithms in the face of this uncertainty?
- **Governance, ownership, and liability**: Given the interconnectedness of infrastructure, who gets to control the Smart City and who is responsible if something goes wrong?

3.4.2. Recommendations

• Support research that explores sustainable electricity supply. The solutions sought must be tailored to different urban environments, e.g. high and low density residential settings, and to different energy uses, e.g. residential, industrial, commercial. They

should also study tradeoffs of moving clean and inexpensive electricity versus moving energy intensive data processing (Data Center Loads).

- Support research on the coordination of volatile renewable generation with storage and load control (demand response).
- Study the opportunities offered by load control in order to maximally utilize supply infrastructure while ensuring reliability and resilience. At the same time, privacy issues need to be considered in monitoring and load disaggregation for the purpose of identifying vulnerabilities, improving forecasts and assessing availability of load control resources.
- Study the opportunities provided for co-optimizing electricity supply with other Smart City infrastructures. Data from other infrastructures will enable better decision-making and control of electricity supply, and vice-versa.
- Support research on retail Marginal Cost (MC) pricing to promote efficiency and synergy. Spatiotemporal MC-based market clearing at distribution/retail locations can lead to consensual and socially optimal *scheduling* of flexible load and distributed energy resource *capacity* among *Real Power, Reactive Power and various types of Reserves*. System wide costs, sustainability (renewable generation), and reliability can improve significantly by the resulting more effective energy balance and reserve provision.
- Research is necessary to develop distributed/massively parallel algorithmic and information architectures which can result in computation and information exchange tractability.
- Develop extensive sensing/measurement and spatiotemporal control of flows and reservoirs necessary for effective water and flood management in Smart Cities.

3.5. HEALTH AND SOCIAL FACTORS

Contributors: Nigel Jacob, William Stewart, Yannis Paschalidis

3.5.1. Significance, Obstacles, and Opportunities

Among the various functions of a smart city, *public health* is perhaps the most consequential. Often, however, the benefits of these services bypass impoverished neighborhoods. In the digital age of health care where insurance coverage is available to all, access to affordable high quality health care for residents of low income neighborhoods continues to be a concept, not a reality. Over the past 50 years, an impressive diversity of studies, demonstration projects, and social programs have attempted to solve the problem of making it easier for people living in poverty to have **routine access to high quality health care**, but no scalable, sustainable solution has been invented. Some progress has been made (e.g., the creation and support of federally qualified health centers). Yet, barriers persist because of a failure to design systems of care relevant to the needs of residents in low income neighborhoods. The overwhelmingly common symptom of this social problem has resulted in the most expensive means to obtain primary care -- the Emergency Department (ED) in hospitals.

Most of health care delivery in the US is at the beginning of a second revolution. Health systems are increasingly using sophisticated digital infrastructure to transform the health care experience into one that is affordable, timely, and individualized. Leading healthcare systems are making substantial advances in obtaining and using data and sophisticated means of communication to solve the access and fragmentation problems, effectively building intelligent and highly functional "networks", where the network's "nodes" (e.g. providers, call center support services, etc.) are organized and "connected" by data, knowledge, and information technology, to ensure that patients receive the timely care they need. Yet, health systems are not having an impact on impoverished communities, even though their hospitals face growing financial losses in providing primary care through emergency departments. Increasingly, health systems are compelled to care about these communities and motivated to contribute to sustainable solutions.

With the growing digitization of health care, unique opportunities exist today to support collaborations among health systems, local governments and universities, and residents of impoverished communities and to design sustainable systems of care that are relevant to the needs of residents.

3.5.2. Recommendations

 Develop modern constructs for the smart design of health systems that address health care needs of impoverished communities in a manner that is adaptable, flexible, and sustainable.

- Identify effective and sustainable means of data sharing among community service providers for both population health management and to address individual health needs.
- Support research for integrating algorithmic solutions in health care that aim at predicting and preventing rather than acute treatment. Algorithmic solutions are scalable and offer personalized attention to each patient's record, which the health care system does not have the means and the bandwidth to provide. Such algorithms can *alert* medical providers and direct their attention to the cases where preventive actions can have the most impact.
- Provide support for collaboration among local and regional stakeholders (e.g., health systems, universities, local government, community organizations and residents, foundations) which is necessary for the recommendations above to be realized.