Multimedia Wireless Sensor Networks: Perspectives and Future Directions

Sajal K. Das

Center for Research in Wireless Mobility and Networking

The University of Texas at Arlington

das@uta.edu http://crewman.uta.edu

[Funded by NSF, AFOSR, Texas ARP]

Outline

- Multimedia Wireless Sensor Networks (MWSNs)
- Challenges in MWSNs
- Ambiguous Context Mediation
- Quality-Aware Context Determination
- Security Issues
- Future Directions

Sensing the Physical World: Cyber-Physical System








We live in a physical world, which we need to understand, serve, and control

Wireless Sensor Networks (WSNs)

Computation

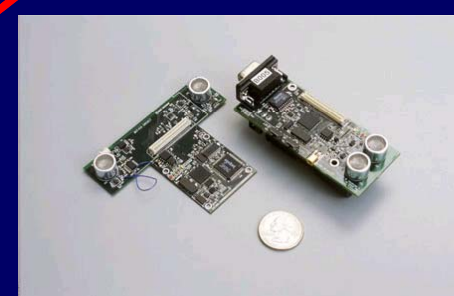
Sensory Data: A/D conversion, Compression, Filtering, Aggregation, Analysis

Communication (Wireless)

Broadcast sensory data, Dissemination, Routing

Control (Sensing / Actuation)

Sensing the physical world: temperature, humidity, pressure, light, velocity, sound, image



Cyber-Physical Systems (CPS)

- CPS integrate seamlessly the physical and computational worlds
- CPS exploit pervasive, networked computation, sensing, and control, i.e., “Internet of things” (IoT)

CPS Critical Infrastructures

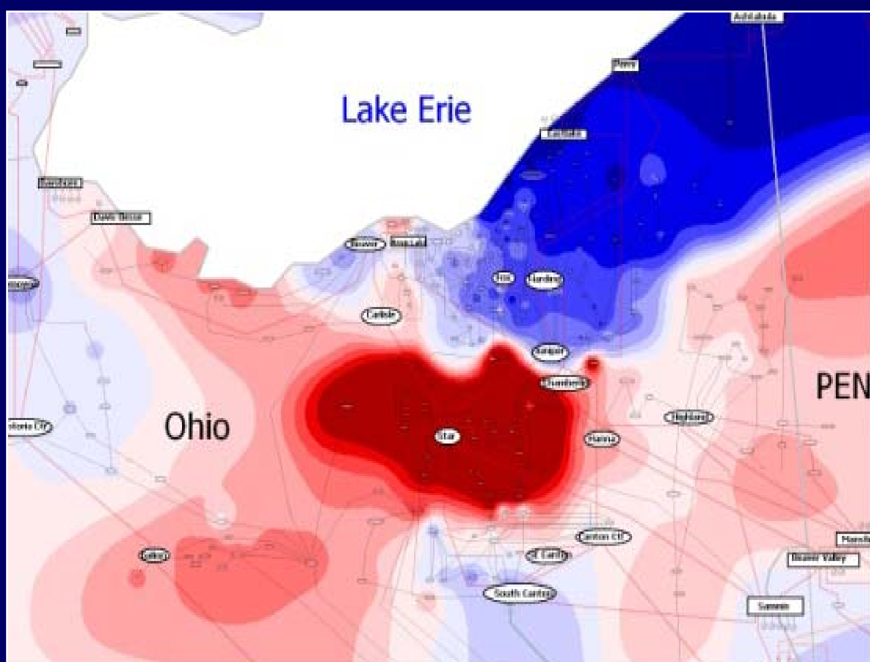
Transportation	▪ Faster and more energy efficient aircraft ▪ Improved use of airspace ▪ Safer, more efficient cars	
Energy, Sustainability, Automation	▪ Homes and offices that are more energy efficient and cheaper to operate ▪ Distributed micro-generation for the grid	
Healthcare and Biomedical	▪ Increased use of effective in-home care ▪ More capable devices for diagnosis ▪ New internal and external prosthetics	
Critical Infrastructure	▪ More reliable, efficient (smart) power grid ▪ Highways that allow denser traffic with increased safety	

CPS are natural and engineered physical systems that are integrated monitored, and controlled by an intelligent computational core

REWIMAN

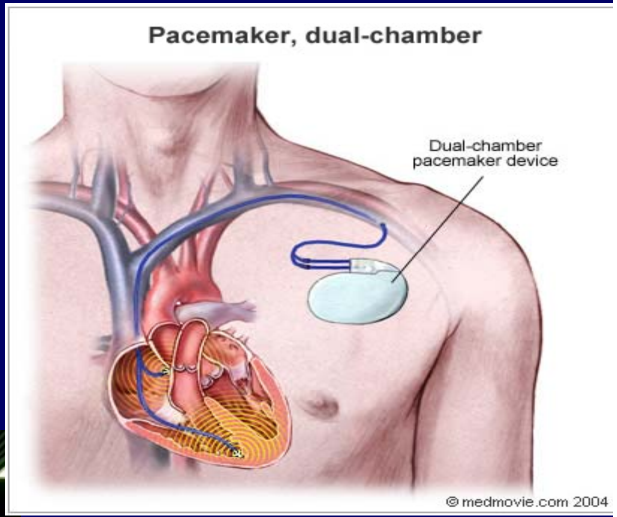
Energy and Sustainability

- Smart appliances, buildings, power grid
  - Net-zero energy buildings
  - Minimize peak system usage
  - No cascading failures



Smart Health Care

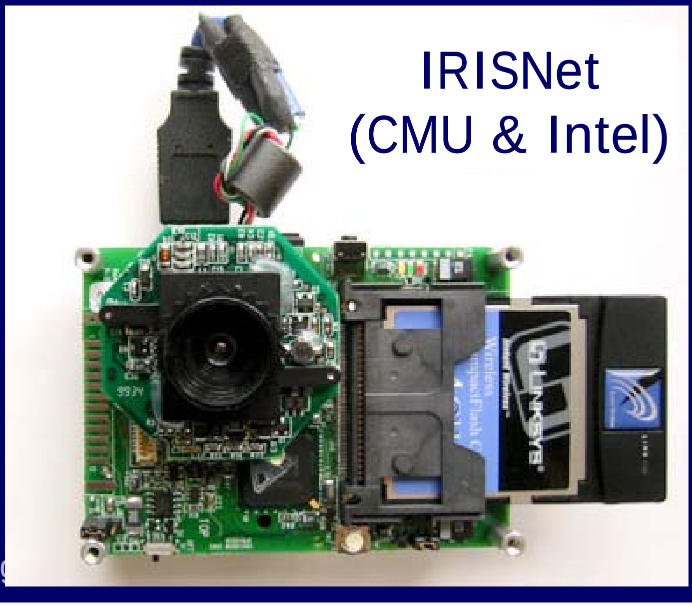
- Embedded medical devices and smart prosthetics; operating room of future; integrated health care delivery
  - Patient records at every point of care
  - 24/7 monitoring and treatment
  - Assisted Technology for everyone



Multimedia Wireless Sensor Network (MWSN)

- A network of wireless sensors with image and audio/video streaming capability
  - can also support scalar data
  - combines different media to perform a specific task

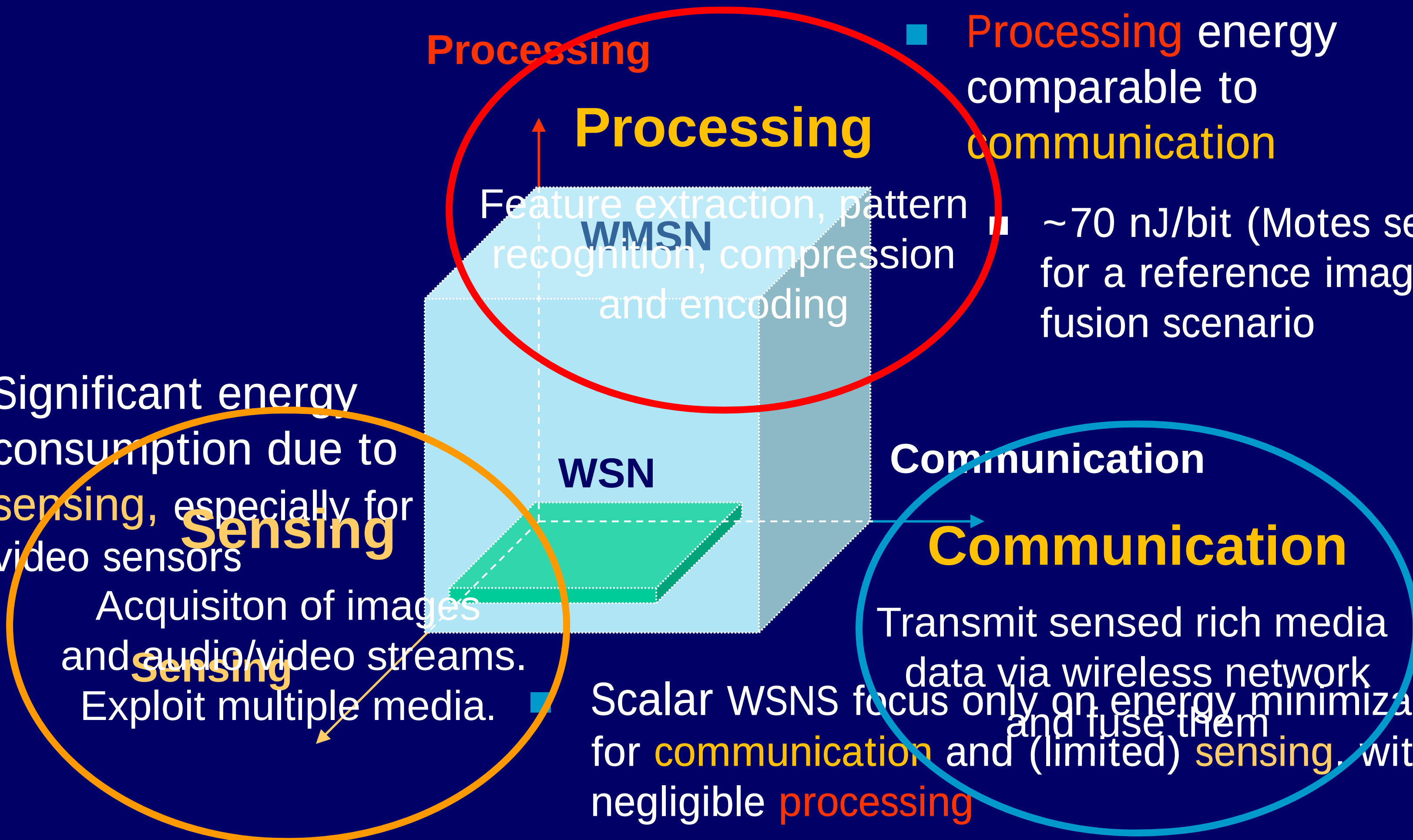
Cyclops (UCLA)



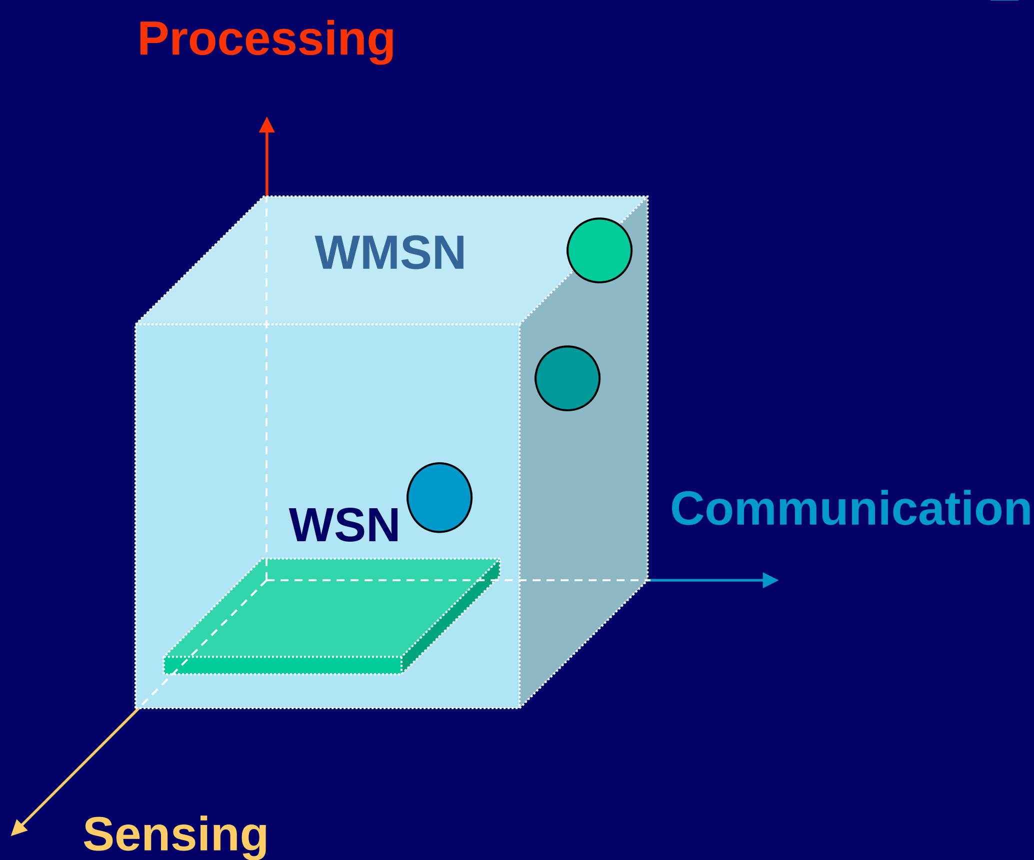
IRISNet
(CMU & Intel)

Energy in Multimedia Wireless Sensor Networks

- Processing energy comparable to communication
  - ~70 nJ/bit (Motes sensor) for a reference image fusion scenario
- Significant energy consumption due to sensing, especially for video sensors
- Scalar WSNS focus only on energy minimization for communication and (limited) sensing, with negligible processing



WMSN Examples



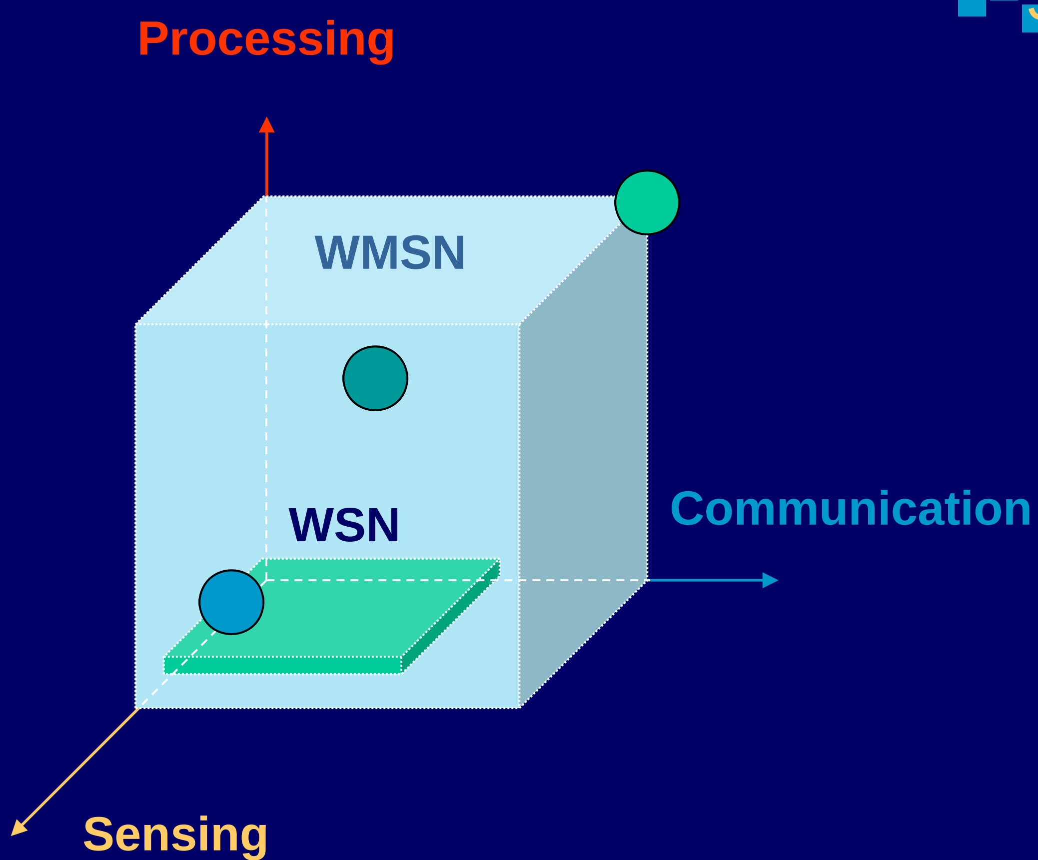
- Security and Protection and Surveillance
  - e.g., homeland security, border protection
  - data integrity and quality
  - privacy concerns, involving confidentiality and authentication

- Smart Health Care
  - e.g., elderly care, remote monitoring of patients
  - multiple classes of data
  - quality of service is important.

- Environment Monitoring
  - e.g., volcano eruptions
  - Forest / Bush Fire
  - every task is involved
  - not too much complex

Devices in Multimedia Wireless Sensor Networks

d13



- Scalar Sensor Nodes
  - provide scalar data
  - more processing capabilities than traditional WSNs
  - example: SunSpots
- Multimedia Sensor Nodes
  - get audio/video streams and still images
  - process them onboard
  - example: CMUCam (CMU)
- Fusion Nodes
  - gateway-class nodes
  - powerful enough for information storage/fusion
  - example: Beagleboard (beagleboard.org, DigiKey)

Slide 12

d13 Replace Tmote with SunSpot
dip, 10/09/2008

Outline

- Next Generation Wireless Networks
- Multimedia Wireless Sensor Networks (MWSNs)
- Challenges in MWSNs
- Ambiguous Context Mediation
- Quality-Aware Context Determination
- Security Issues
- Future Directions

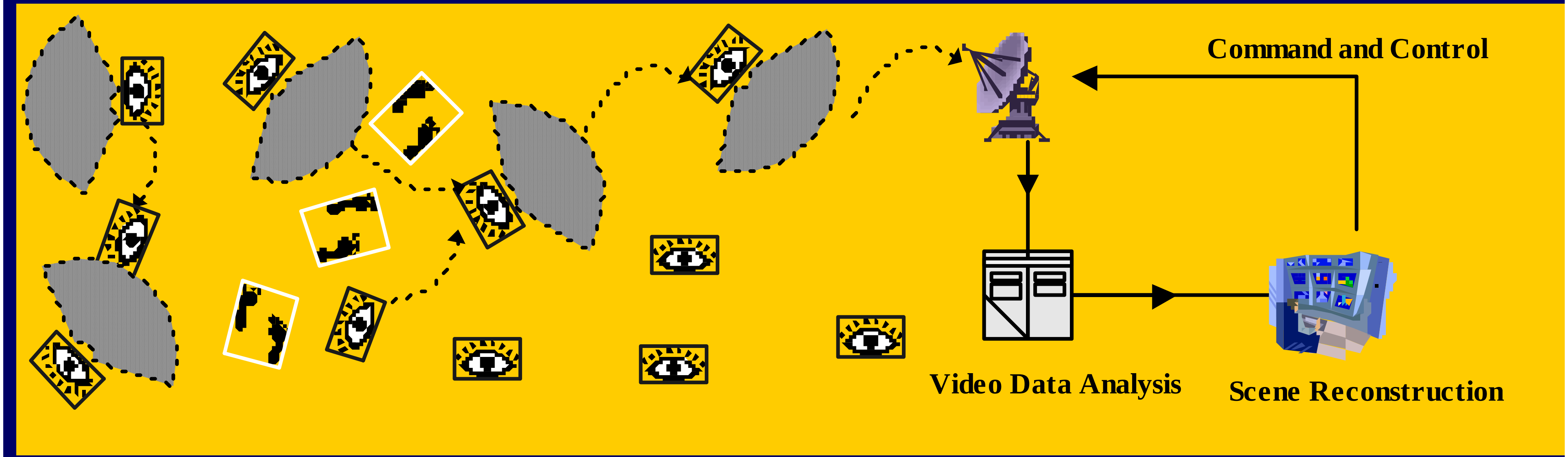
WSN vs. WMSN: New Challenges

Y. Liu and S. K. Das, “Information Intensive Wireless Sensor Networks: Potentials and Challenges”, *IEEE Communications Magazine*, Nov 2006.

- Higher Data Rate
  - Innovative energy-saving architectures, algorithms, and protocols
- Spatio-temporal Data (higher correlation / redundancy)
  - In-network: Fusion, estimation, detection, filtering, gathering, …
- High Information Assurance
  - Accuracy, reliability, fault-tolerance, resiliency, security, robustness, ...
- Emerging Security and Privacy Threats
  - Virus spreading, e.g., *Cabir* for wireless cell phone networks

CREWMAN

Wireless Video Sensor Network



- Higher data rate: 5 frames/second
- Vector data format
- Special platform support
- Higher correlation / redundancy

- Vast applications
  - Border / perimeter control
  - Battle field surveillance
  - Smart health care
  - Airport security

Challenges in WMSNs: QoS Support

- Data quality
  - adequate coverage for sensing
  - proper characterization of the phenomenon
  - security and privacy concerns
- Timeliness
  - latency, jitter
  - deadlines and prioritites
    - different delivery modes, each with specific requirements

Challenges in MWSNs: Information Intensiveness

- Multimedia content is inherently information rich
  - efficient methods to get meaningful representation of information
  - avoid sensing when it does not add information
- Congestion problems for multimedia data
  - reduce data coming into the network
  - use many low-resolution sources and fuse information
  - use new technologies to improve available bandwidth

Research Directions: MWSNs

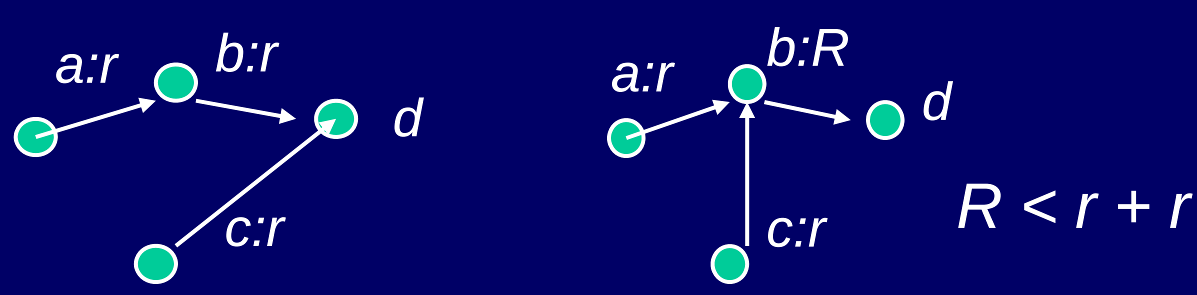
- Semantic Use of Sensor Data
  - Sensor information processing:
    Not just aggregating correlated measurements
  - Sensor information integration:
    Models for multi-sensor information fusion to assess context and situation awareness
  - Information intensive sensing:
    Fusion cost important (e.g., video and multimedia sensors)
  - Quality of Information:
    Sensing quality and QoS, how to measure?

- H.J. Choe, P. Ghosh and S. K. Das, “QoS-aware Data Reporting in Wireless Sensor Networks,” *1st IEEE Workshop on Information Quality and QoS in Pervasive Computing* (IQ2S), Mar 2009.

- N. Roy, G. Tao, S. K. Das, “Supporting Pervasive Computing Applications with Active Context Fusion and Semantic Context Delivery," *Pervasive and Mobile Computing*, 2010.

Fusion Driven Routing of Intensive Information

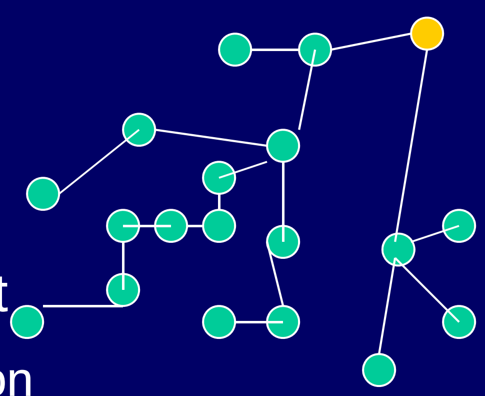
- Aggregation (fusion)
  - Sensory information from proximate nodes is often redundant
    - Highly correlated data (e.g., temperature, humidity, light)
  - Fusion reduces redundancy and communication
    - Curtails network load → less energy consumption, increased lifetime
- Fusion-driven routing algorithm
  - Routing structure depends on (spatio-temporal) data correlation



Aggregation Isn’t Free for MWSNs

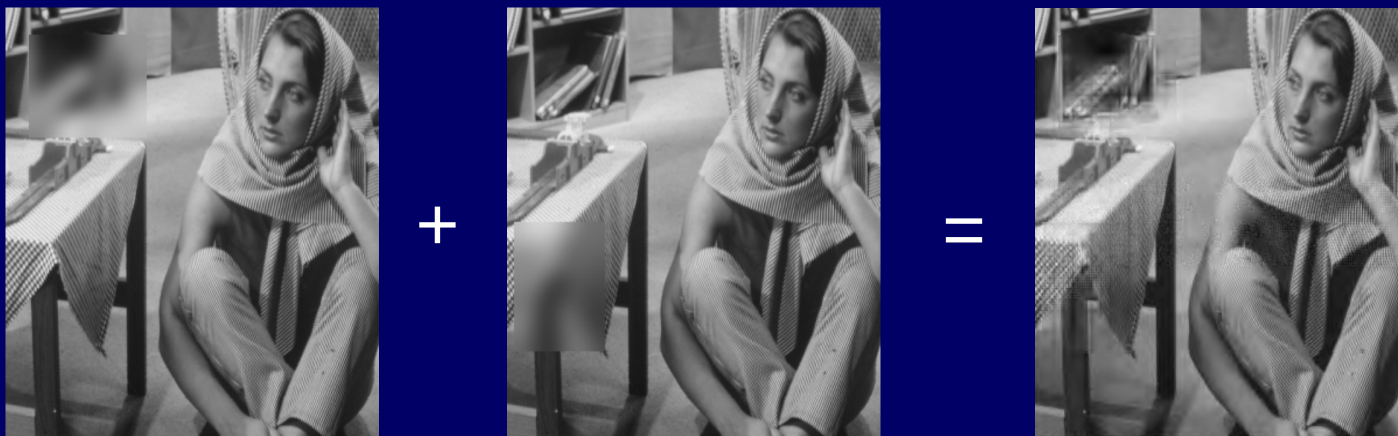
- Fusion is Free (almost zero cost) for scalar aggregation functions
  - Average, count, max / min
- Traditional WSN Routing Goal:
  - Minimize total *communication cost* of the network for gathering all the sensory data – fully exploit the fusion benefit
- Potentially high fusion cost for information intensive WSNs
  - Compression, image fusion, etc.
  - Image fusion: tens of nJ / bit

    – same order as communication



- Fusion cost different from communication cost
  - Depends on inputs, not output of fusion function

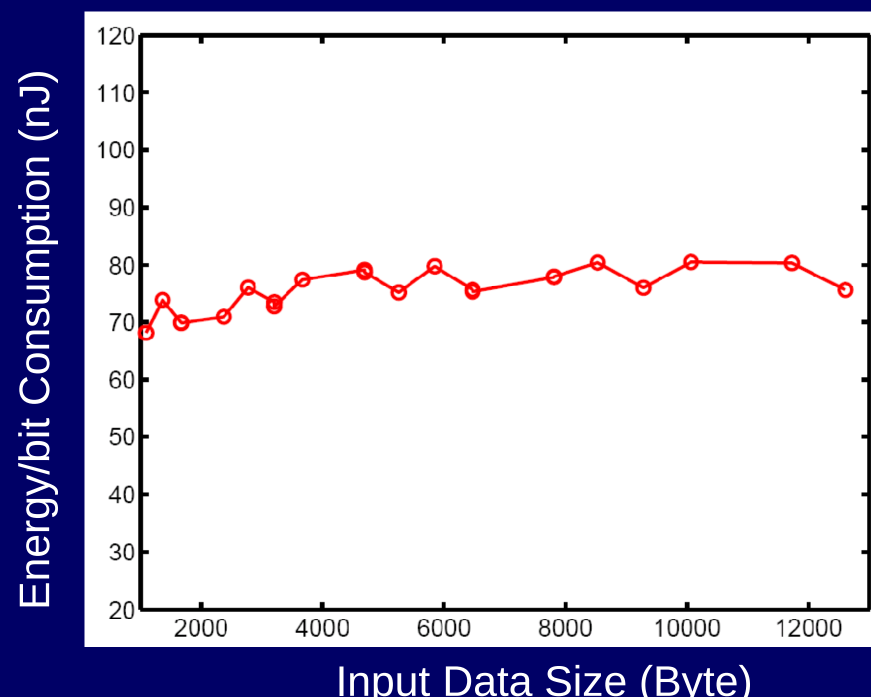
Cost for Fusing Images



Fusion cost is around 70 nJ / bit (Motes)

Communication cost about 100 nJ / bit

They are on the same order!



Dynamic Optimization Problem

- Optimize fusiion routing tree over both communication (link) and fusion (node) costs
- The routing structure shall determine dynamically
  - Whether to fuse or not ?
    - Maximize fusion benefit – Reduction in communication cost vs. increase in fusion cost
  - How to fuse ?
    - When and where

Fusion-Driven, Energy Efficient Routing

New problem demands new solutions!

- H. Luo, Y. Liu, S. K. Das, “Routing Correlated Data with Fusion Cost in Wireless Sensor Networks”, *IEEE Trans. on Mobile Computing*, Vol. 5, No. 11, pp. 1620-1632, Nov 2006.
- H. Luo, Y. Liu, S. K. Das, “Adaptive Data Fusion for Energy Efficient Routing in Wireless Sensor Networks”, *IEEE Trans. on Computers*, Vol. 55, No. 10, pp. 1286-1299, Oct 2006.
- H. Luo, Y. Liu, and S. K. Das, “Routing Correlated Data in Wireless Sensor Networks: A Survey,” *IEEE Network*, Vol. 21, No. 6, pp. 40-47, Nov/Dec 2007.
- H. Luo Y. Liu and S. K. Das, “Distributed Algorithm for En Route Aggregation Decision in Wireless Sensor Networks,” *IEEE Transactions on Mobile Computing*, Vol. 8, No. 1, pp. 1-13, 2009.
- H. Luo, H. Tao, H. Ma, and S. K. Das, “Data Fusion with Desired Reliability in Wireless Sensor Networks,” *IEEE Transactions on Parallel and Distributed Systems,* to appear, 2010.

Research Direction in MWSN: Uncertainty Reasoning

- Uncertainty in sensing, aggregation, wireless communication, mobility, dynamic topology, routing, …
- Uncertainty in distributed collaboration / coordination, fusion, processing, decision making
- Uncertainty in deployment density, battery usage
- How to capture contexts unambiguously despite uncertain (noisy) and incomplete information?

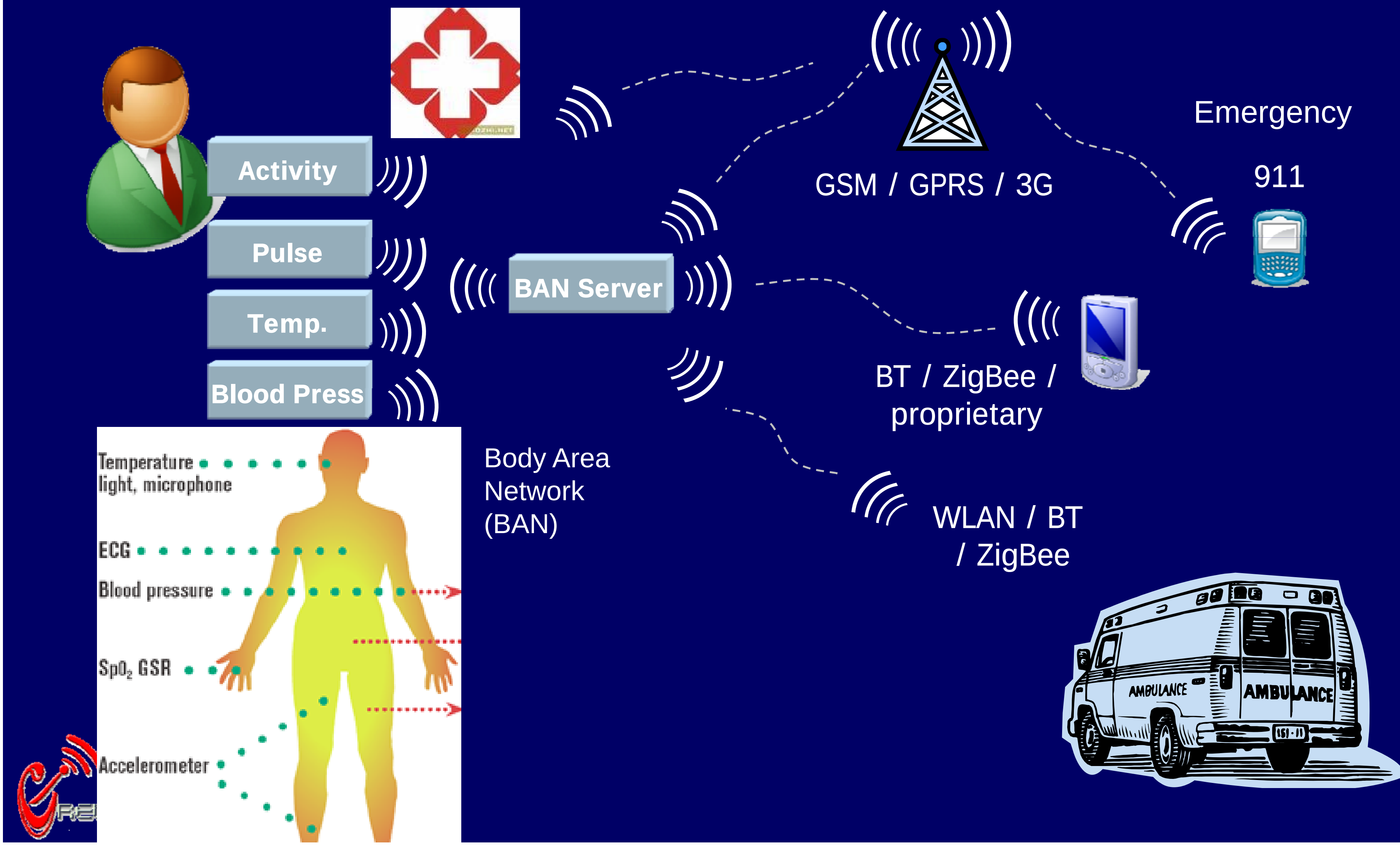
Outline

- Multimedia Wireless Sensor Networks
- Challenges in MWSNs
- Ambiguous Context Mediation
- Quality-Aware Context Determination
- Coverage and Connectivity
- Security Issues
- Future Directions

Pervasive Hearth Care

Different types of services (Priority)

Information Query (Heterogeneity)



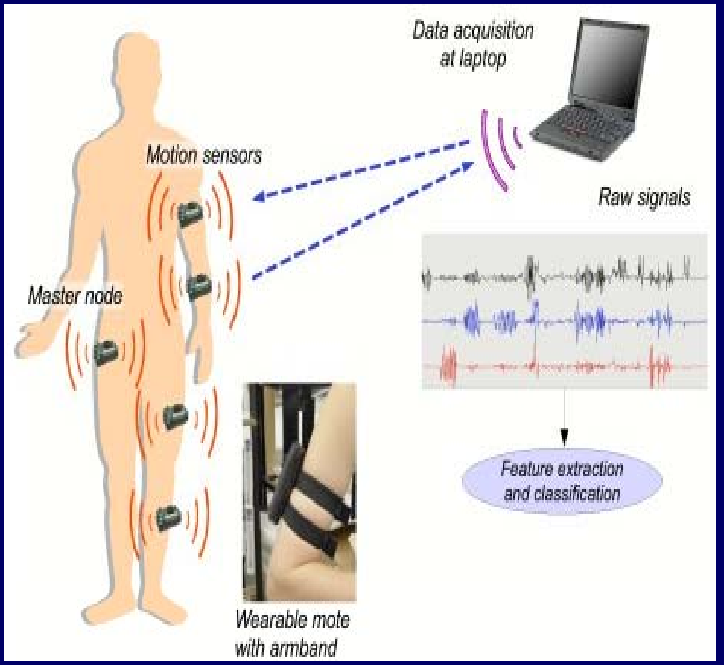
Pervasive Healthcare

- **Situation-aware data collection (e.g., activity, movement, behavior)**

  – Process sensor data stream to determine Activities of Daily Living (ADL)

  – Characterize uncertainty, ambiguity, error in sensor-driven decision processes

  – Context modeling, mediation and determination for higher level properties

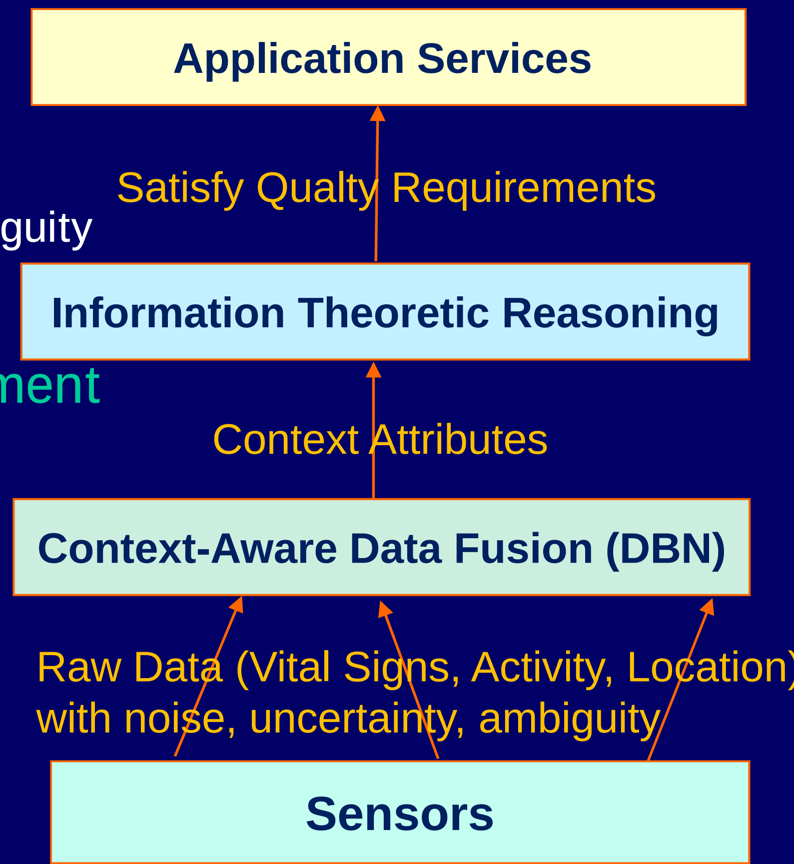


- **Quality-of-Context (QoC) aware sensing protocol**

  – Tune energy efficiency of sensors, analyze information accuracy

Novel Contributions: Techniques

- Context model
  - Abstraction of raw data into high level contexts
- Context aware data fusion
  - Understanding ambiguity
  - Dynamic Bayesian Networks (DBNs) for ambiguity resolution
- Intelligent sensor information management
  - Information theoretic reasoning
  - Optimal sensor parameter selection
  - Reduction in ambiguity/error in state estimation process
- Quality-aware context determination
  - Tradeoff communication cost vs. accuracy
- Validation with SunSPOT sensor test bed

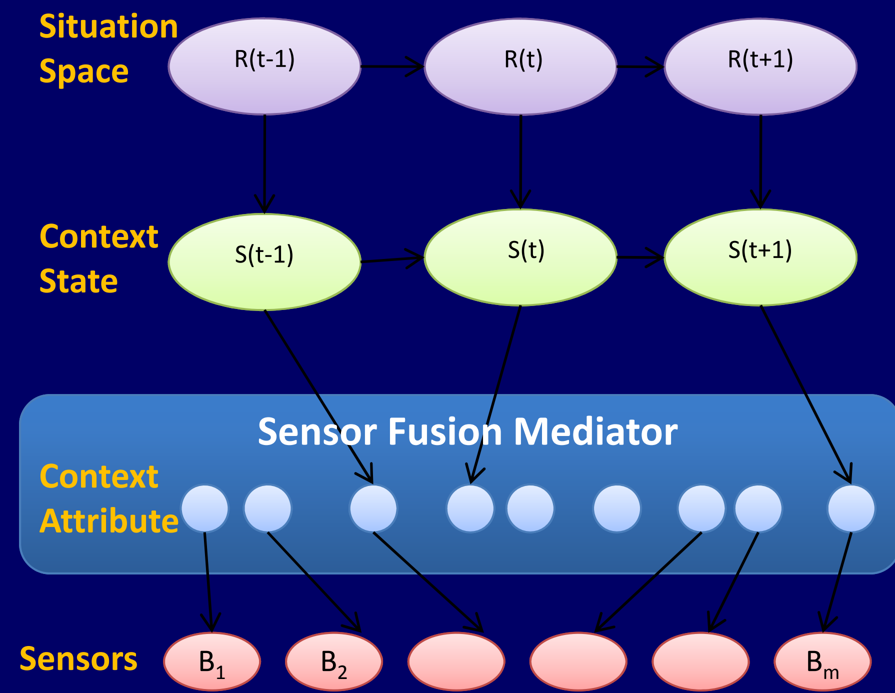


Context-Aware Data Fusion Framework

- Context-Aware Data Fusion
  - **Top-down Inference**

    Given context state, select relevant ambiguity-reducing context attributes (e.g., time, blood sugar, frequency of getting up from bed)
  - **Bottom-up Inference**

    Given a set of context attributes, infer context states with varying (reported) ambiguities



- Dynamic Bayesian Network (DBN)
  - Coherent and unified hierarchical probabilistic framework
  - Sensory data representations, integration and inference
- Compute Ambiguity-Reducing Utility:

$$V_i = \max_{i=0}^{K} \sum_{j=0}^{N} \left[p\left\langle a_j^R \,\middle|\, a_i^t \right\rangle \right]^2 - \min_{i=0}^{K} \sum_{j=0}^{N} \left[p\left\langle a_j^R \,\middle|\, a_i^t \right\rangle \right]^2$$

a_i^t = Context attribute a_j^R = Situation space

Intelligent Sensor Management

- What information should each selected sensor send to enable the fusion center to

  - best estimate the current situation state

  - while satisfying the application's QoC requirements and

  - minimizing the state estimation error?

- Model assumptions

  - Noisy observations across sensors are independently and identically distributed (i.i.d.) random variables

  - Each sensor has a source entropy rate $H(a_i)$; i.e., to send data about attribute a_i requires $H(a_i)$ bits of data

N. Roy, C. Julien, and S. K. Das, "Resource-Optimized Quality-Assured Ambiguous Context Mediation in Pervasive Environment," *Proceedings of QShine 2009* (**Best Paper Award**).

CREWMAN

Information Theoretic Reasoning

- B = set of sensors, A = set of context attributes
- (B × A) matrix where *Bmi* = 1 iff sensor m sends attribute *ai*
- **Goal:** Find the best (B × A) within capacity constraint Q that minimizes the estimation error of the situation space

$$\sum_m \sum_i H(a_i) * B_{mi} < Q \text{ and minimize } [P_e = P\{\bar{R} \neq R\}]$$

- Use Chernoff theorem to maximize information content
  - Ideally, each sensor sending exactly one bit of information is optimal

Implication: Multiple sensor fusion exceeds the benefits of detailed information from each individual sensor

Quality-Aware Context Sensing

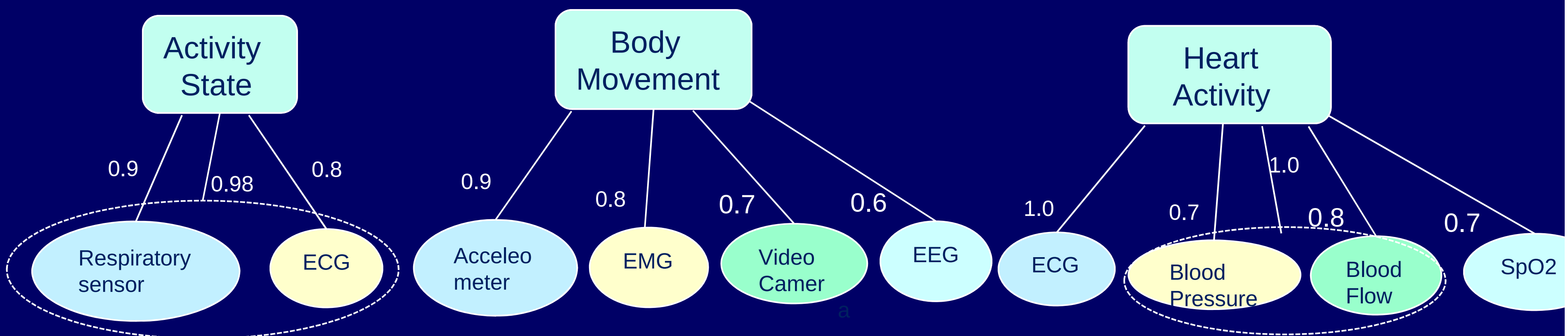
- Automated determination of context
  - We assume an underlying set of sensor data streams that can be aggregated into context data
- Estimation problem over multiple sensor data streams
  - Compute the best set of sensors + associated *tolerance* values
  - Satisfy a target *quality*
  - Minimize the *cost* of sensing
- Tolerance range
  - Measured in terms of a sensor's data reporting frequency
  - Ensure acceptable accuracy of the derived context
- Sensing Cost
  - Measured in terms of communication overhead (energy cost)

Quality of Context (QoC) Function

- **QoC Function = Potential error of measure from true value**
  = (1 – Average Estimation Error)

$$Quality_C(\Theta, Q_\Theta) = 1 - \frac{\sum_{x \in \Lambda_C} err_C(x, \{(s_i, q_i) : s_i \in \Theta, q_i \in Q_\Theta\})}{|\Lambda_C|}$$

C = context, Θ = the set of sensors, $Q_\Theta = \{q_1, q_2, \ldots, q_n\}$ = collection of tolerance ranges



Impact of different sensor subset selection on QoC

Quality vs. Cost Tradeoff

- **Cost measure:** the cost of using a sensor is a function of its assigned tolerance range (q):

$$COST(\theta, q_\theta) = \sum_{s_i \in \theta} c_i(q_i)$$

- When the cost is communication overhead, it scales with hop count, and we can use:

$$COST(\theta, q_\theta) = \kappa * \sum_{i \in \theta} \frac{h_i}{q_i^2}$$

  - where κ is a scaling constant and h_i is the hop count

- Formulate the *best* sensor selection as an optimization problem:

$$(\hat{\Theta}, \hat{q}_\Theta)_{F_{\min}} = \underset{\Theta \subseteq S, q_\Theta}{\arg\min}\, COST(\Theta, q_\Theta)$$

$$\text{such that } Quality_C(\hat{\Theta}, \hat{q}_\Theta) \geq F_{\min}$$

Quality vs. Cost Tradeoff

- Solving for arbitrary functions requires brute-force approach
- Certain forms are more tractable – when the QoC of an individual sensor is expressed by an inverse exponential:

$$Quality_i = 1 - \frac{1}{\nu_i} e^{\frac{-1}{\eta_i q_i}}$$

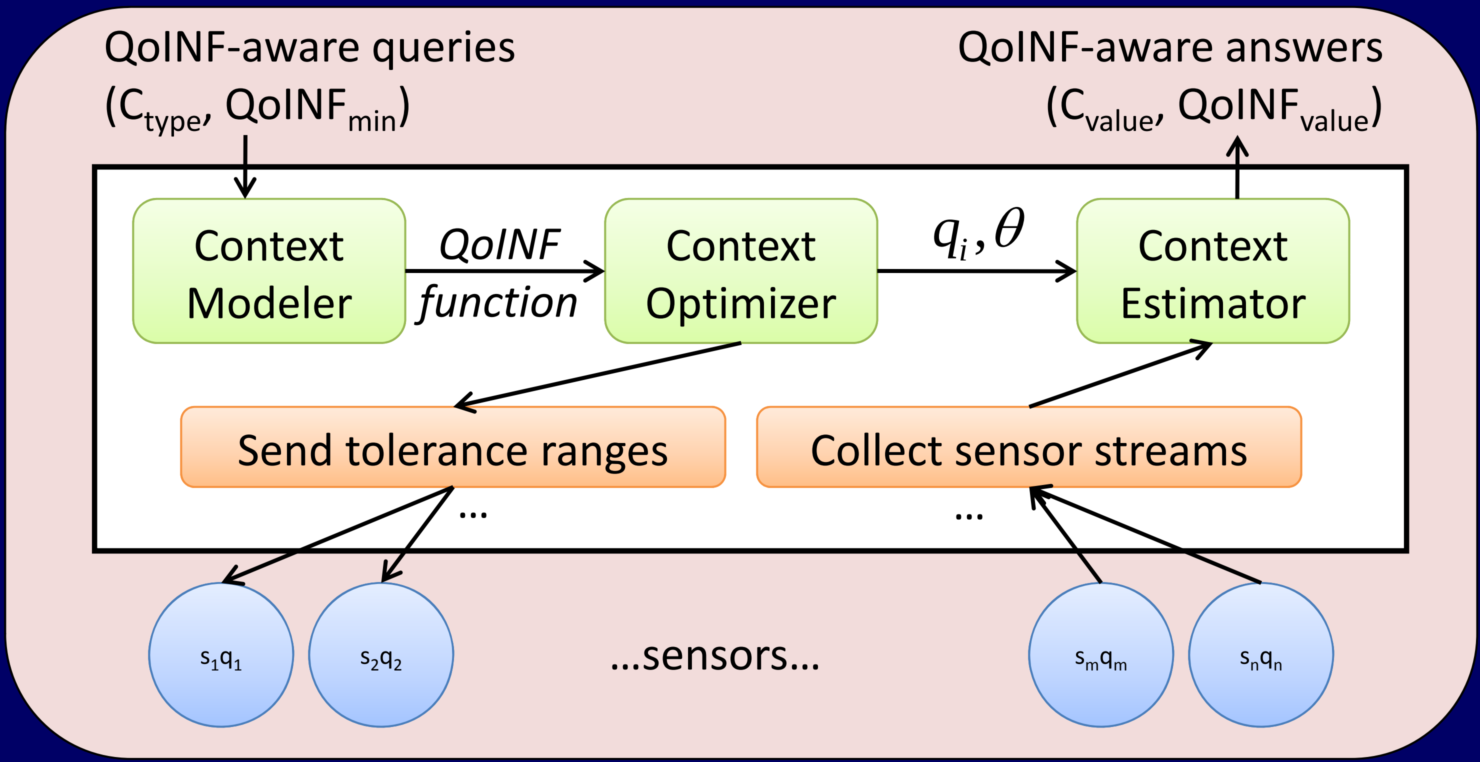
  - where η_i and ν_i are sensitivity constants for sensor s_i
- Then the problem becomes: (Lagrangian Optimization)

$$\text{minimize } COST(\Theta, q_\Theta) \text{ subject to } Quality_C(\Theta, q_\Theta) \geq F_{\min}$$

$$\text{minimize } \sum_{s_i \in \Theta} \frac{h_i}{q_i^{\,2}} + \lambda \left[1 - \prod_{s_i \in \Theta} \left[\frac{1}{\nu_i} e^{\frac{-1}{\eta_i q_i}} \right] - F_{\min} \right]$$

Context Sensing Architecture

- Activity monitoring specifies minimal acceptable QoC
- Context Optimizer
  - Compute optimal set (θ) of sensor data streams
  - Determine optimal tolerance range (q_i) for each selected sensor



QoC-Aware Context Determination Architecture

Experimental Evaluation

SunSPOT (Sun Small Programmable Object Technology)

- **SunSPOT Processor Board**

  2.4 GHz IEEE 802.15.4 radio with integrated antenna

- **SunSPOT Sensor Board**

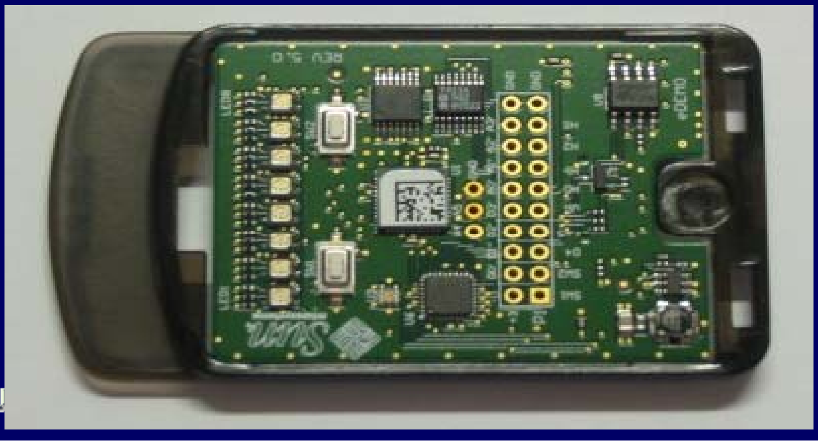
  3-axis accelerometer(2G or 6G),

  light and temperature sensor

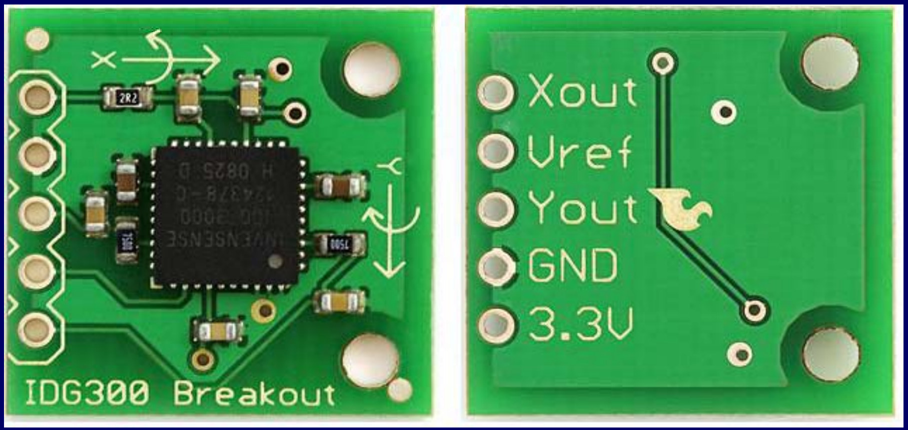
- **Single chip dual axis Gyro sensor board**

Gyro with SunSPOT

SunSPOT Sensor Board



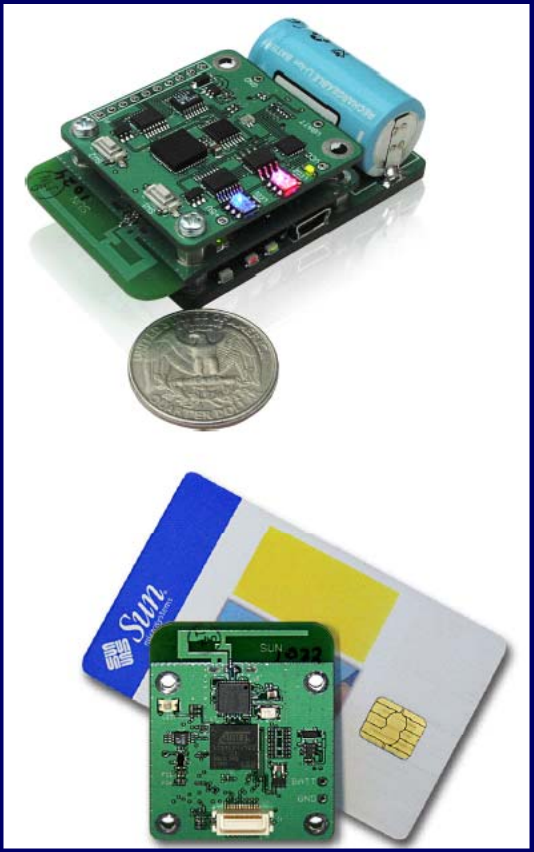
Gyro Breakout board



More Powerful Sensors (Sun Microsystems)

SunSPOTs: Small Programmable Object Technology

- CPU: 180 MHz 32 bit ARM9 core ARM7
- Memory: 512 KB RAM, 4 MB Flash
- Communication: Chipcon 2024 Radio
    - 2.4 GHz Zigbee (IEEE 802.15.4)
- USB Interface
- 3.7V rechargeable 750mA lithium ion battery
    - 40µA in deep sleep mode
- Double sided connector for stackable boards



Test bed Setup

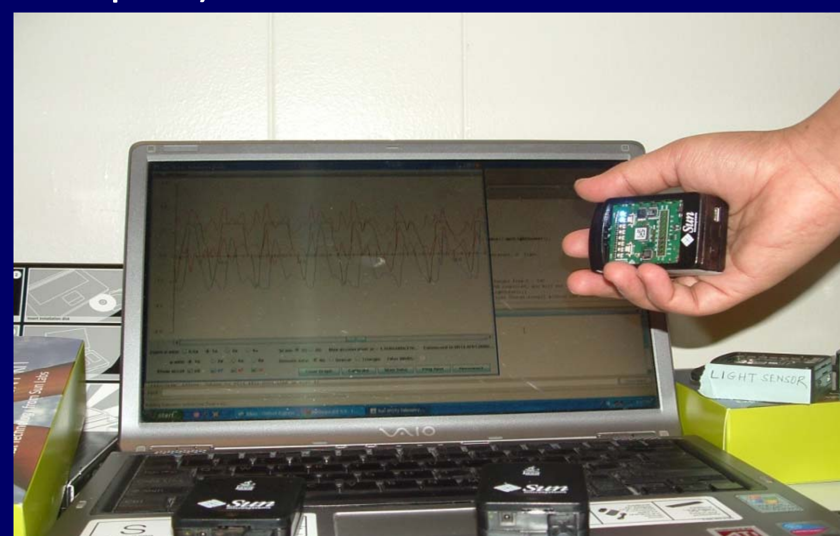
Accelerometer Values for different context states

Ranges of Tilt Values (in degree)	Context State
85.21 to 83.33	*Sitting*
68.40 to 33.09	*Walking*
28.00 to -15.60	*Running*

Light Sensor Values for different context states

Avg. Range of Light level (lumen)	Context State
10 to 50	Turned on (active)
0 to 1	Turned off (sleeping)

- **Trace Collection: Five users engaged in different activities**
  - Sitting, walking, running for 30 days
  - Sampling frequency 5.5 Hz (2000 samples)

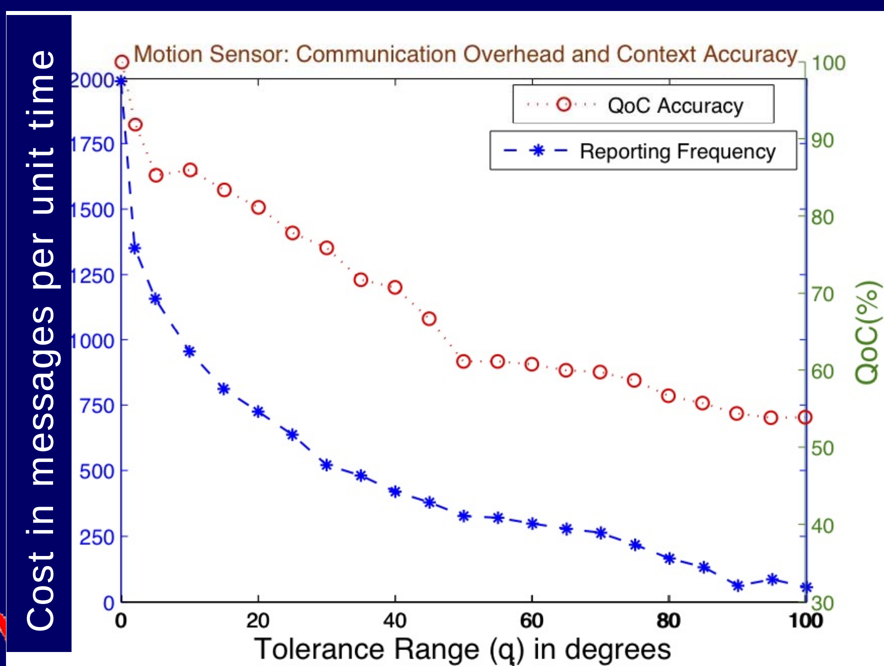


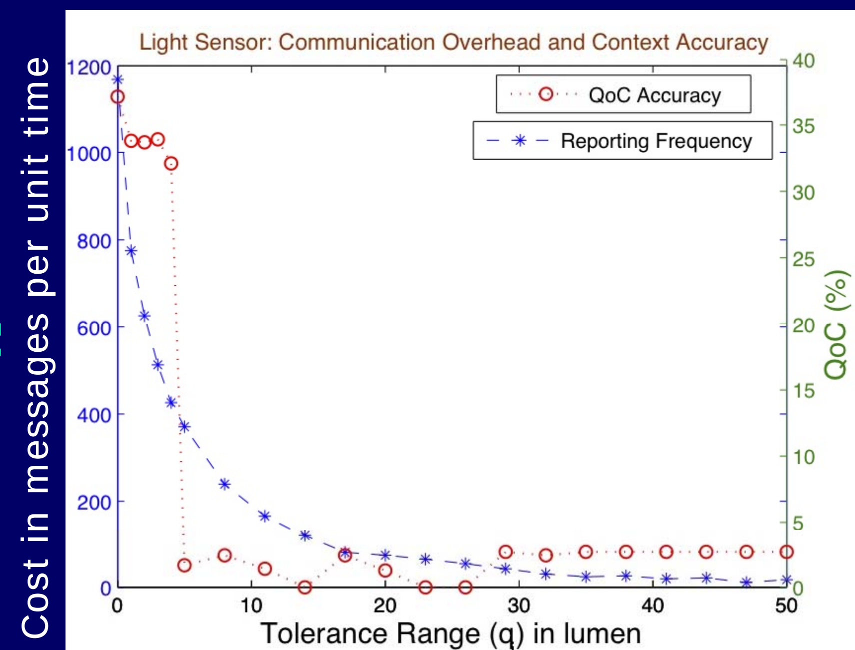
Experimental Evaluation: Sample Results

- Quality of context measured as the accuracy of measurement to the known ground truth

- Significant reduction in reporting frequency (communication cost) for moderate loss in fidelity:

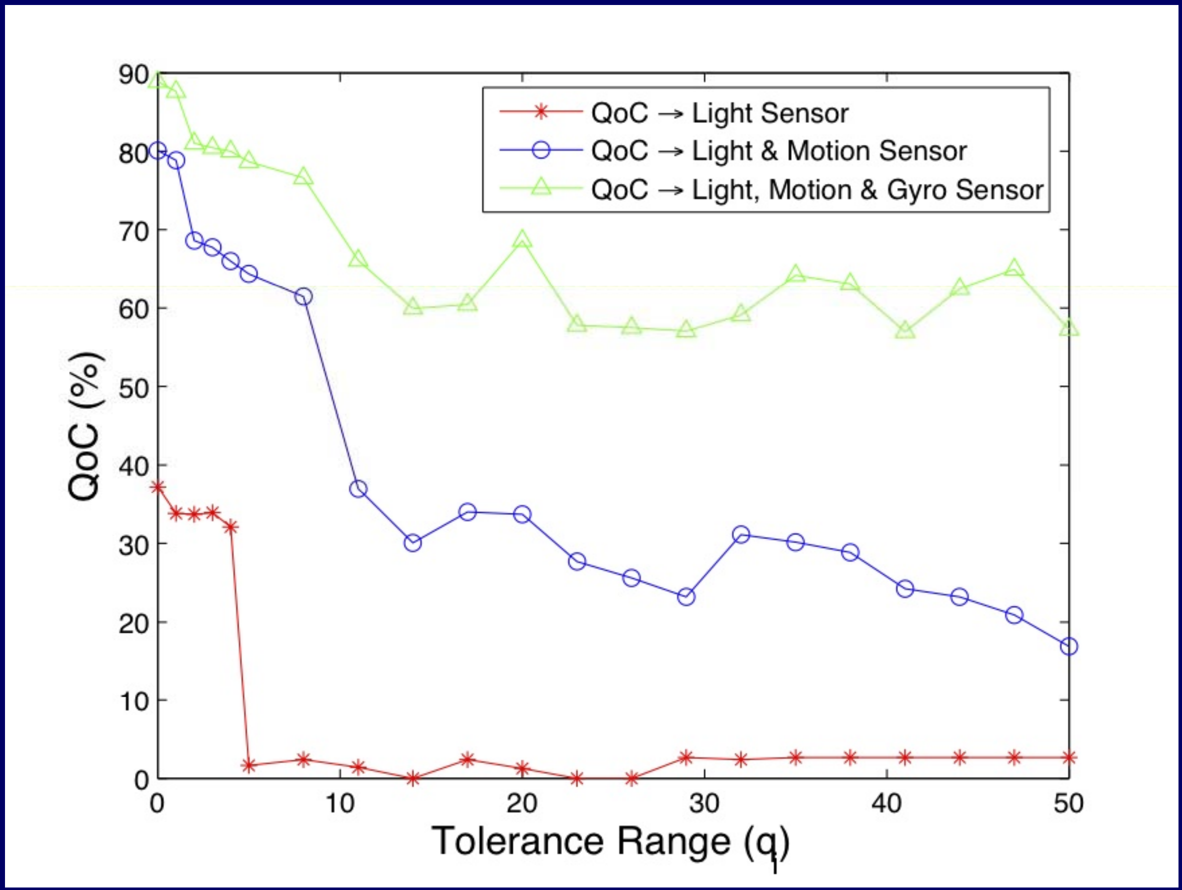
  ~85% reduction in QoC ➔cost reduction from1953 to 248 for motion sensor





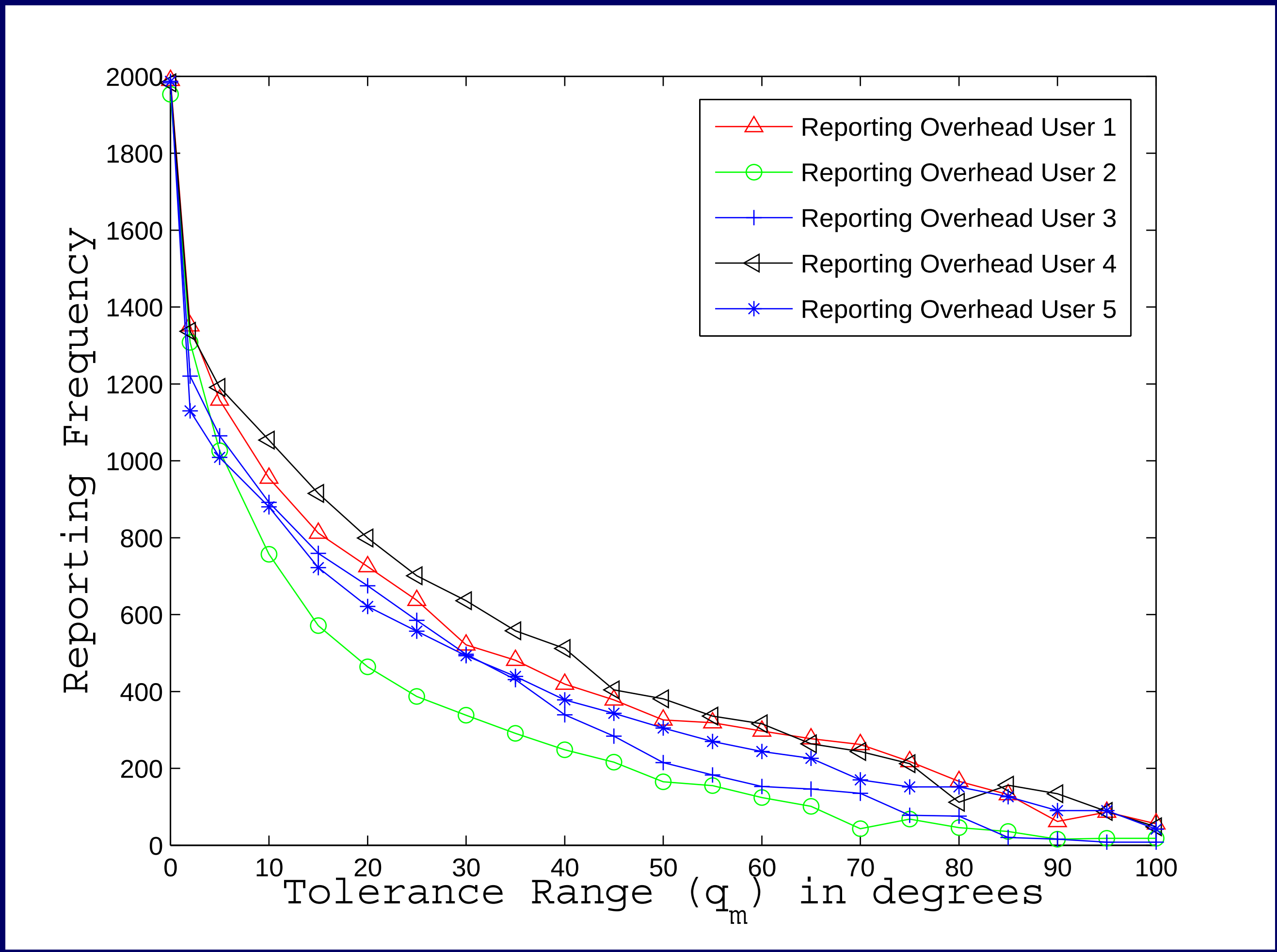
Benefit of Joint Sensing

- Context accuracy improves using multiple sensors
  - QoC obtained through combination of light and motion sensor is higher than that of a single sensor, at a lower cost
  - QoC is less susceptible to individual range variation



Experimental Results: Multiple Users

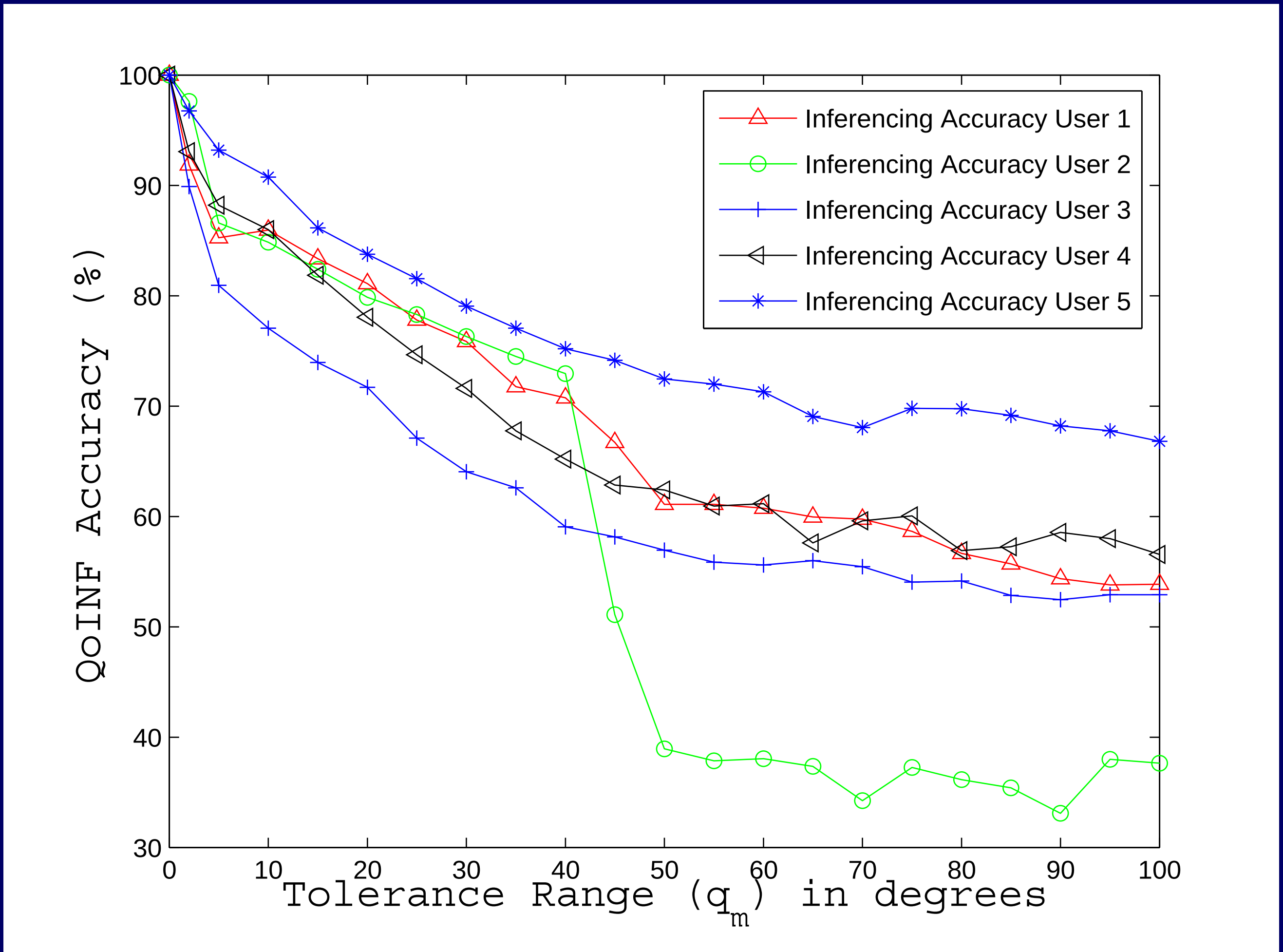
Communication Cost vs. Tolerance Range (Motion Sensor)



- **For tolerance range q = 20, worst case reduction in cost is 60% for User 4**
- **Sensitivity of the tradeoff to individualized activity patterns**

Experimental Results: Multiple Users

Context Accuracy vs. Tolerance Range (Motion Sensor)



- **For tolerance range q = 20, lower bound of accuracy is 71% for User 3**
- **Personalization of QoC function**

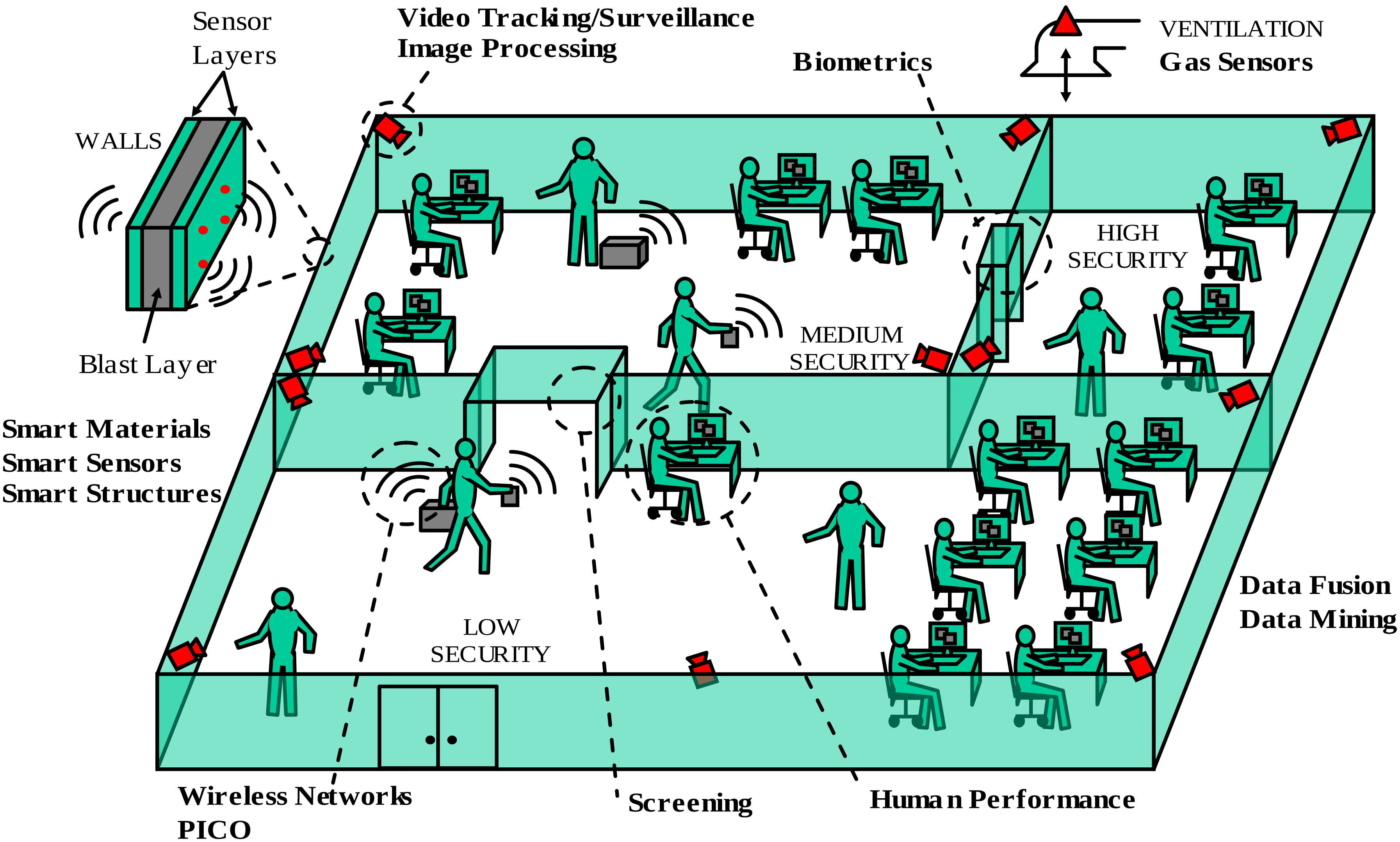
Summary

- Towards an understanding of the quality of collected and inferred information in sensor-based pervasive computing environments
  - Where the information may be imprecise or ambiguous due to dynamics, errors, and unpredictability
- We apply a suite of techniques to help resolve context ambiguity
- We empower applications to be *quality-aware*
  - Through explicit codification of cost/accuracy tradeoff

Outline

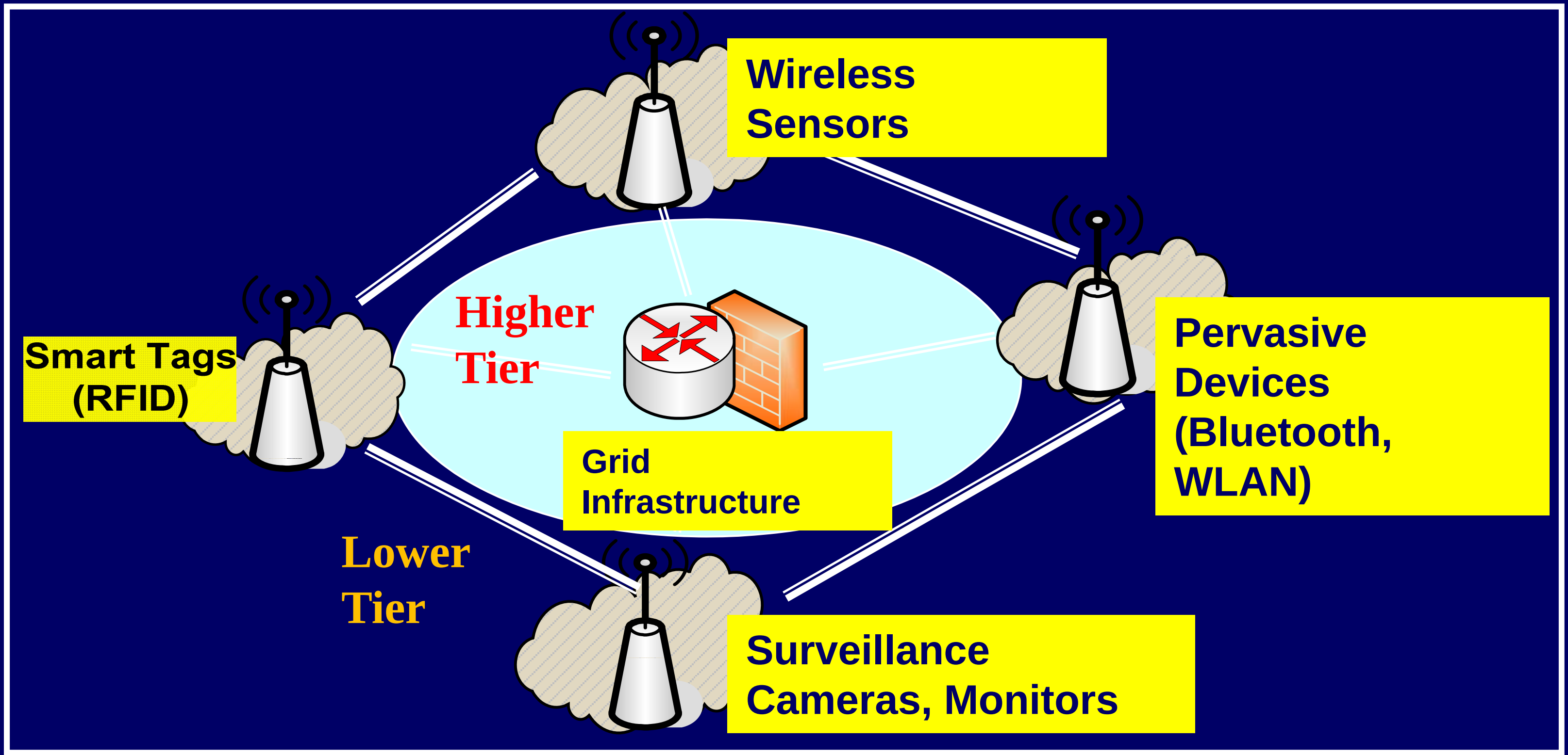
- Multimedia Wireless Sensor Networks
- Challenges in MWSNs
- Ambiguous Context Mediation
- Quality-Aware Context Determination
- Security Issues
- Future Directions

Pervasive Security



NSF ITR Project – Pervasively Secured Infrastructures (PSI): Integrating Smart Sensing, Data Mining, Pervasive Networking and Community Computing, 2003-2010. http://crewman.uta.edu/psi

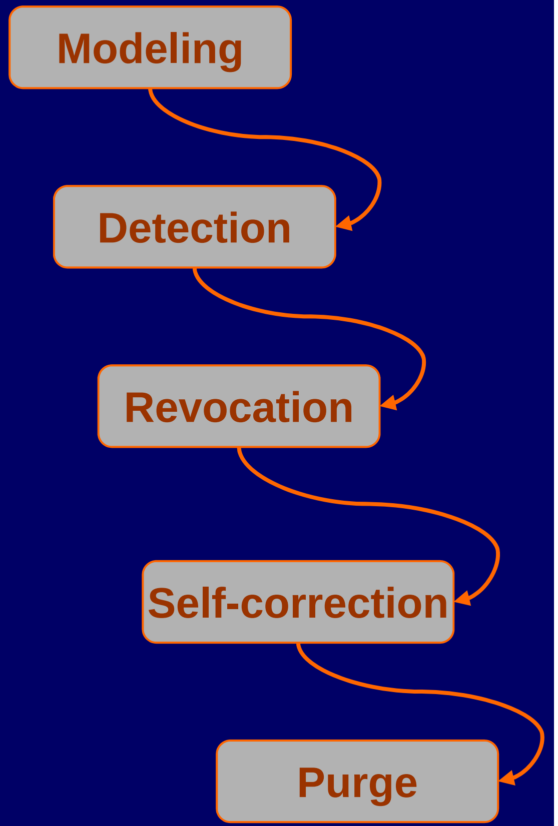
Pervasive Security: Research Goals



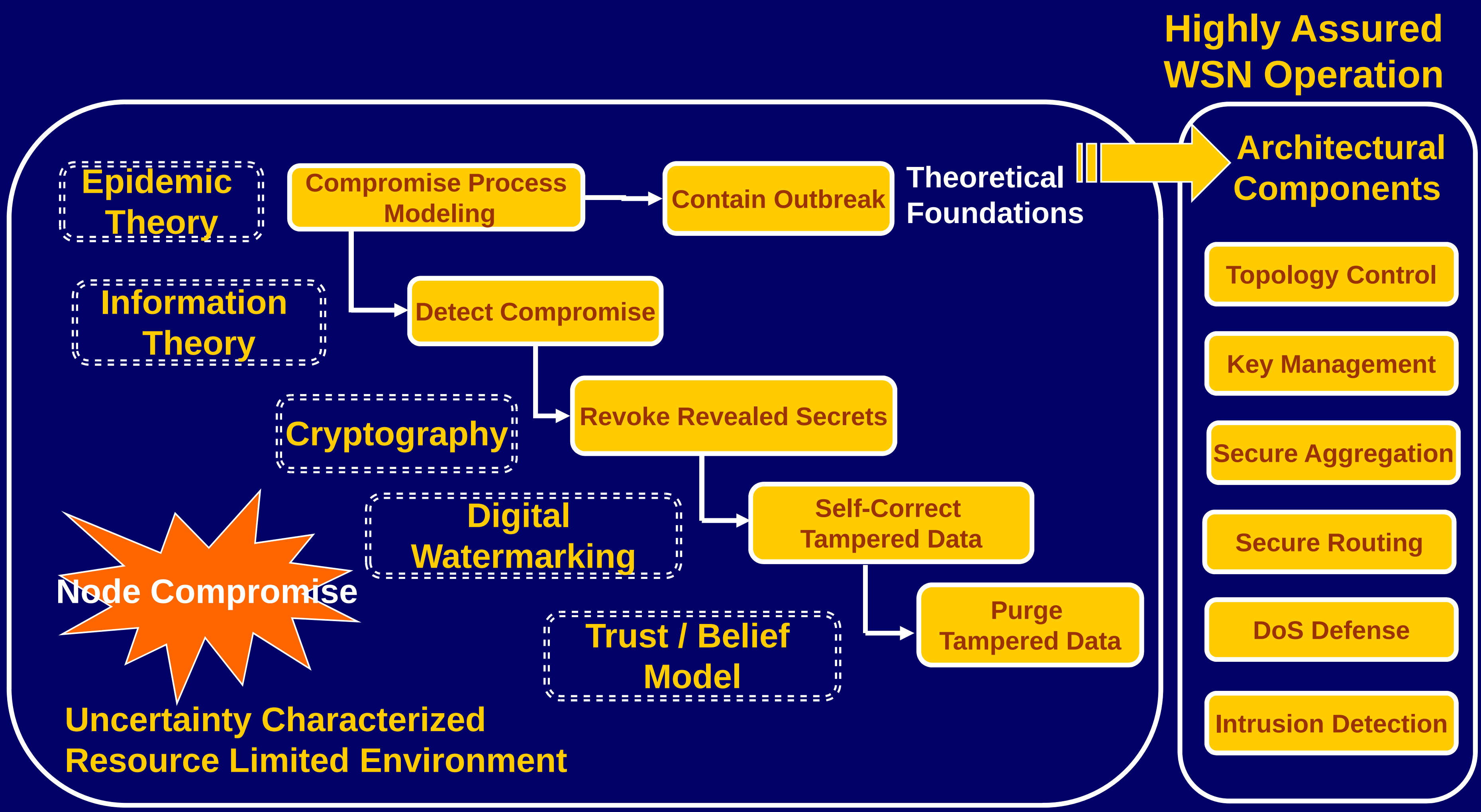
- Context / situation-aware data collection and aggregation (fusion) from heterogeneous sensors, surveillance, and tracking devices
- Data Mining to discover knowledge and patterns, leading to anomaly detection and hence potential security threats
- Intelligent decision making in integrated, adaptive, autonomous and scalable manner for mission-critical safety and security services

Multi-Level Security Solution

- Defend attacks at multiple levels
  - Modeling node compromise propagation
    - trojan virus spreading
  - Detect forged data
    - abnormal reports
  - Revoke revealed secrets
    - broadcast confidentiality
  - Self-correct and purge false data
    - average temperature calculation



Multi-Level Integrated Security Architecture



Security in Sensor Networks

- P. De, Y. Liu, and S. K. Das, "An Epidemic Theoretic Framework for Vulnerability Analysis of Broadcast Protocols in Wireless Sensor Networks," IEEE Transactions on Mobile Computing, Vol. 8, No. 3, pp. 413-425, Mar 2009. (Preliminary version in IEEE MASS 2007)
- P. De, Y. Liu, and S. K. Das, "Deployment Aware Modeling of Node Compromise Spread in Sensor Networks," ACM Transactions on Sensor Networks, Vol. 5, No. 3, pp. 413-425, May 2009.
- W. Zhang, S. K. Das, and Y. Liu, "Secure Data Aggregation in Wireless Sensor Networks: A Watermark Based Authentication Supportive Approach," Pervasive and Mobile Computing, Vol. 4, No. 5, pp. 658-680, Oct 2008.
- W. Zhang, S. K. Das, and Y. Liu, "A Trust Based Framework for Secure Aggregation in Wireless Sensor Networks," IEEE SECON 2006.
- J.-W. Ho, M. Wright, D. Liu, and S. K. Das, "Distributed Detection of Replicas with Deployment Knowledge in Wireless Sensor Networks," Ad Hoc Networks Journal, Vol. 7, No. 8, pp. 1476-1488, Aug 2009.

Outline

- Multimedia Wireless Sensor Networks
- Challenges in MWSNs
- Ambiguous Context Mediation
- Quality-Aware Context Determination
- Security Issues
- Future Directions

Ongoing Projects

- Paradigm shift: Asynchronous sampling, architectures, protocols and optimization in information intensive WSNs
  - Ultra-energy efficient, Scalable, Reliable, Secured
  - J. Wang, Y. Liu, and S. K. Das, “Energy Efficient Data Gathering in Wireless Sensor Networks with Asynchronous Sampling," ACM Transactions on Sensor Networks, to appear, 2010. (IEEE INFOCOM 2008)
  - H. Luo, H. Tao, H. Ma, and S. K. Das, “Data Fusion with Desired Reliability in Wireless Sensor Networks,” *IEEE Transactions on Parallel and Distributed Systems,* to appear, 2010.
- Reprogramming: Debugging (mobile) sensor networks
  - Large scale, high density deployment, often inaccessible
  - P. De, Y. Liu and S. K. Das, “Energy Efficient Reprogramming of a Swarm of Mobile Sensors,” *IEEE Transactions on Mobile Computing, Vol. 9, 2010. (Preliminary version in IEEE PerCom 2008)*

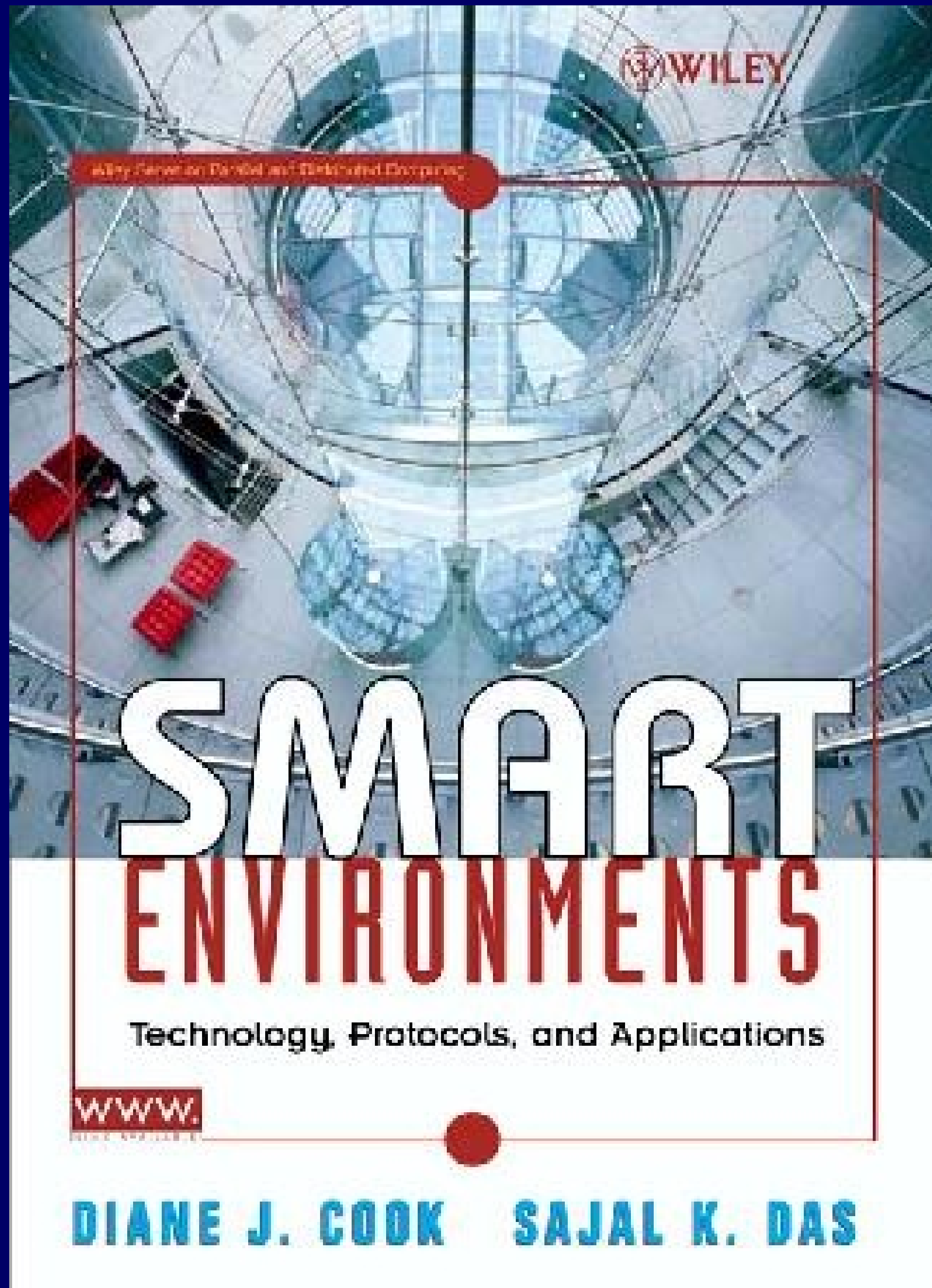
Ongoing Projects

- Performance Modeling, Localization, Information Quality on real sensor-actor test bed for data intensive applications (e.g., smart environments, health care, security)

- Modeling, analysis and decision making in the presence of ambiguous contexts and ontology – multiple contexts from one sensor, or single context from multiple sensors

- \- N. Roy, G. Tao and S. K. Das, "Supporting Pervasive Computing Applications with Active Context Fusion and Semantic Context Delivery," Pervasive and Mobile Computing, Vol. 6, No. 1, pp. 21-42, Feb 2010.

  \- N. Roy, C. Julien, and S. K. Das, "Resource-Optimized Quality-Assured Ambiguous Context Mediation in Pervasive Environments," 6th Int'l Conf on Heterogeneous Networking for Quality, Reliability, Security and Robustness (QShine'09), Spain, pp. 232-248, Nov 2009. (Best Paper Award). *IEEE Trans. on Mobile Computing*, to appear, 2010.


WILEY
SMART
ENVIRONMENTS
Technology, Protocols, and Applications
WWW.
DIANE J. COOK
SAJAL K. DAS

Smart Sensor-Actuator Systems

- **Smart** Environments: Autonomously *acquire* and *apply* knowledge about user interactions with environments (e.g., devices, networks, cyber-physical systems), and *adapt* to improve user experience *without explicit awareness*

- **Contexts:**

  - Tangible: Mobility, Activity, Switching … can be measured quantified with the help of pervasive devices/networking technologies

  - Intangible: Intent / Desire, Behavior, Mood, … how to precisely define and model them? Could they be captured via social interactions and networking? Socio-Cultural Policy and Psychology implications?

- **Context-Awareness: Major Issues**

  - Early Detection and semantic interpretation of sequences of contexts, leading to **situations** (or crisis) even in the presence of noisy sensor readings and uncertain information

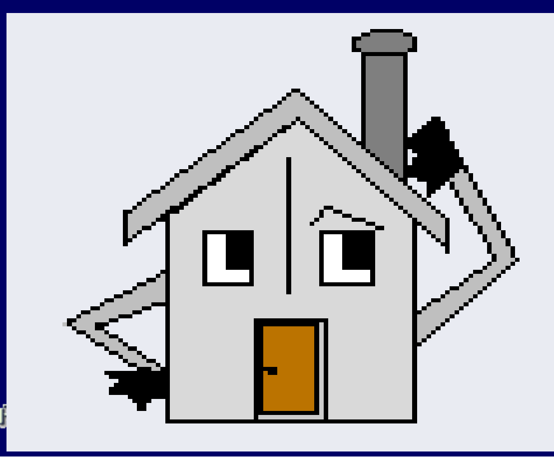
  - Context Quality and Disambiguation, Context Privacy / Anonymity

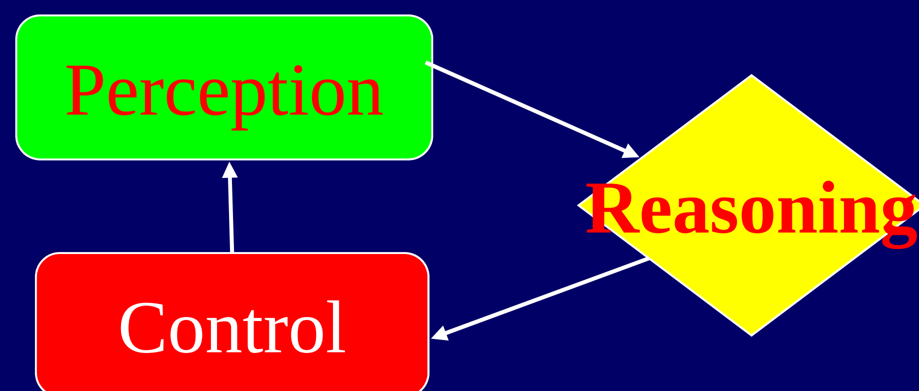
Research Challenges

- Sensing / Perception: How to unambiguously perceive state of the (uncertain) environment, and extract meaningful contexts/situations by fusing spatio-temporal information from heterogeneous sources for dynamically evolving scenarios?

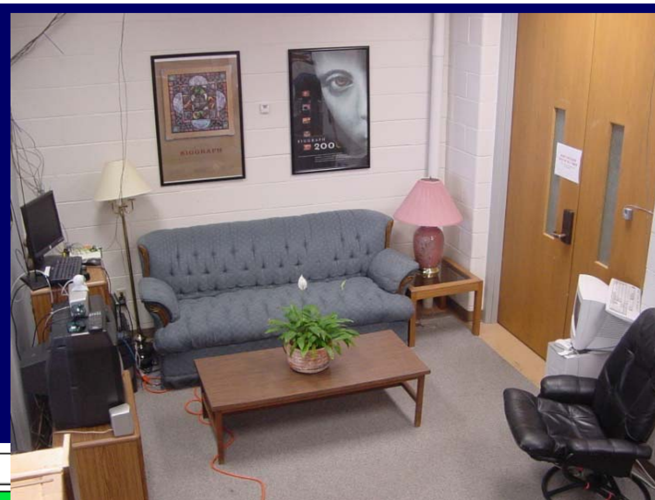
- Reasoning: How to understand, analyze (reason about), and “correlate” seemingly unrelated events w/o external knowledge and “discover” hidden links and patterns? How to learn and predict potential anomalies (e.g. threats) with minimum false positive or false negatives?

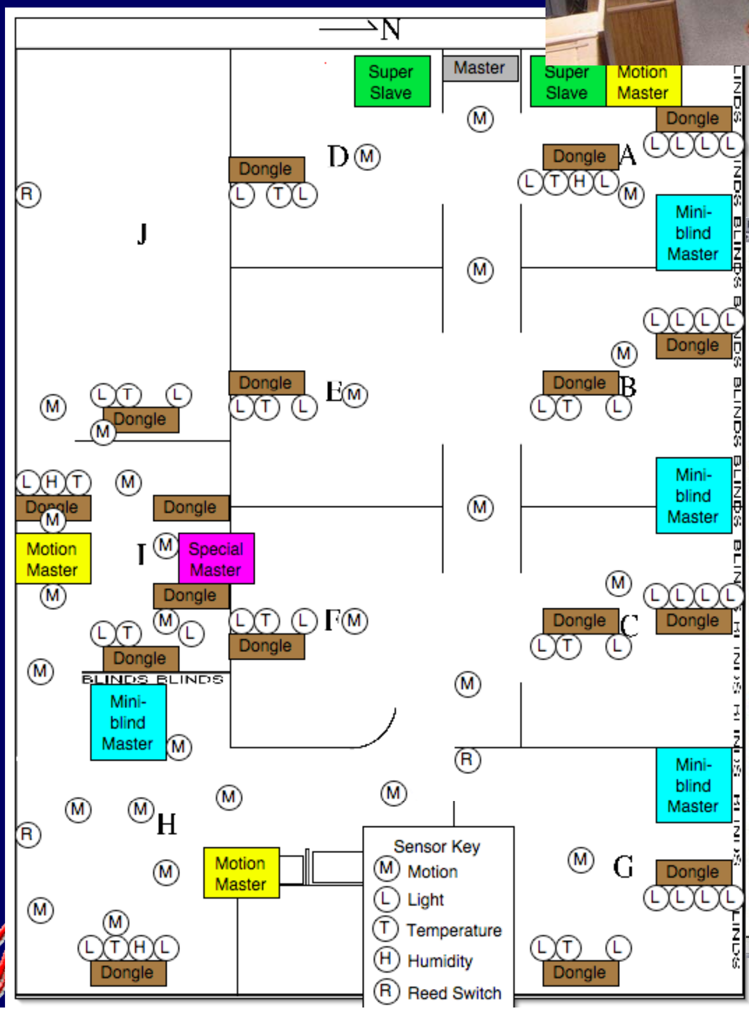
- Decision Control: How to make adaptive (robust), intelligent decisions to take pro-active actions?

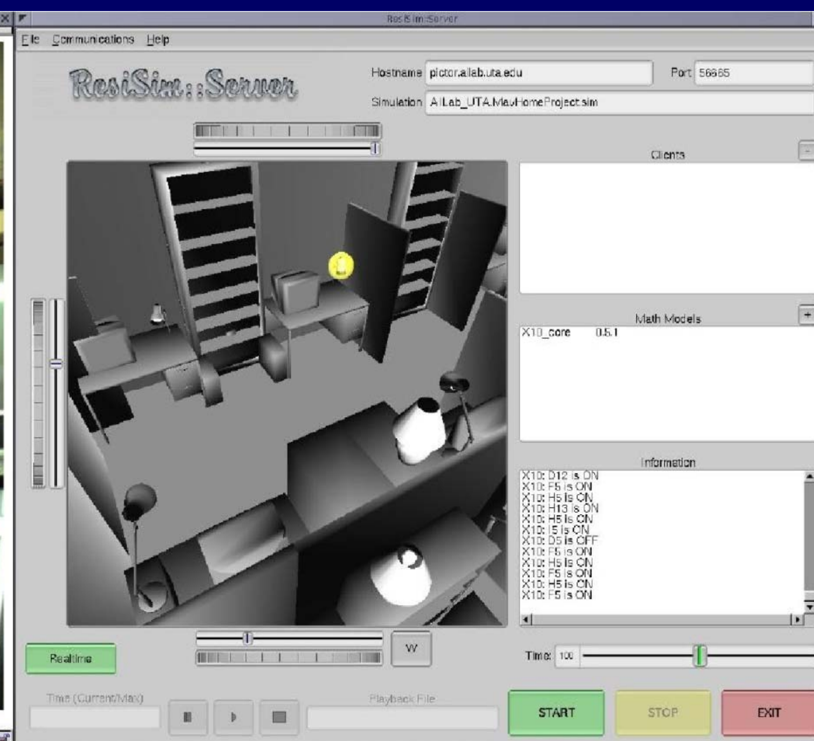




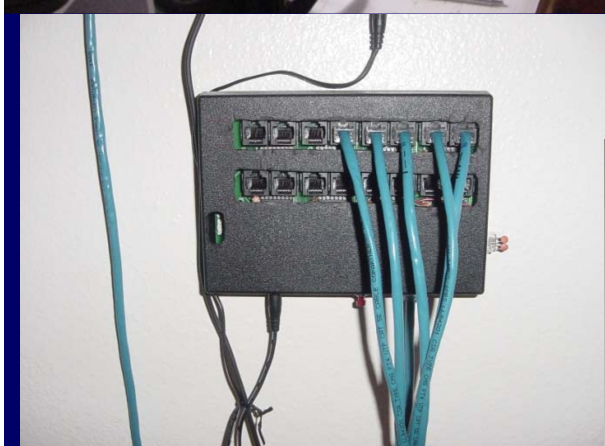
MavLab




N
Super Slave
Master
Motion Master
Dongle
Mini-blind Master
Special Master
BLINDS
Sensor Key
M Motion
L Light
T Temperature
H Humidity
R Reed Switch

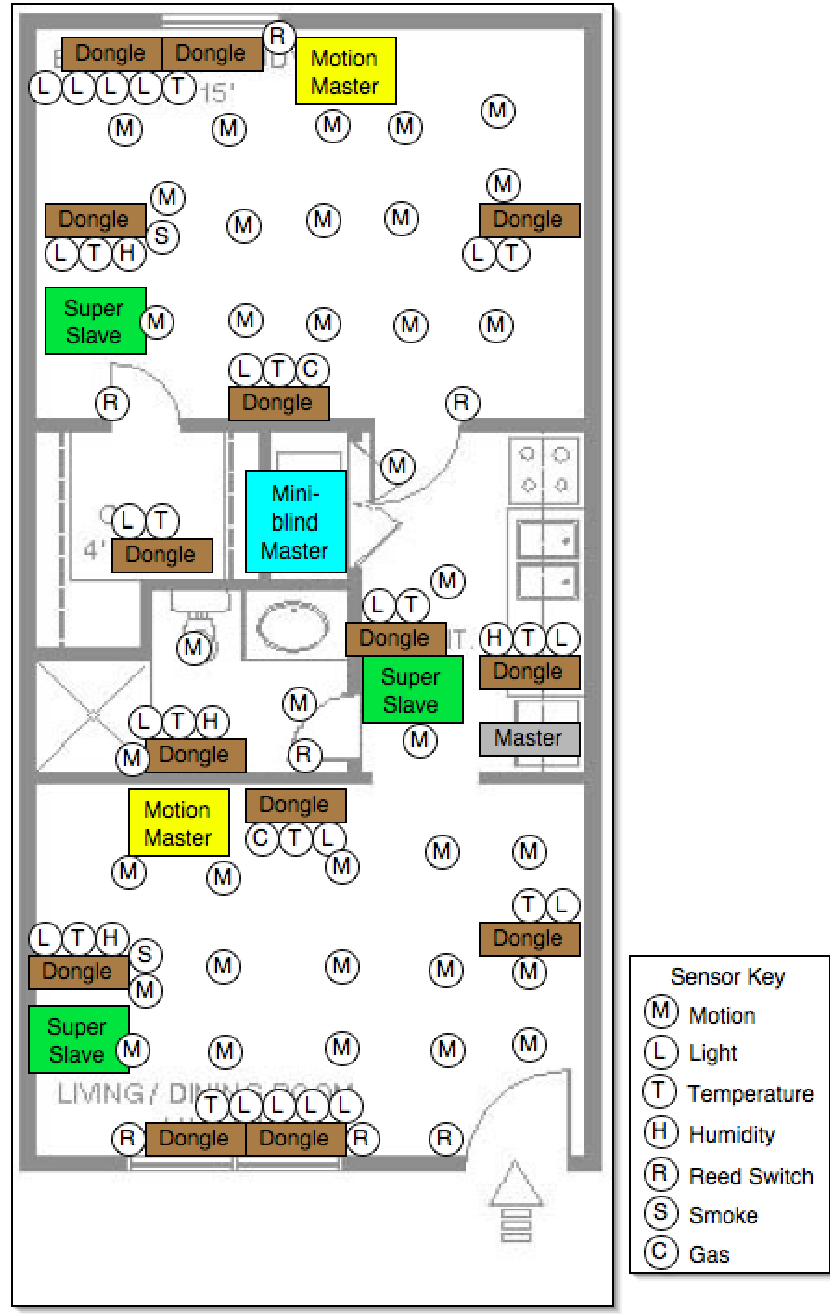

ResiSim::Server
Hostname
Port
Simulation
Clients
Math Models
Information
Realtime
START
STOP
EXIT

MavPad: Smart Dorm Apartment



MavPad Environment

- **Sensors**
  - **Motion, light, temperature, humidity, door, water leak, smoke, CO2**
- **Controllers**
  - **Lights, fans, TV, receiver, mini-blinds, HVAC, diffusers**



Publications in Smart Environments

- D. J. Cook and S. K. Das, *Smart Environments: Technology, Protocols and Applications*, John Wiley, 2005.
- A. Roy, S. K. Das and K, Basu, "A Predictive Framework for Location Aware Resource Management in Smart Homes," *IEEE Transactions on Mobile Computing*, Vol. 6, No. 11, pp. 1270-1283, Nov 2007.
- D. J. Cook and S. K. Das, "How Smart Are Our Environments? An Updated Look at the State of the Art," *Pervasive and Mobile Computing* (Special Issue on Smart Environments), Vol. 3, No. 2, pp. 53-73, Mar 2007.
- S. K. Das, N. Roy and A. Roy, "Context-Aware Resource Management in Multi-Inhabitant Smart Homes: A Framework Based on Nash H-Learning," *Pervasive and Mobile Computing* (Special Issue on IEEE PerCom 2006 Selected Papers), Vol. 2, No. 4, pp. 372-404, Nov. 2006.
- S. K. Das, D. J. Cook, A. Bhattacharya, E. Heierman, and J. Lin, "The Role of Prediction Algorithms in the MavHome Smart Home Architecture," *IEEE Wireless Communications* (Special Issue on Smart Homes), Vol. 9, No. 6, pp. 77-84, Dec 2002.

New Directions and Paradigms

- *Consumer Sensing*: Sensor enabled mobile phones
- *Ubiquitous Connectivity*: Internet of things
- *Persuasive Sensing*
- *Participatory, Personal, Social Sensing:* User-centric or Opportunistic
  - Recreational sports, healthcare, gaming
  - Integration of sensing with mobile social networks
  - Energy, environment, green ICT, zero carbon networking

Emerging Research Challenges

- Science of Socio-Sensing Systems
- Architectures at Scale
- Human Interaction Models
- Security, Privacy, Trust
- Inter-disciplinary Research:
  - Sensing and networking
  - Data management and mining
  - Machine learning
  - Feedback control
  - Psychology, social and cognitive science

Epilogue

*"*A *teacher* can never truly teach unless he is still learning himself. A lamp can never light another lamp unless it continues to burn its own flame. The teacher who has come to the end of his subject, who has no living traffic with his knowledge but merely repeats his lesson to his students, can only load their minds, he cannot quicken them".

Rabindranath Tagore (Nobel Laureate, 1913)

Call for Papers

IEEE PerCom 2011 + IQ2S 2011

9th IEEE International Conference on Pervasive Computing and Communications

+

3rd Workshop on Information Quality and QoS in Wireless Sensor Networks (IQ2S)

March 20-24, 2011

Seattle, Washington

www.percom.org + www.iq2s.org

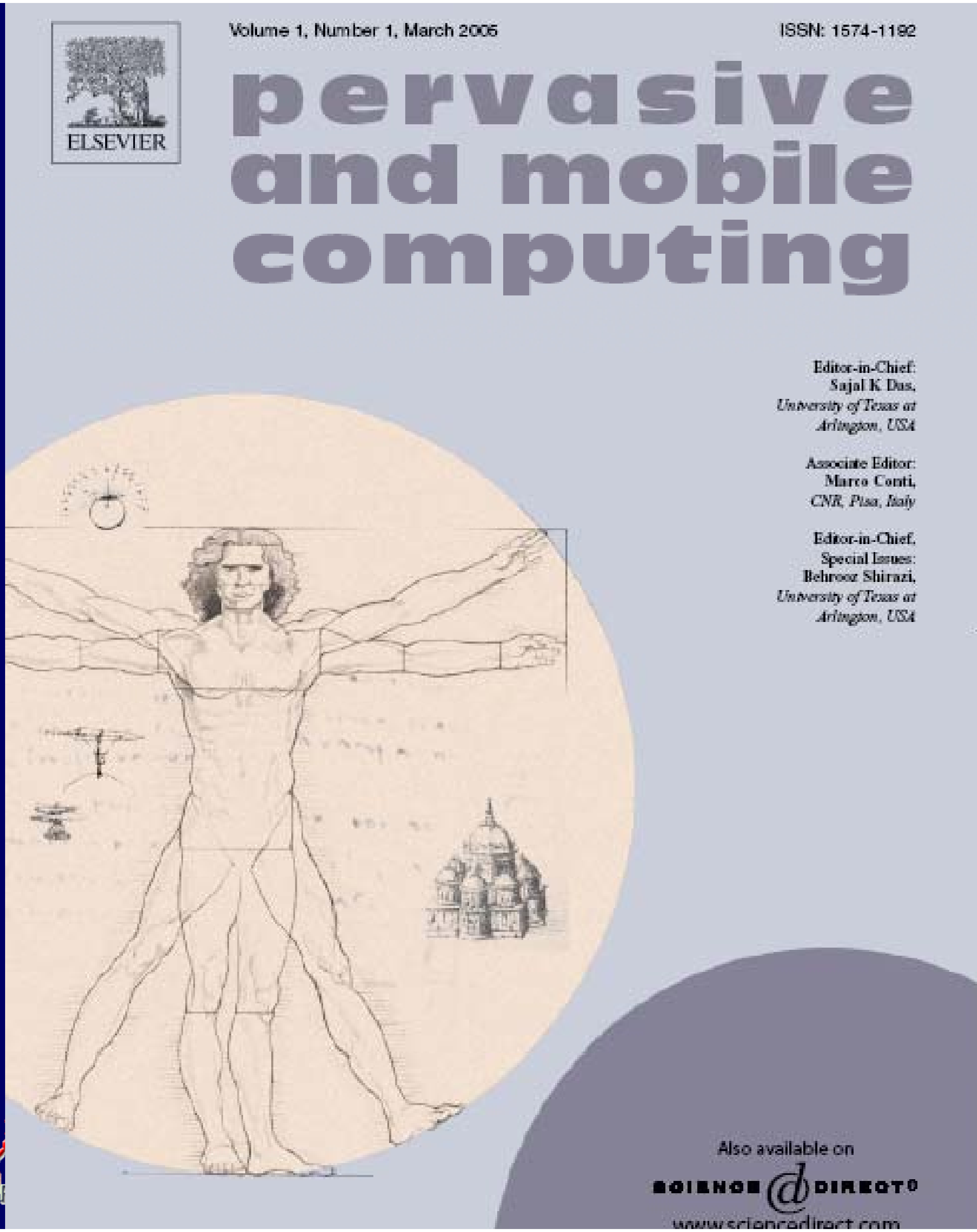
Call for Papers

IEEE WoWMoM 2011

13th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks

June 21-24, 2010
Lucca, Italy

www.ieee-wowmom.org



www.elsevier.com/locate/pmc