Wireless Sensor Networks: New Capabilities and Potentials

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Networked Embedded Computing

Microsoft Research

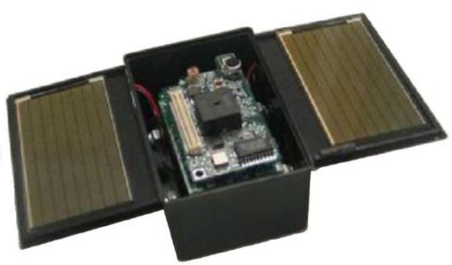
Based on research carried out at: UCLA Microsoft Research

Three New Capabilities

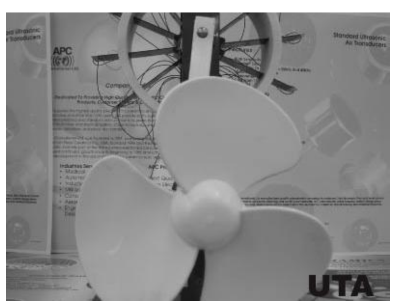
Performance Issue	New Capability
ENERGY SCARCITY	Harvest from Environment
SENSING RESOLUTION	Low Complexity Controlled Motion
DEPLOYMENT	Peer Production

Energy Harvesting

- Energy aware algorithms extend battery life: but battery size is **finite**
- Harvesting from environment: **infinite** energy
  - Power is finite

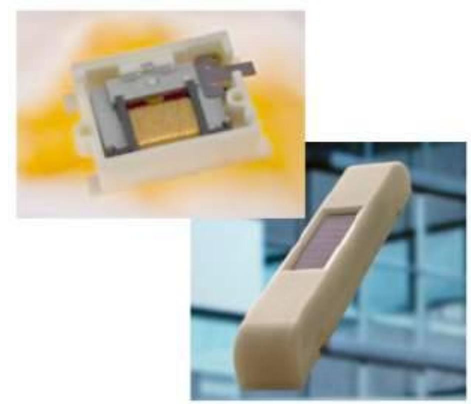


Heliomote (Solar, UCLA) 2003



Piezoelectric Windmill (Wind, UT Arlington) 2004

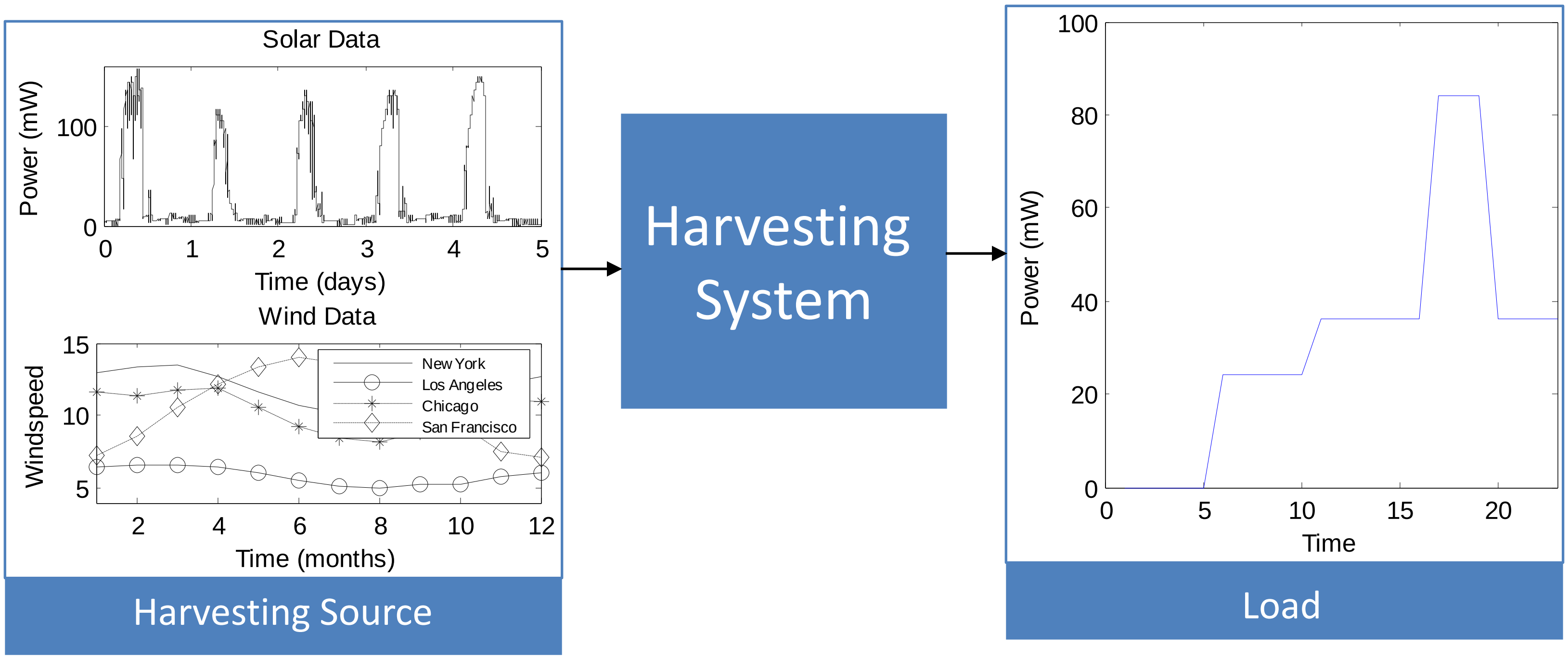
Trio/Prometheus (Solar, UC Berkeley) 2005



EnOcean (Solar/Mechanical) Commercial

Harvesting Issues

- Harvested power level varies in time
  - independent of energy usage profile
- Solution: match consumption to production



Harvesting Theory

- Energy buffer: size B, efficiency η, leakage P_{leak}
- Harvested source power $P_s(t)$, Load power $P_c(t)$

Energy conservation

$$B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{leak}(t)dt \geq 0 \quad \forall T \in [0, \infty)$$

Battery size limitation

$$B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{leak}(t)dt \leq B \quad \forall T \in [0, \infty)$$

where: $[x]^+ = x$ if $x>0$, 0 otherwise

Performance Guarantee

- Definition:

$P(t)$ is called (ρ,σ_1,σ_2) if

$$\int_{\tau}^{\tau+T} P(t)dt \leq \rho T + \sigma_1$$
$$\int_{\tau}^{\tau+T} P(t)dt \geq \rho T - \sigma_2$$

For all positive T and τ

(Modeling "burstiness")

- **Theorem:** If $P_s(t)$ is $(\rho_1,\sigma_1,\sigma_2)$ and $P_c(t)$ is (ρ_2,σ_3), then energy neutrality can be achieved for

$$\rho_2 \leq \eta\rho_1 - \rho_{leak}$$
$$B_0 \geq \eta\sigma_2 + \sigma_3$$
$$B \geq B_0$$

Proof: "Power Management in Energy Harvesting Sensor Nodes", *ACM Trans. Embedded Computing Systems.*

Designing Practical Systems

What battery size to use?

- Directly calculate from theorem

Adapt performance at each node

- maximize performance at energy neutrality

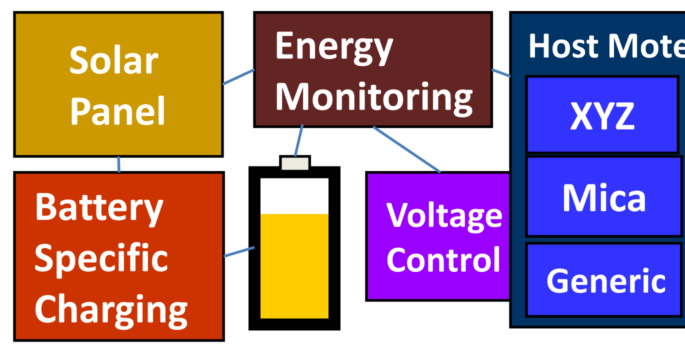
Adaptation across network

- Adapt workload allocation to spatio-temporal harvesting profile

Experimental Harvesting Node

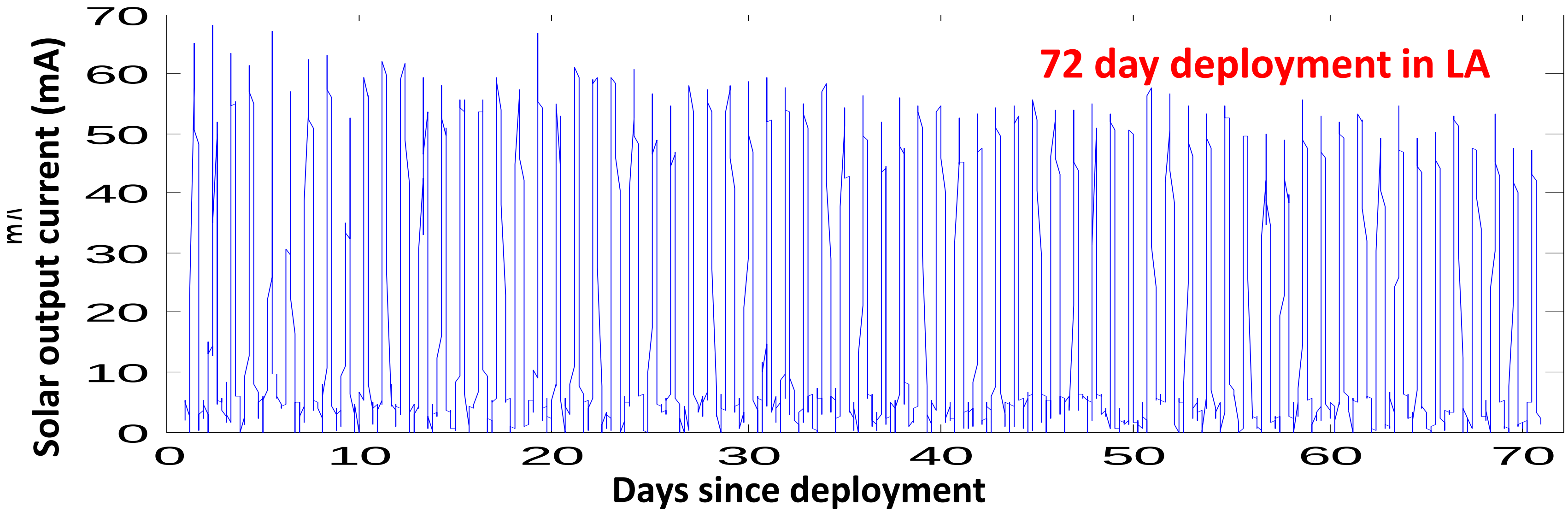
- Hardware Design
  - Maximal power point matching for solar cell
  - Storage management
    - Technology: NiMH vs Li+ vs. ultracapacitor
    - Switching between battery and solar cell
  - Energy **measurement interface** for adaptive algorithms
- Heliomote v2
  - Fully autonomous (no dependence on host mote), >80% efficiency
  - Deployed by many research groups
  - Commercially available [ATLA Labs]

Heliomote v2. UCLA 2005

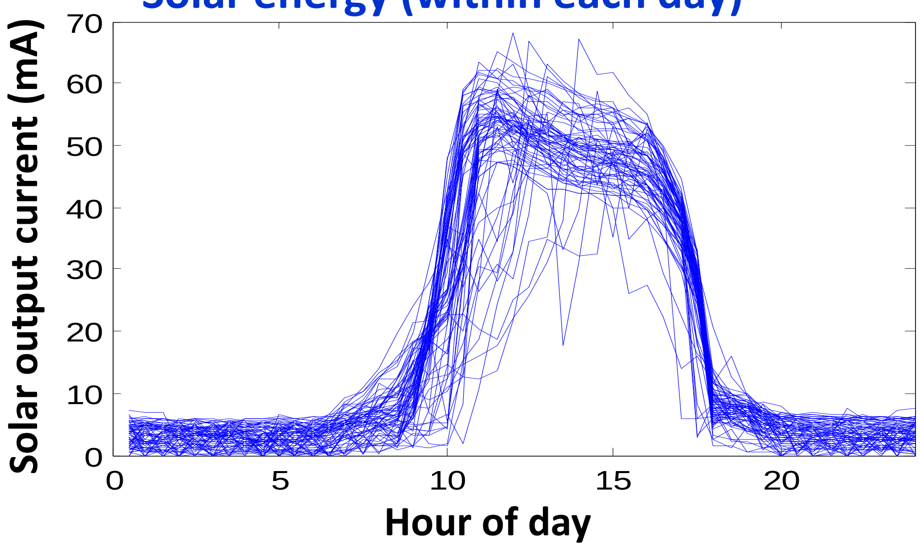


Details: "Design considerations for energy harvesting wireless embedded systems", ACM/IEEE IPSN, 2005.

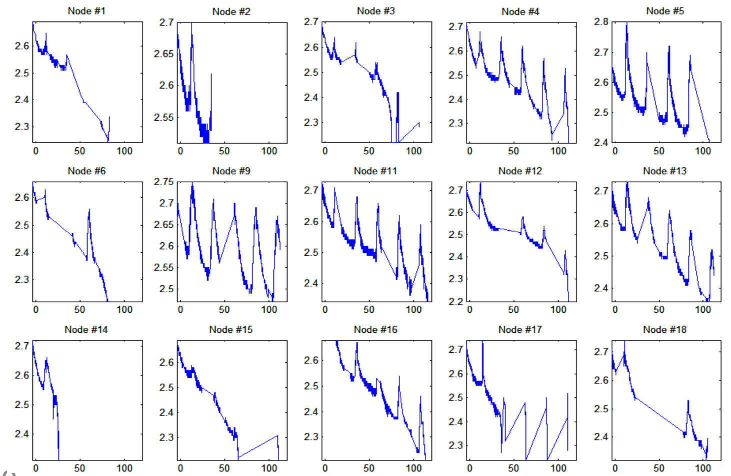
Observed Harvesting Opportunity



Solar energy (within each day)



Multiple nodes, 1 week



Real Time Adaptation

- Change duty cycle, D, to control consumption
  - Higher duty cycle has higher utility

Maximize utility over time window N_W

$$\max \sum_{i=1}^{N_w} D(i)$$

Subject to

(1) Energy conservation

$$B(i)-B(i+1)=\Delta T D(i)\left[P_c-P(i)\right]^{+}-\eta\Delta T P(i)\left\{1-D(i)\right\}-\eta T D(i)\left[P(i)-P_c\right]^{+}$$

(2) Energy neutrality over N_w

$$B(1)=B_0$$

$$B(N_w+1)=B_0$$

B(i) > 0

Embedded Algorithm

Predict availability over N_w

$E^k(i+1)=a*E^k(i)+(1-a)*E^k_{av}$

↓

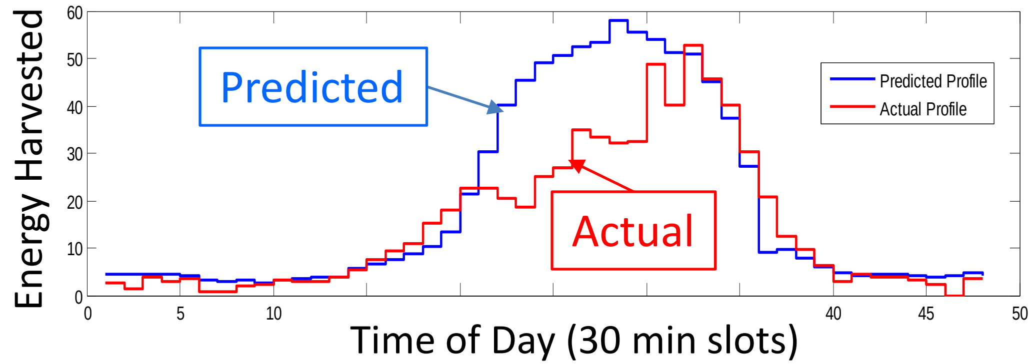
Allocate duty cycles over N_w

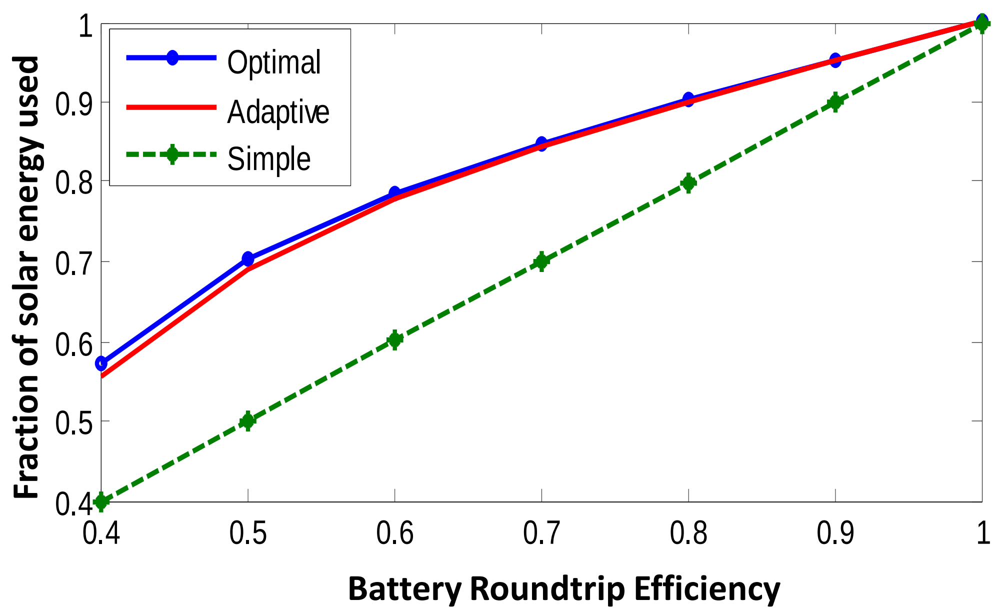
Exploit structure to solve LP

↓

Adapt to energy harvested

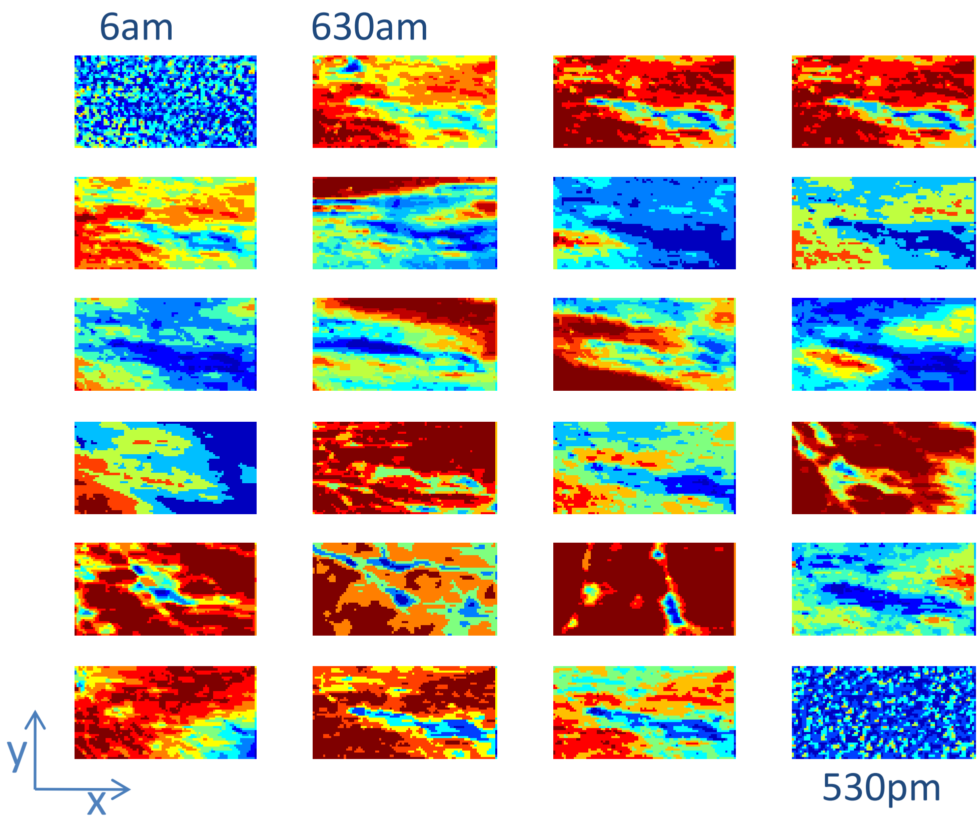
Actual varies from predicted





Algorithm: "Adaptive Duty Cycling for Energy Harvesting Systems", ISLPED 2006.

Harvesting in a Network

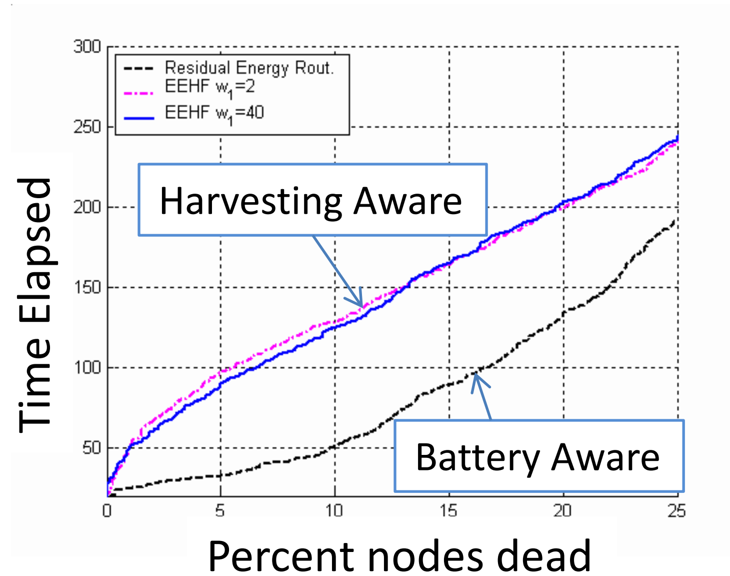


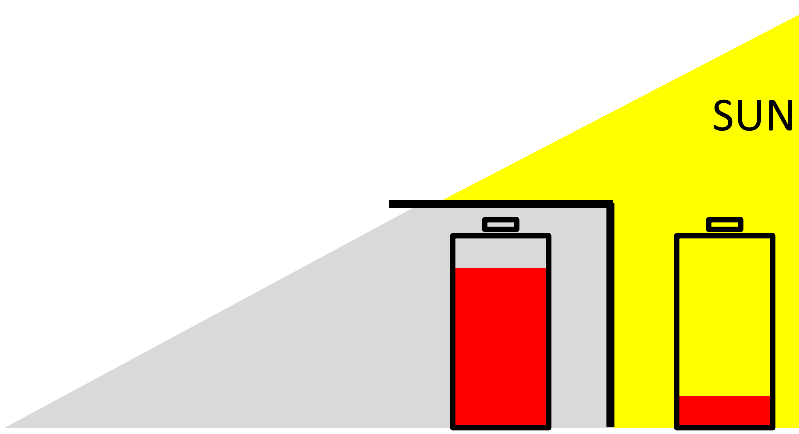
Spatial harvesting opportunity,
at different times of day
(a region in James Reserve, CA)

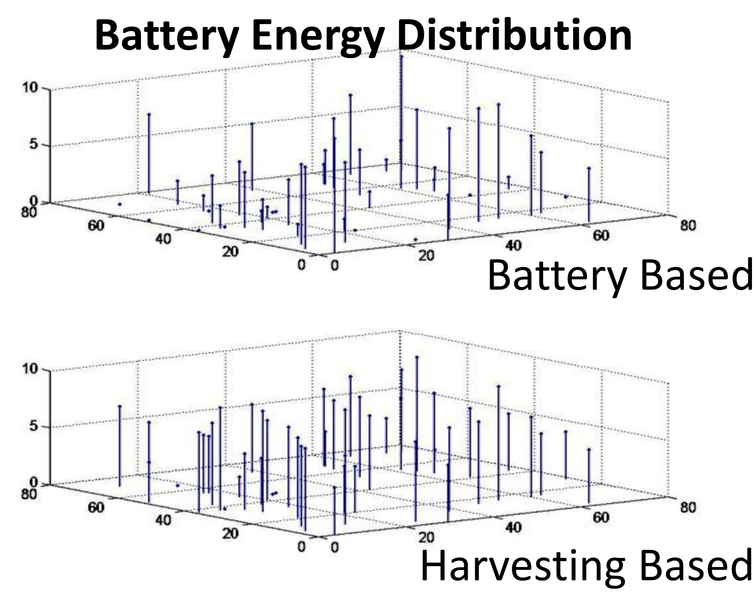
- Example: **Routing**
  1. Field monitoring
     - Data transmission load dominates
  2. Event detection
     - Listen mode energy dominates

Field Monitoring

- Routing based on harvesting potential
  - Include current battery level to avoid short term failure



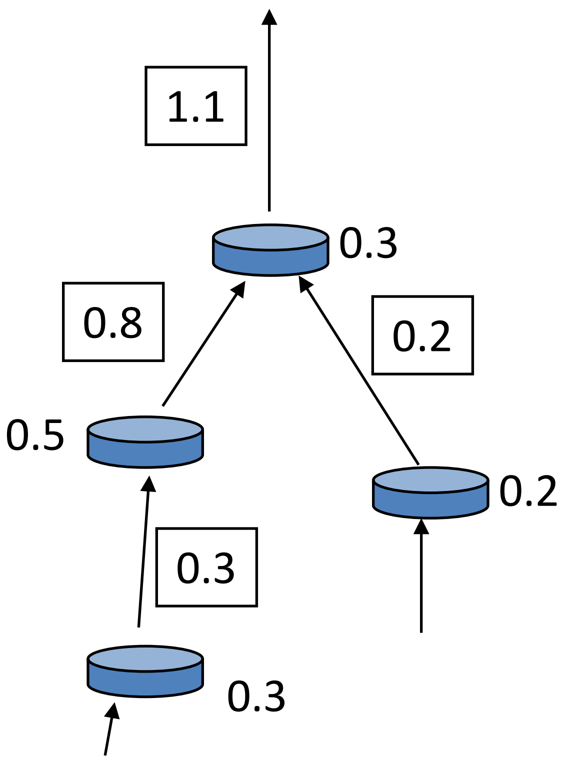


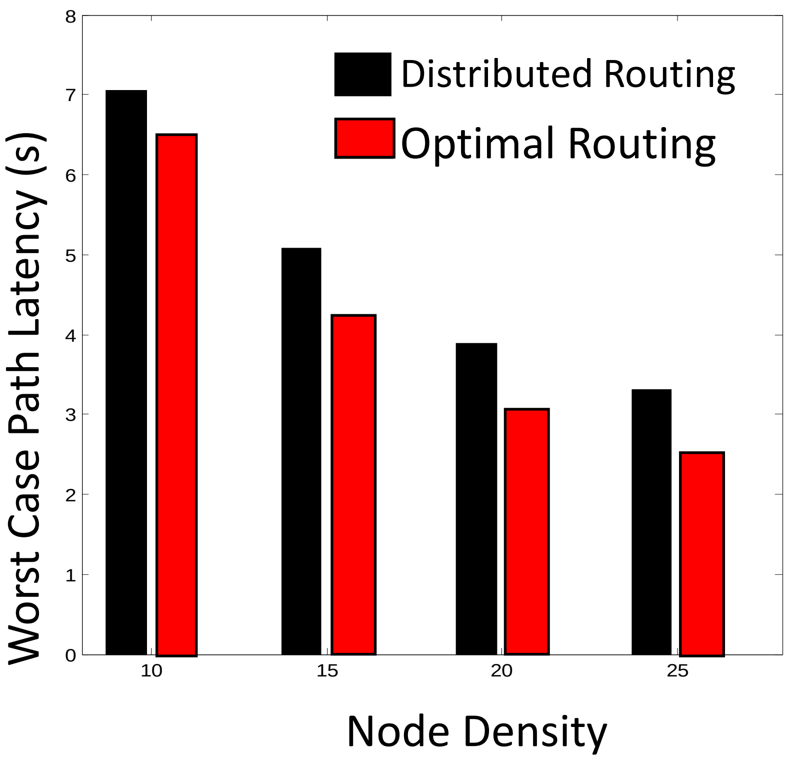


Details: "An environmental energy harvesting framework for sensor networks", ACM/IEEE ISLPED, 2003.

Event Detecting Network

– Energy neutral duty cycle: latency sensitive routing
  - Distributed algorithm to discover best route to base
    – Without exchanging all link costs





Details: "Performance Aware Tasking for Environmentally Powered Sensor Networks", ACM SIGMETRICS, 2004.

Three New Capabilities

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SENSING RESOLUTION	Low Complexity Controlled Motion
DEPLOYMENT	Peer Production

Coverage Resolution

Coverage: Total extent of sensing (area, volume)

Resolution: sensor capability (pixels)

15 pixels/m

1MP aggregate sensing resource

200 pixels/m

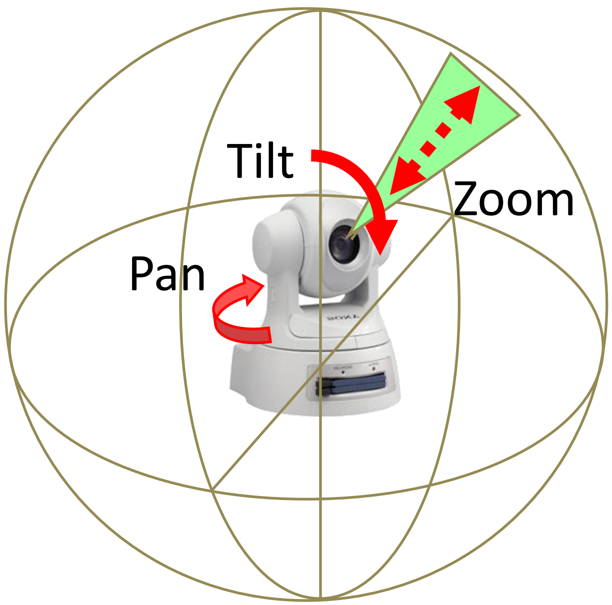
784MP aggregate sensing resource

Mobility

- Mobility useful when static network cannot achieve required coverage resolution
  - Eg. If the space, bandwidth, management resource, or cost for 784MP is not justified for given application
- Mobility helps by:
  - Adaptively allocating sensors where needed
  - Minimizing overlap and occlusions
- Key Trade-off: Motion delay
  - Depends on number of sensors

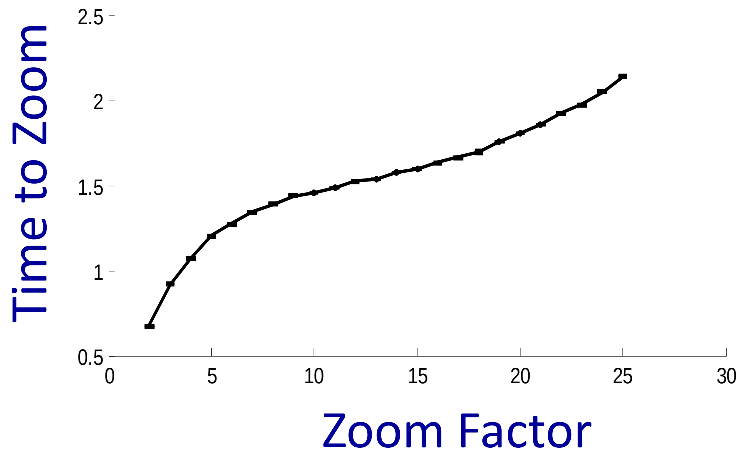
Low Complexity Motion: *Motility*

- Navigational ease
- Low energy
- Feasible in tethered nodes
- Low delay

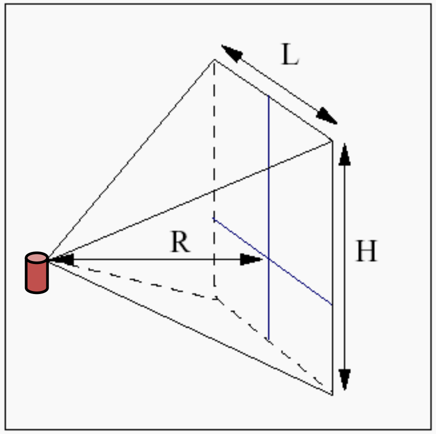


Motion delay for Sony SNC RZ 30N

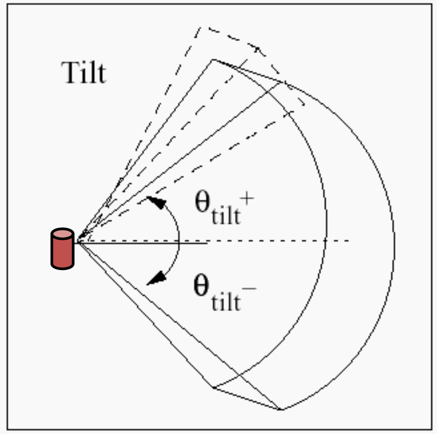
Actuation	Range	Speed
Pan	340º	170º/s
Tilt	115º	77º/s
Zoom	25X	See plot



Motility Advantage

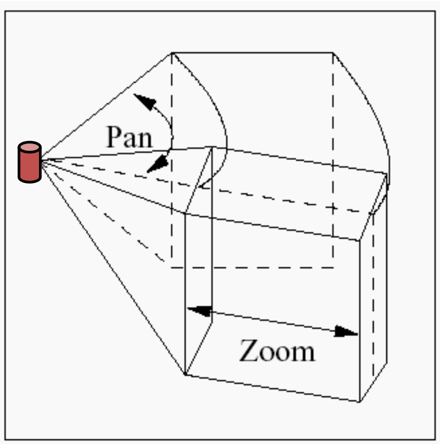


1. Coverage Model

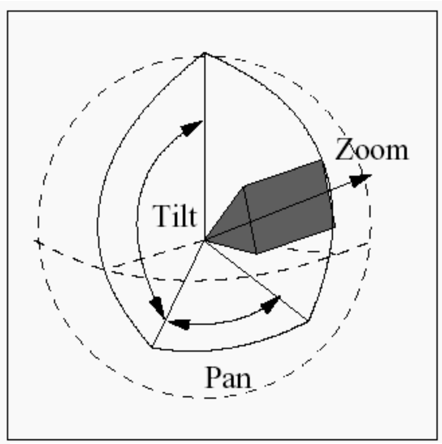


2. With Tilt

$$g_{pzt} = (3z-2) + \frac{\theta_{tilt}R}{2Hl}(3z^2+1) + \frac{\theta_{pan} z^3 R^2 (1-\cos\theta_{tilt})}{LHl^2} + \left[\frac{cos\theta^-_{tilt} + cos\theta^+_{tilt}}{2L}\right]\frac{\theta_{pan}R}{2l}(3z^2+1)$$



3. Pan and Zoom

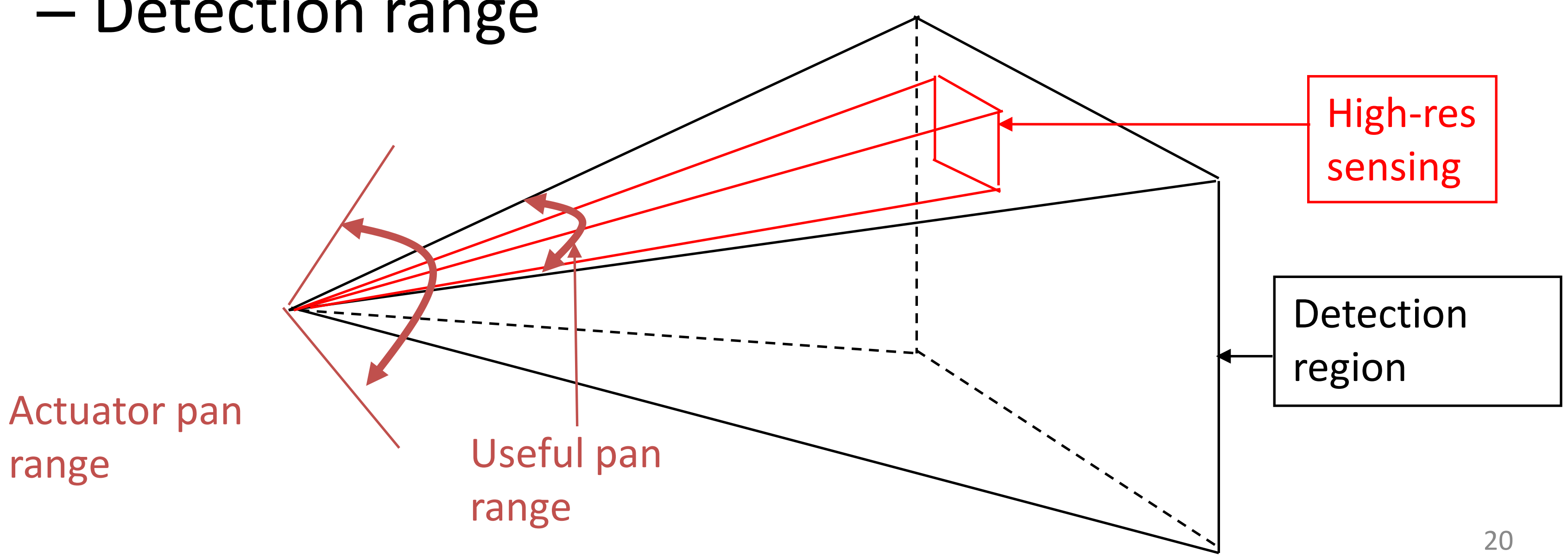


4. Pan, Tilt, Zoom

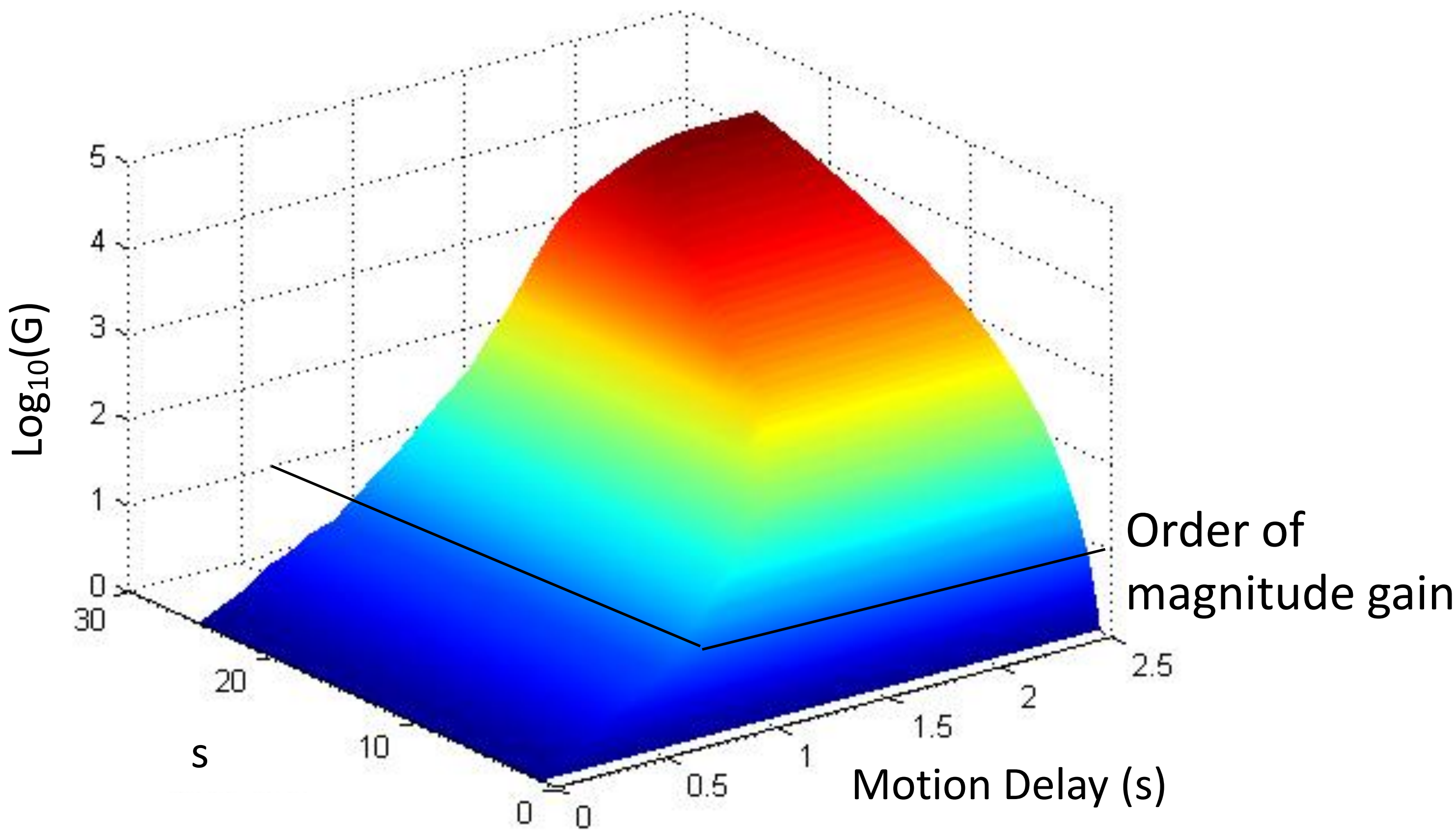
Pan	7.74
Tilt	4.04
Zoom	73
Pan and Zoom	6361
Pan, Tilt and Zoom	226940

Practically Achievable Advantage

- Detect at low res., then sense at high res.
  - Ratio of coverage resolutions: s
- Range of allowed motion limited by
  - Tolerable motion delay
  - Detection range



Practically Achievable Advantage



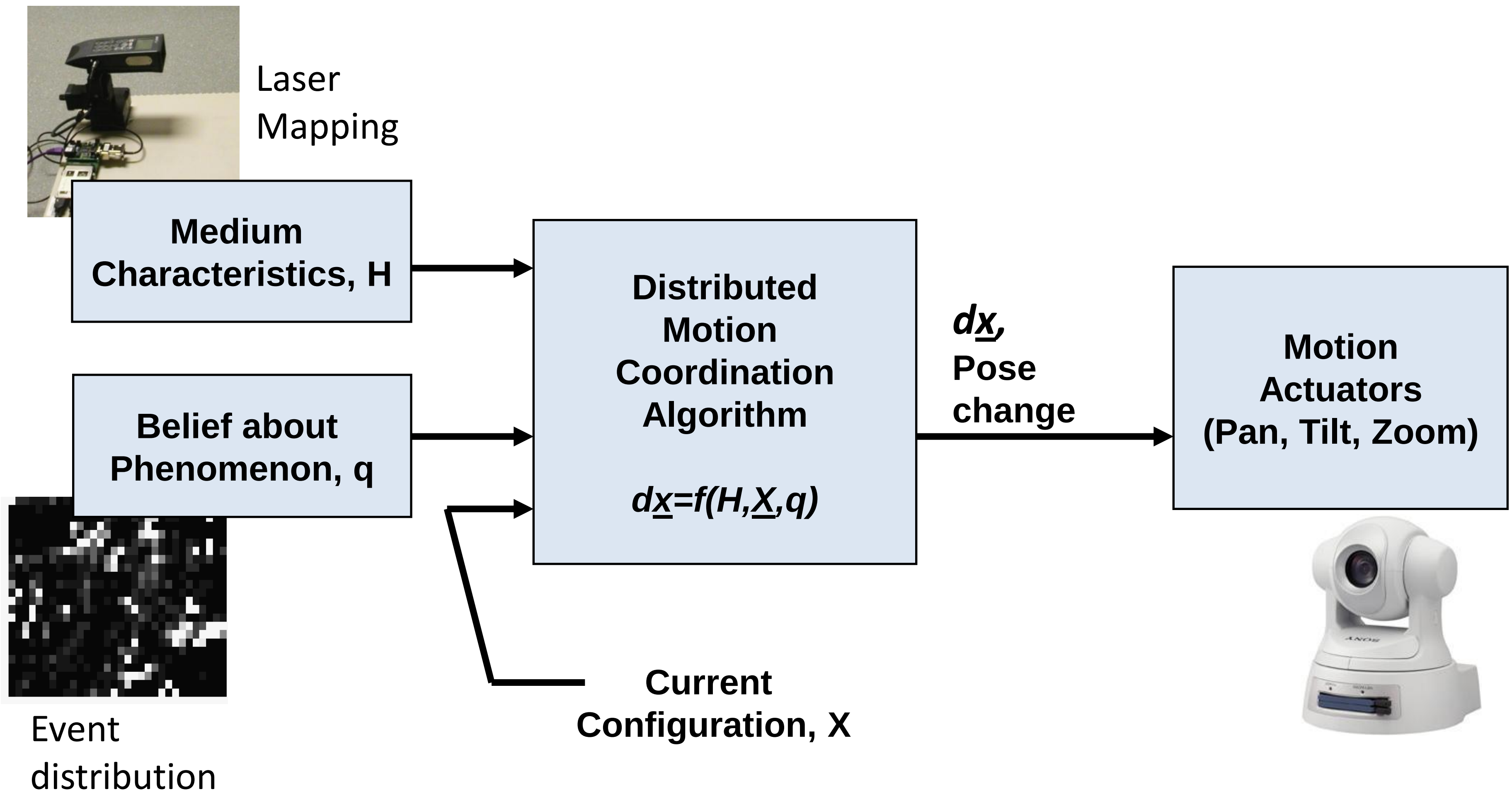
Advantage in a network: "Reconfiguration Methods for Mobile Sensor Networks," *ACM Transactions on Sensor Networks*

Coordination Algorithm

1. **Proactive Phase:** Minimize delay to create a semblance of hi-density deployment
   - Place network in a pose from where responding to sensing demands is quick

2. **Reactive Phase:** Control motility based on real time dynamics
   - Event based
     - Eg: Surveillance - high resolution coverage on intruders
   - Query based
     - Eg: Live view of planet - metro regions may be more queried

Proactive Phase Coordination



Proactive Phase Performance Metric

1. Motion delay
   - Let $\tau(p)$ be the delay to actuate (pan,tilt,zoom) in to point p in covered region:

$$\tau(p) = max\{\delta\theta_p * \omega_p, \delta\theta_t * \omega_t, t_p(\delta_z)\}$$

2. Detection quality, $c(p)$
   - Obstacles (available line of sight), resolution

3. For each point in covered region
   - Linear combination, weight depends on application

$$f(p) = w * c(p) + (1 - w)\frac{1}{\tau(p)}$$

Multiple Sensors, Multiple Points

- For each point consider best camera covering it
  - One that yields highest *f(p)* at *p*
- Weighting by event probability, ***q(p)***

$$u(p) = f(p) * q(p)$$

- Sensing utility of a given network configuration
  - Given area A and pose of each node $\boldsymbol{S}_i = \{pan_i, tilt_i, zoom_i\}$

Optimization Objective

$$U(\mathbf{S}) = \sum_{p \in \mathcal{A}} u(p)$$

Optimization search space:

$$\mathcal{S} = \mathcal{S}_1 \times \mathcal{S}_2 \times \ldots \times \mathcal{S}_N$$

Distributed Algorithm

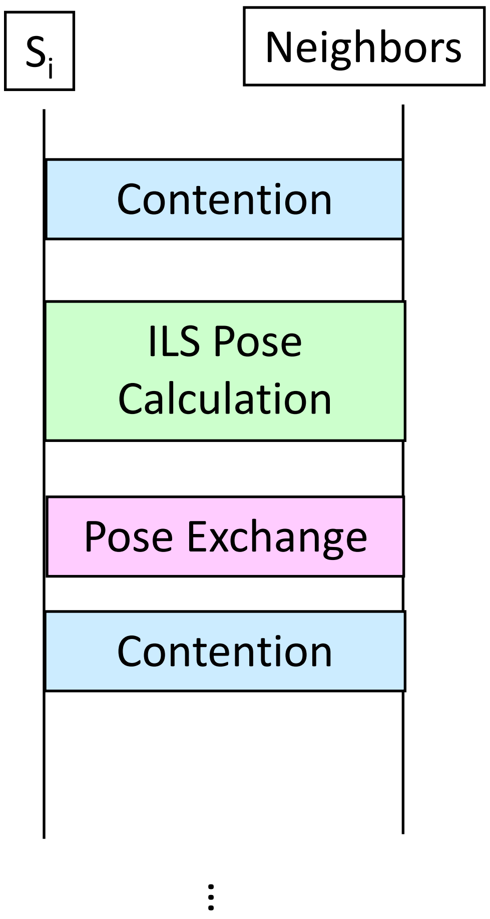
- $U(\mathbf{S})$ can be partitioned such that each sensor i can evaluate the component of utility metric, U_i, affected by sensor i
  - Sensors which affect U_i from any pose are in set ω_i
- Incremental Line search (ILS):
  - When $\boldsymbol{i}$ moves, sensors in ω_i stay static, other sensors may move
    - Sensor $\boldsymbol{i}$ knows configuration of all sensors in ω_i
  - Sensor $\boldsymbol{i}$ chooses configuration $\boldsymbol{S}_i$={p,z,t} to maximize utility locally

$$\theta_p(i) = \max_{\theta_p \in [\theta_p^{min}, \theta_p^{max}]} U_i$$

(for pan angle)

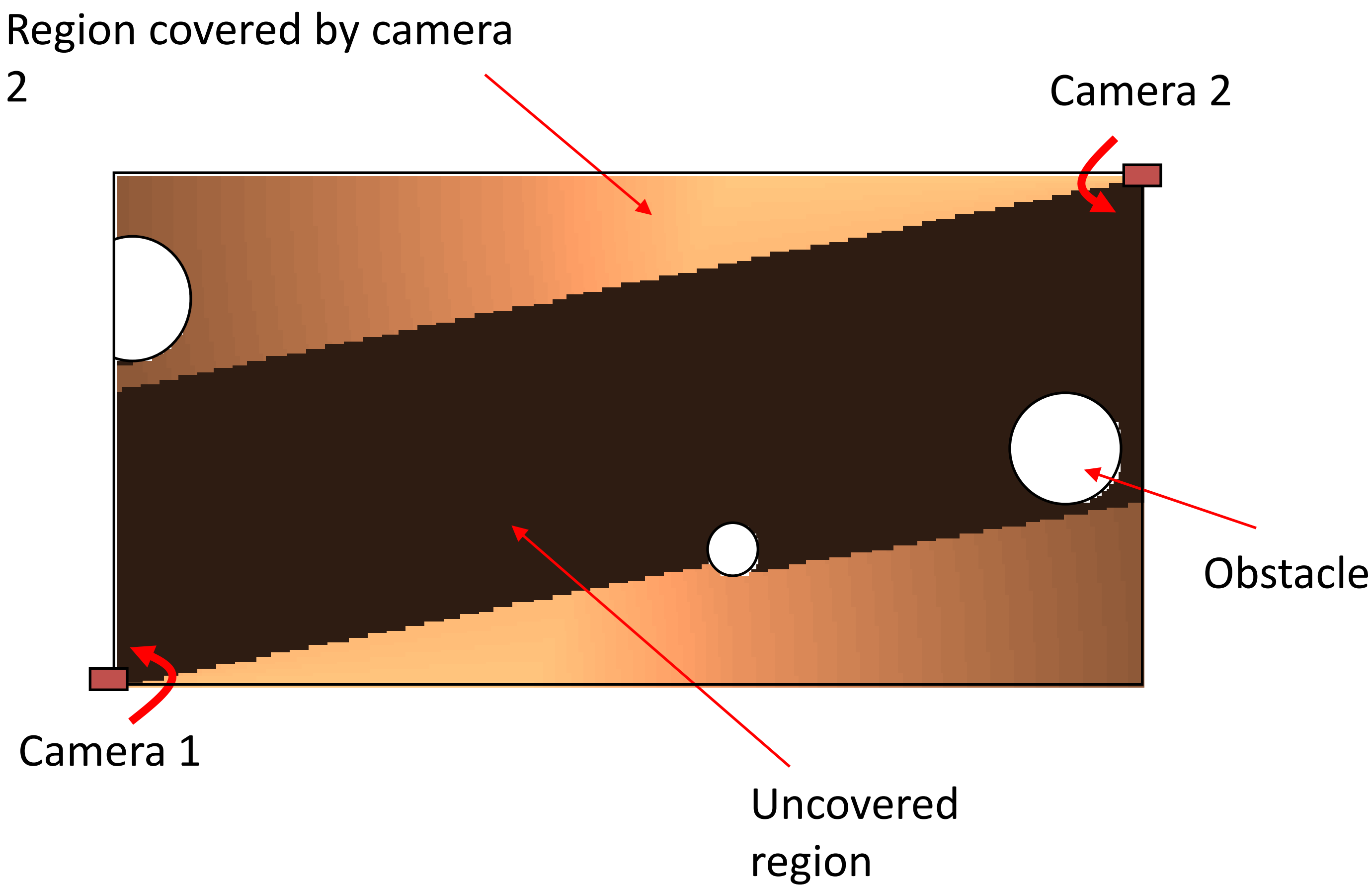
Protocol to Implement ILS

- Local Communication
  - Discover set ω_i based on location
  - Assume reliable message delivery to neighbors
- Coordination of motion within ω_i
  - Randomized contention: select moving sensor
    - Random wait and transmit Request To Update (RTU)
    - If no CONFLICT, RTU successful
  - Execute ILS to choose pose update
    - Transmit Update Finish (UF): informs neighbors of selected sensor pose



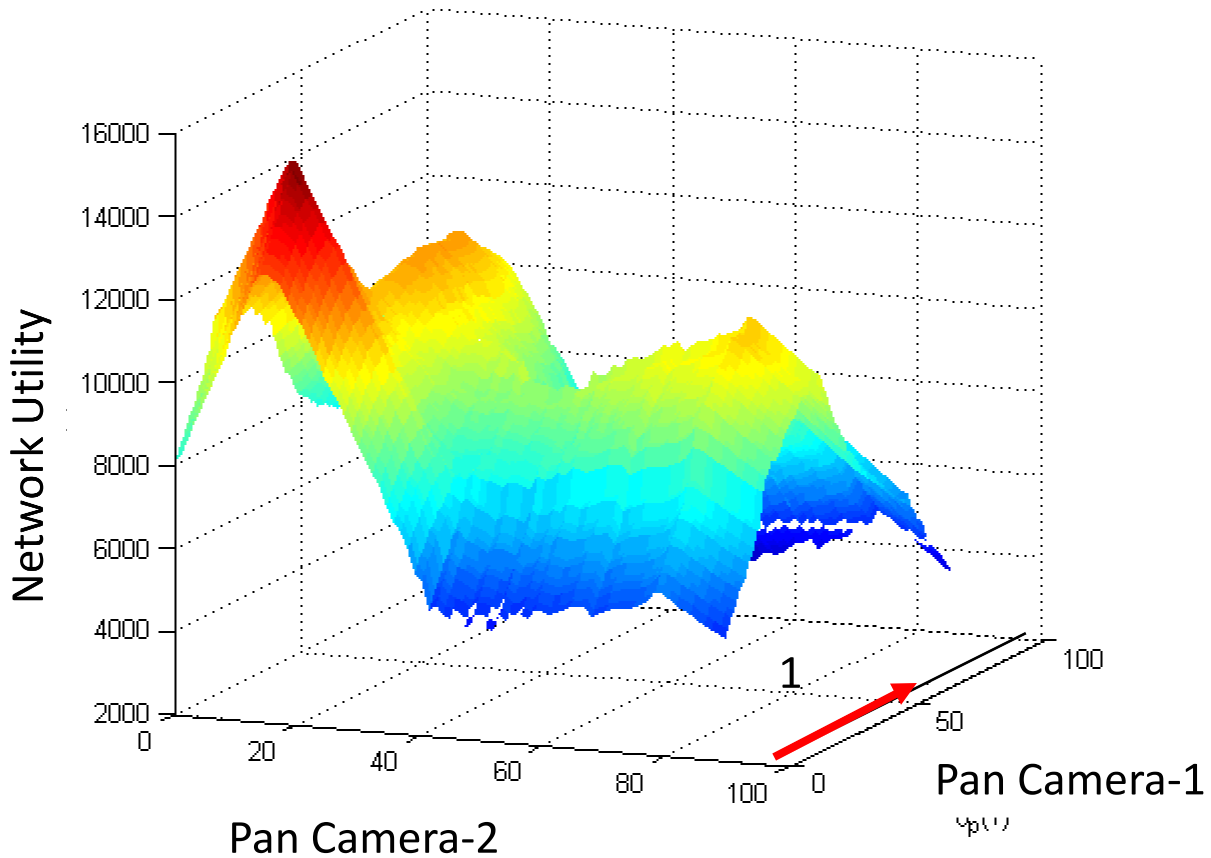
Algorithm details: "Virtual High Resolution for Sensor Networks," *ACM SenSys 2006.*

Visualizing ILS

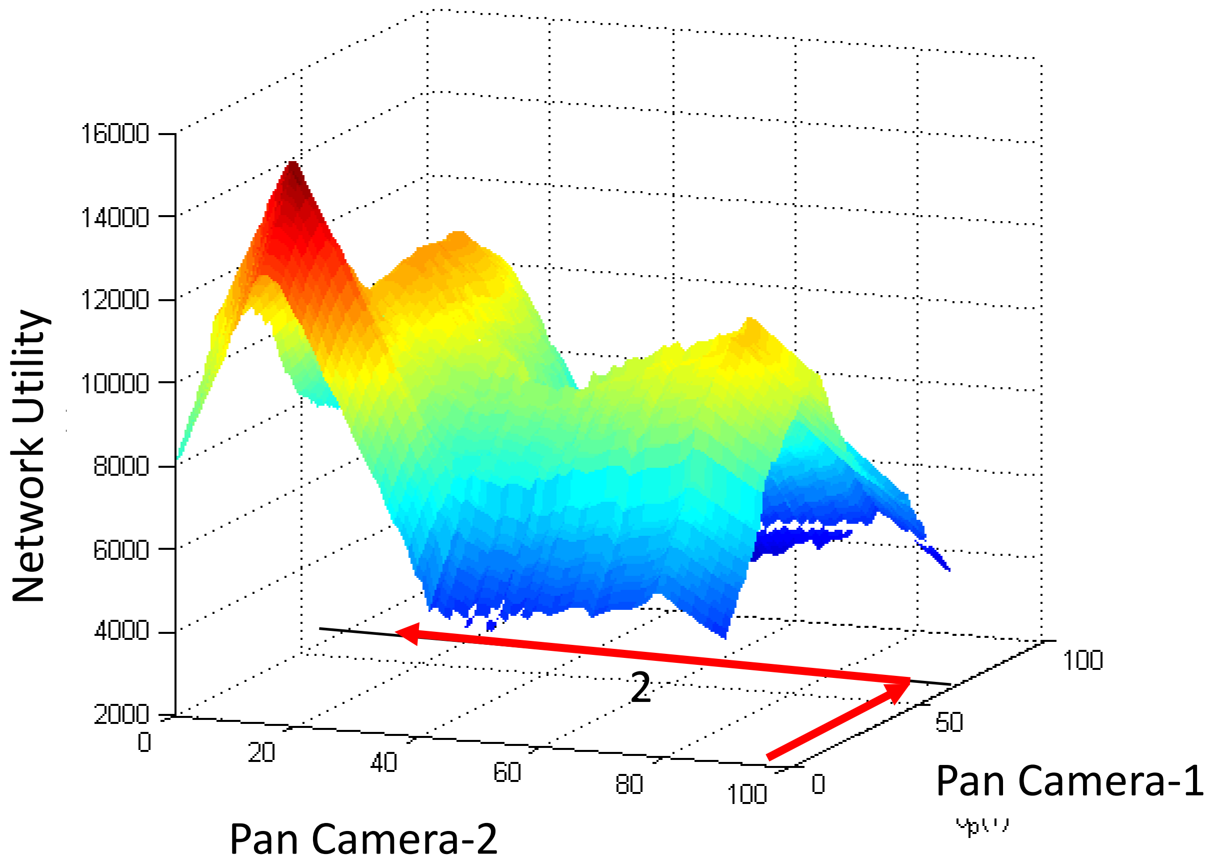


Visualizing ILS

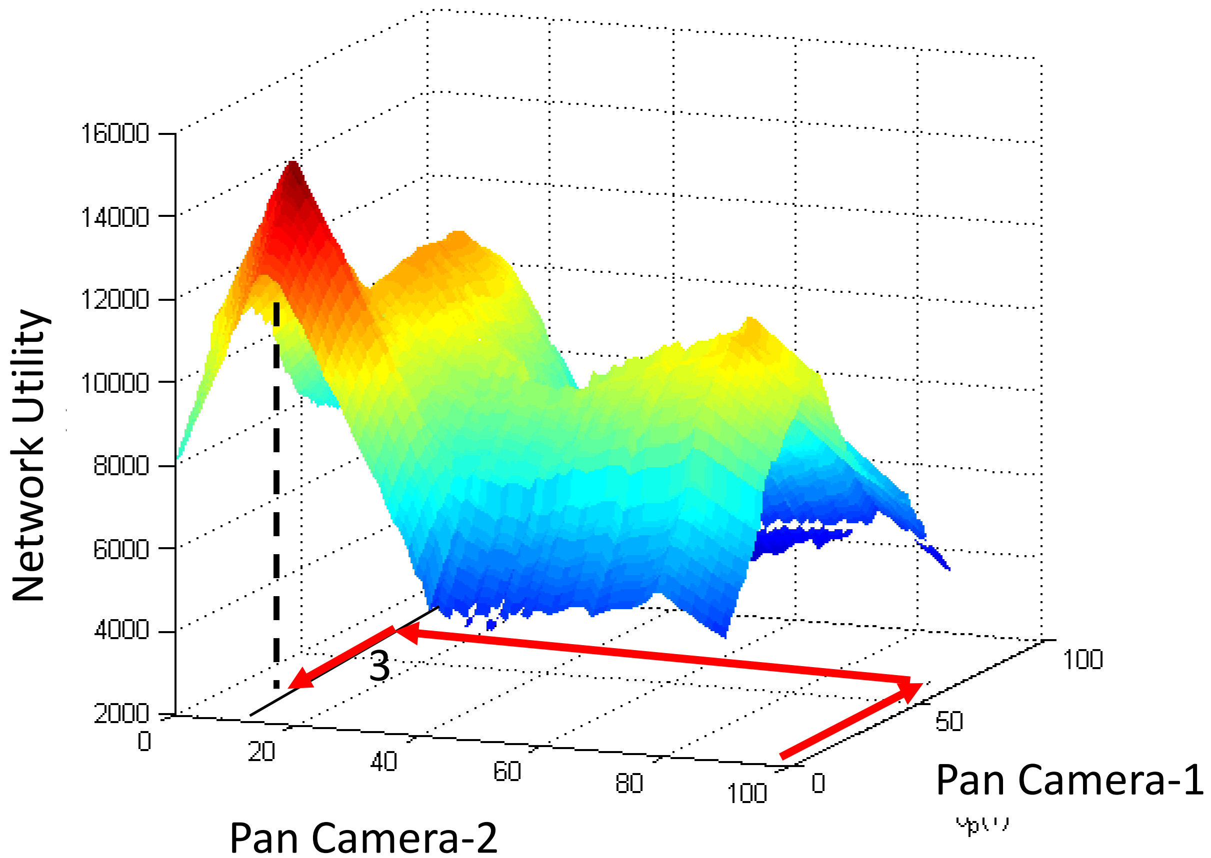
Utility function for all possible network configurations



Visualizing ILS



Visualizing ILS



Convergence of Distributed Algorithm

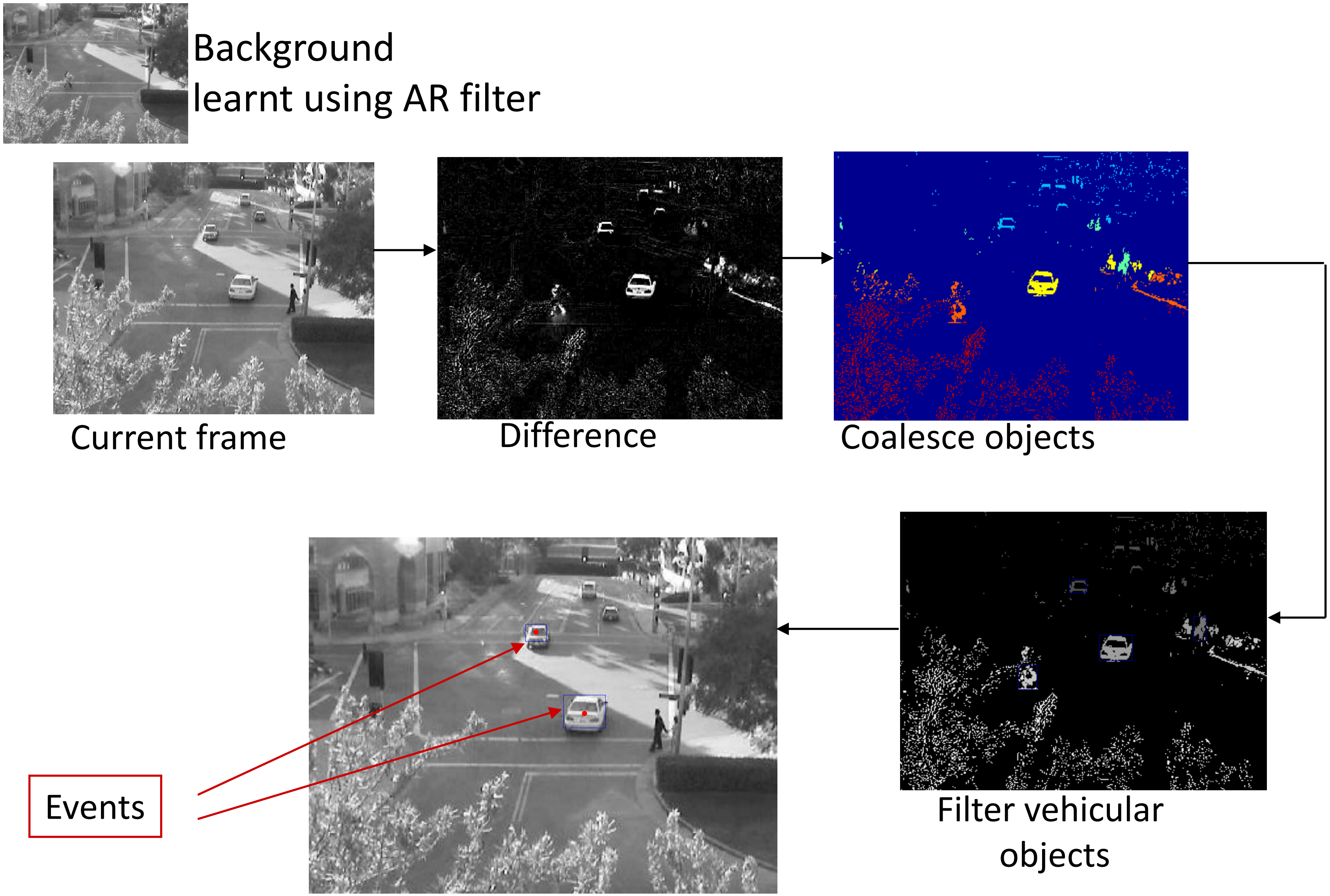
- **Theorem 1:** Under ILS, the network converges to a stable configuration in a finite number of steps
- Convergence speed
- Proximity to true optimum

Proof, Simulations: "Reconfiguration Methods for Mobile Sensor Networks," *ACM Transactions on Sensor Networks*

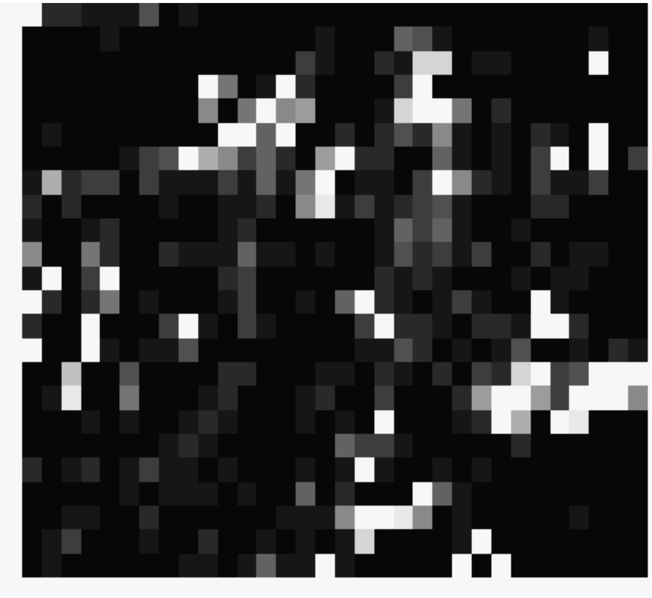
Experiments with Real World Data

- Application: Log images of vehicles approaching E4 building at UCLA
  - Detect vehicles at low resolution using motion detection
  - Minimize delay in high resolution coverage

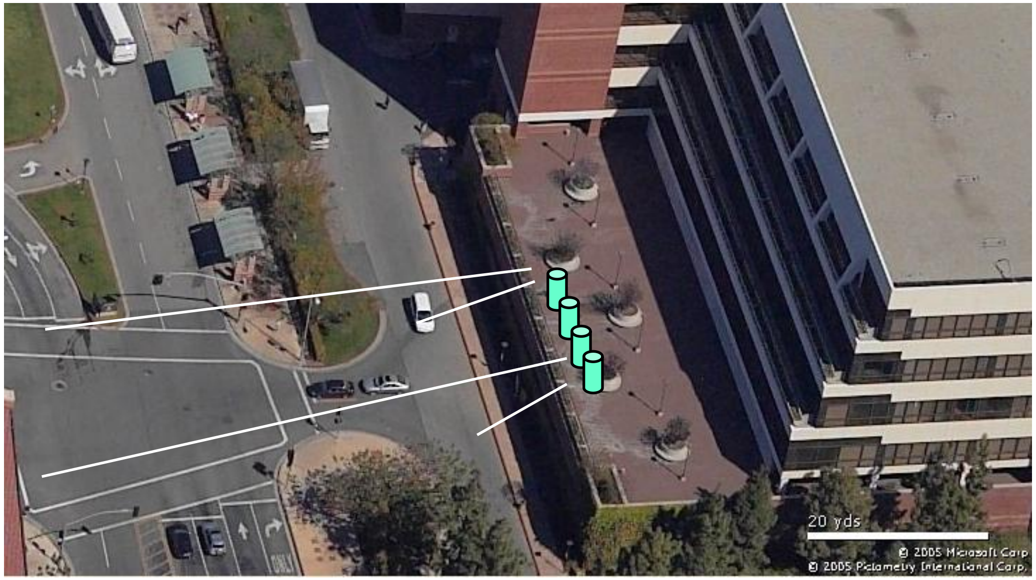
Event Detection



Experiment

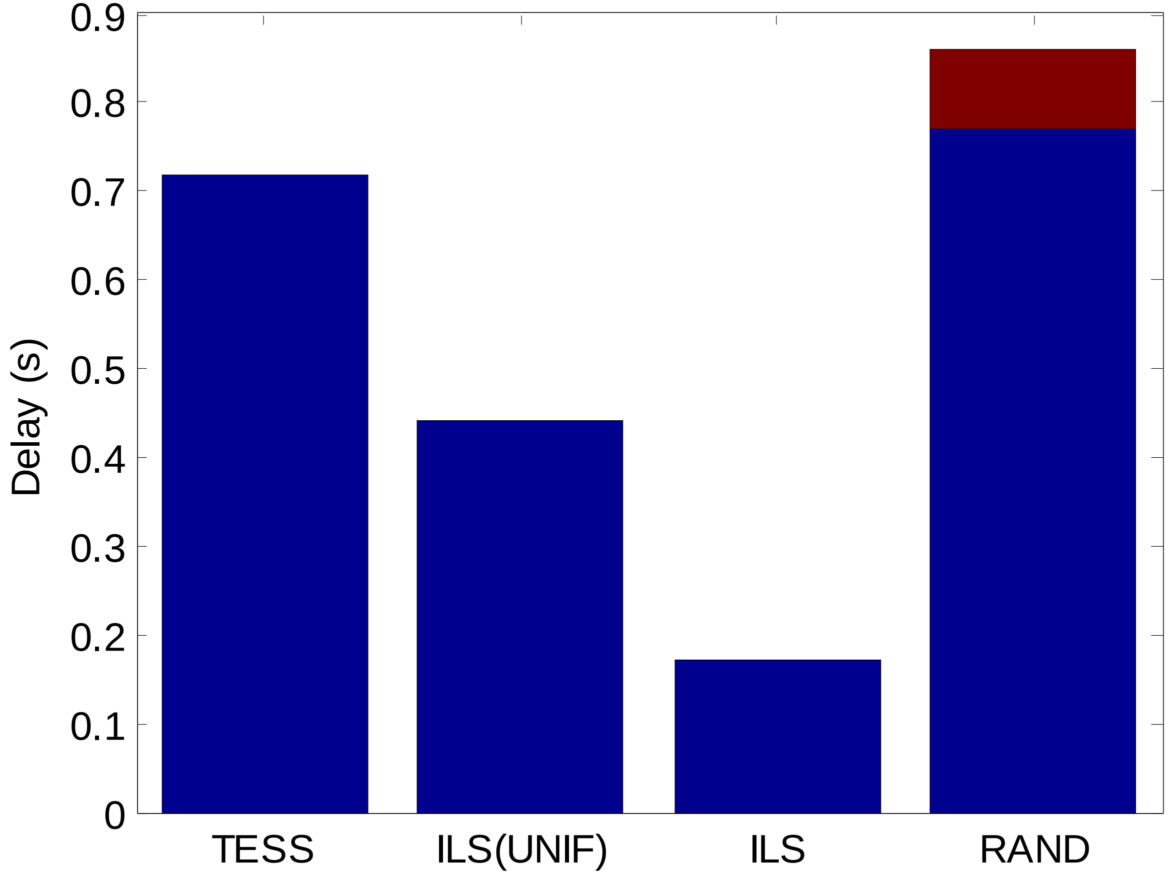


Event Trace



- A trace of 5000 events collected
  - Also used to learn event density
- ILS evaluation scenario
  - 4 cameras mounted on one side (camera calibration separated)
  - Actuation delay for event: measured for best camera covering it

ILS Delay Performance

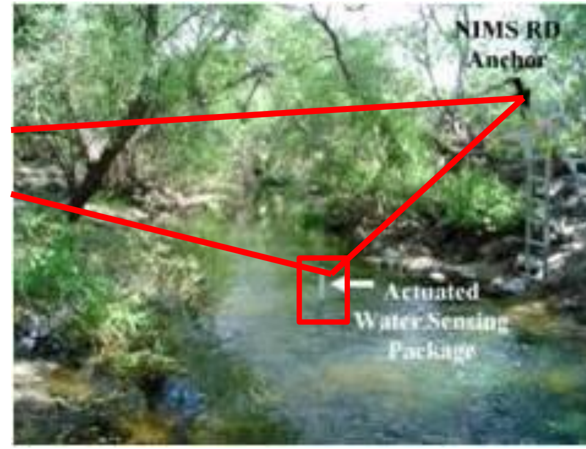


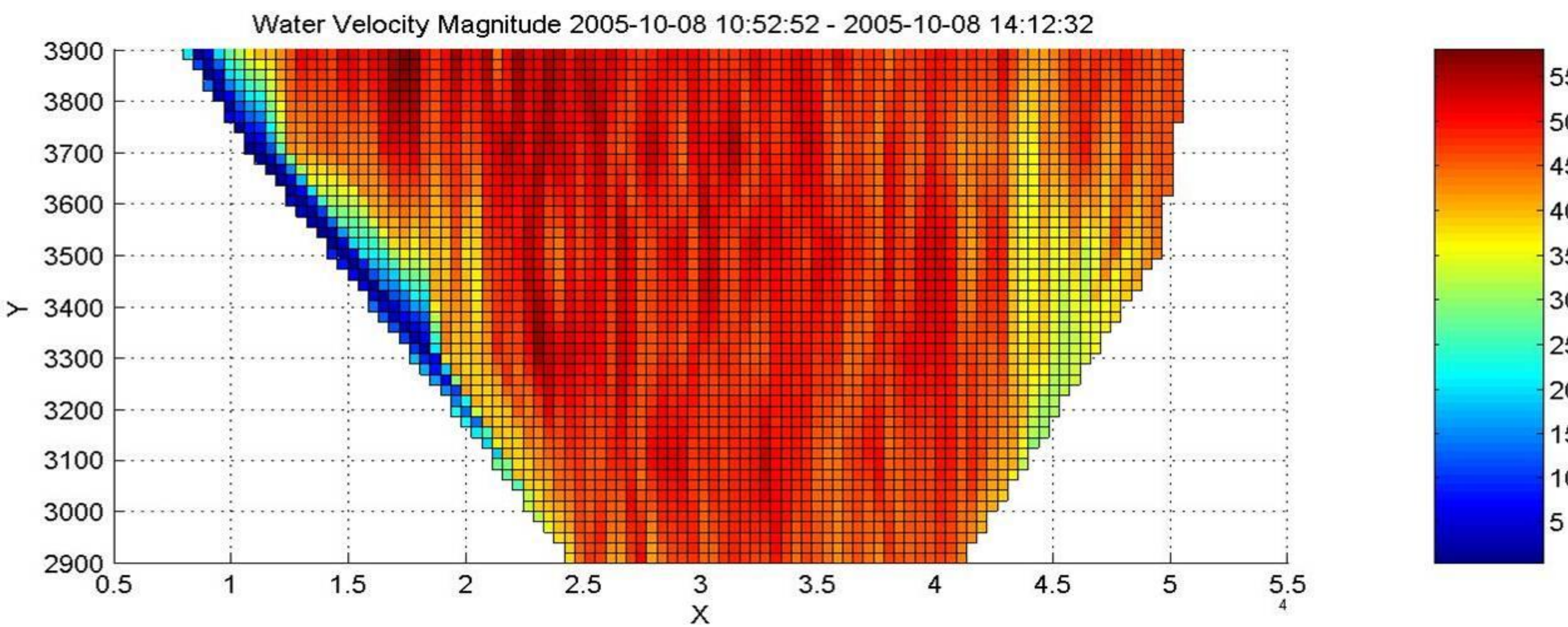
10 runs for RAND

More: "Reconfiguration Methods for Mobile Sensor Networks," *ACM Transactions on Sensor Networks*

Motility for Other Sensors

Point sensors: nitrate concentration measurement across river cross-section with constrained motion





Low Complexity Motion

- Can help achieve previously unachievable sensing resolutions
  - Orders of magnitude advantage over static networks
- Motion delay is a key issue
  - Leverage motion maximally within tolerable delay

Three New Capabilities

Performance Issue	New Capability
ENERGY SCARCITY	Harvest from Environment
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DEPLOYMENT	Peer Production

Peer Production

- Sharing resources for mutual advantage
  - Multiple contributors and multiple users: costs efficiently amortized

WIKIPEDIA

SETI HOME

SecondLife
YouTube
…

Peer Produced Sensor Networks

Standalone deployments

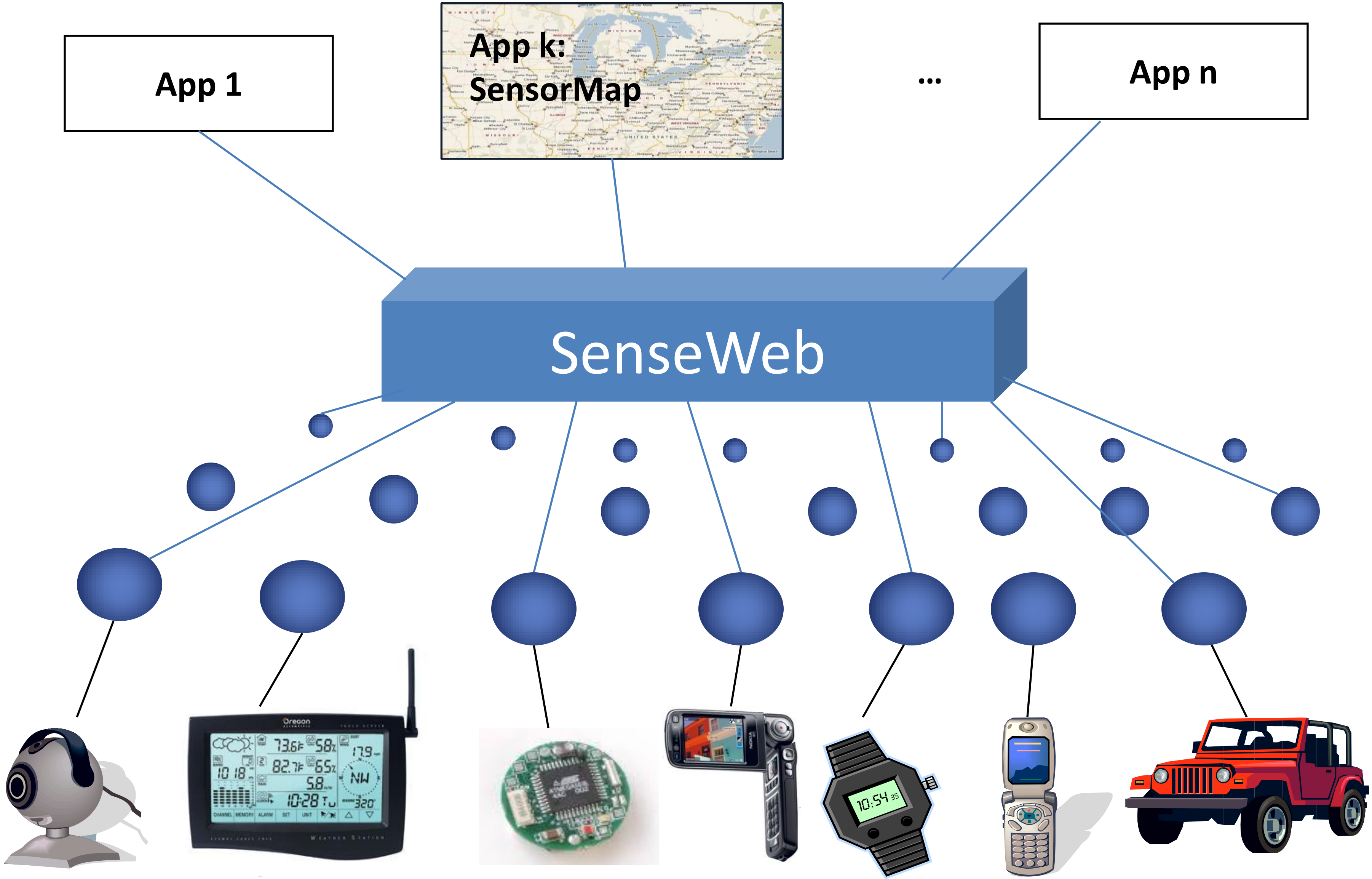
- Large scale deployment is challenging: cost, access rights, network/ power infrastructure, maintenance overhead
- Sensors and data are underused, replicated

SenseWeb: shared sensor networks

- Many sensor owners deploy at small scale
- Shared system yields large coverage
- Common sensors used by multiple apps

SenseWeb

http://atom.research.microsoft.com/sensormap



Challenges

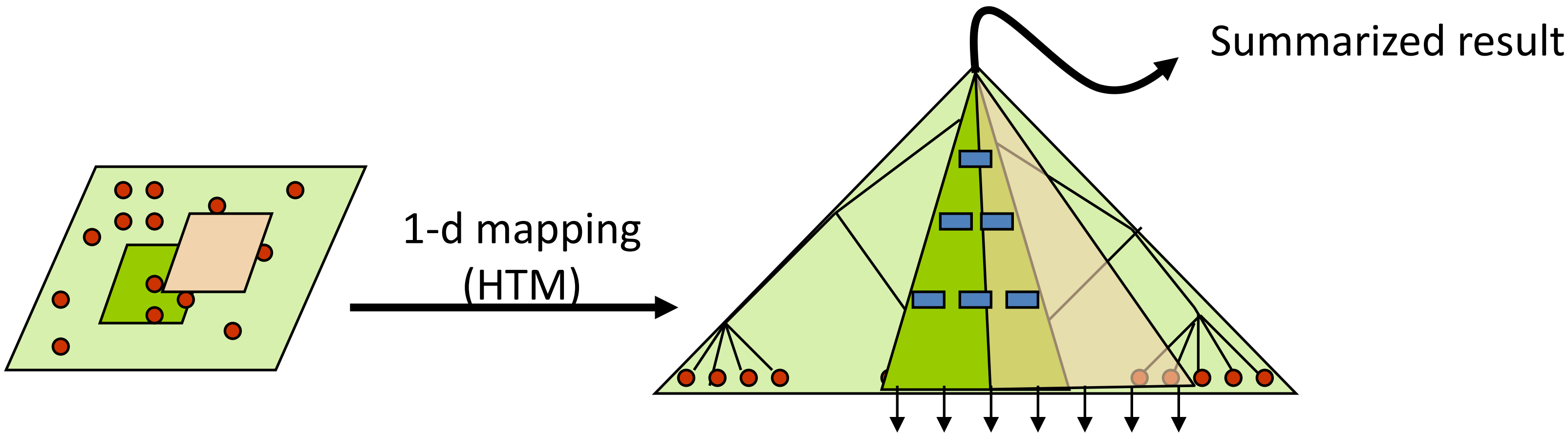
- Heterogeneity
  - Resource capability: bandwidth, power, computation
  - Willingness to share
  - Measurement accuracy
- Scalability
  - Streaming all raw data from all sensors to all applications not feasible
- Security and Privacy
- Data Verifiability, Trust

Data Re-use

- Sensor access provided through SQL-like queries
- Many applications may need similar data
  - within a tolerable latency of each other
  - From overlapping region
- Can cache data at server to reduce load on sensors and network
  - Overlap may be partial: computed aggregates may need partial new data

COLR-Tree (COLlection R-Tree)

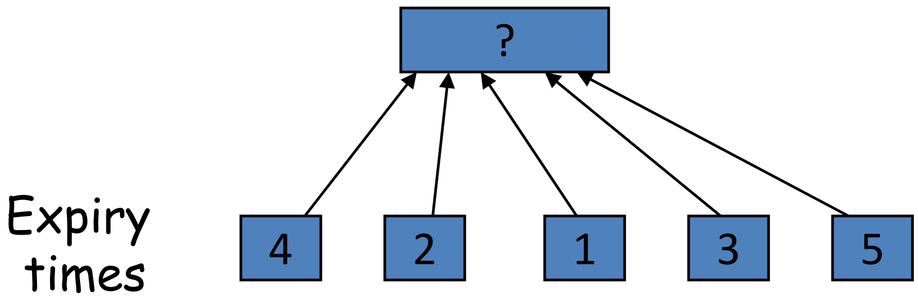
Index 2-D data with aggregates



- Minimizing sensor access
  - Cached data may have skewed distribution
  - Sample more from non-cached region
- Implemented on MS-SQL Server: usable with all SQL server capabilities

COLR-Tree: Aggregates

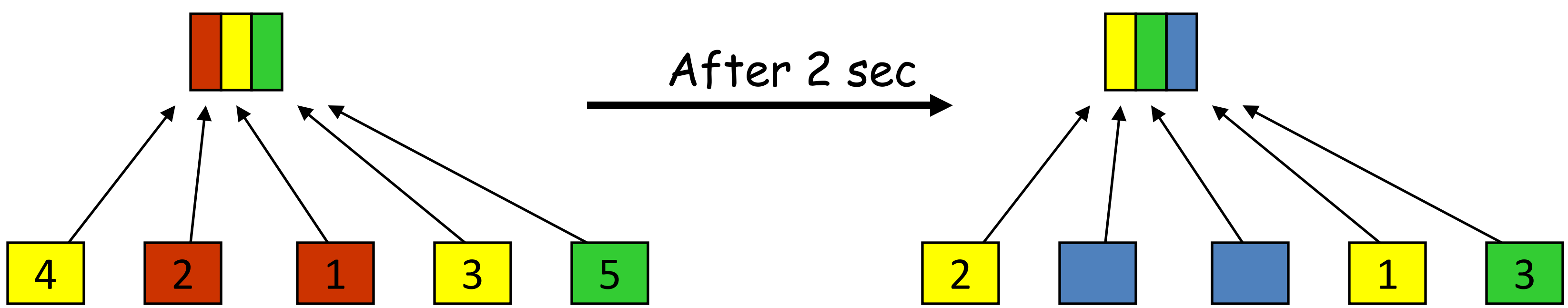
- Challenge: temporal aggregation



1: discard aggregate data after 1 sec (not much sharing)

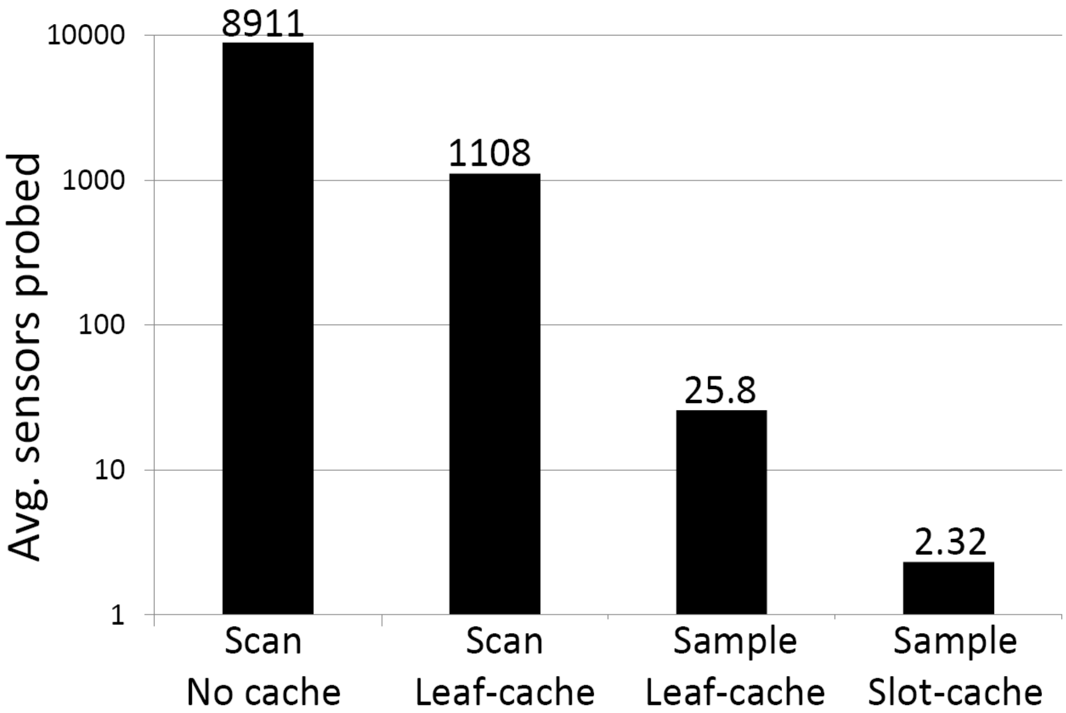
5: invalid after 1 sec

Solution: slotted aggregation



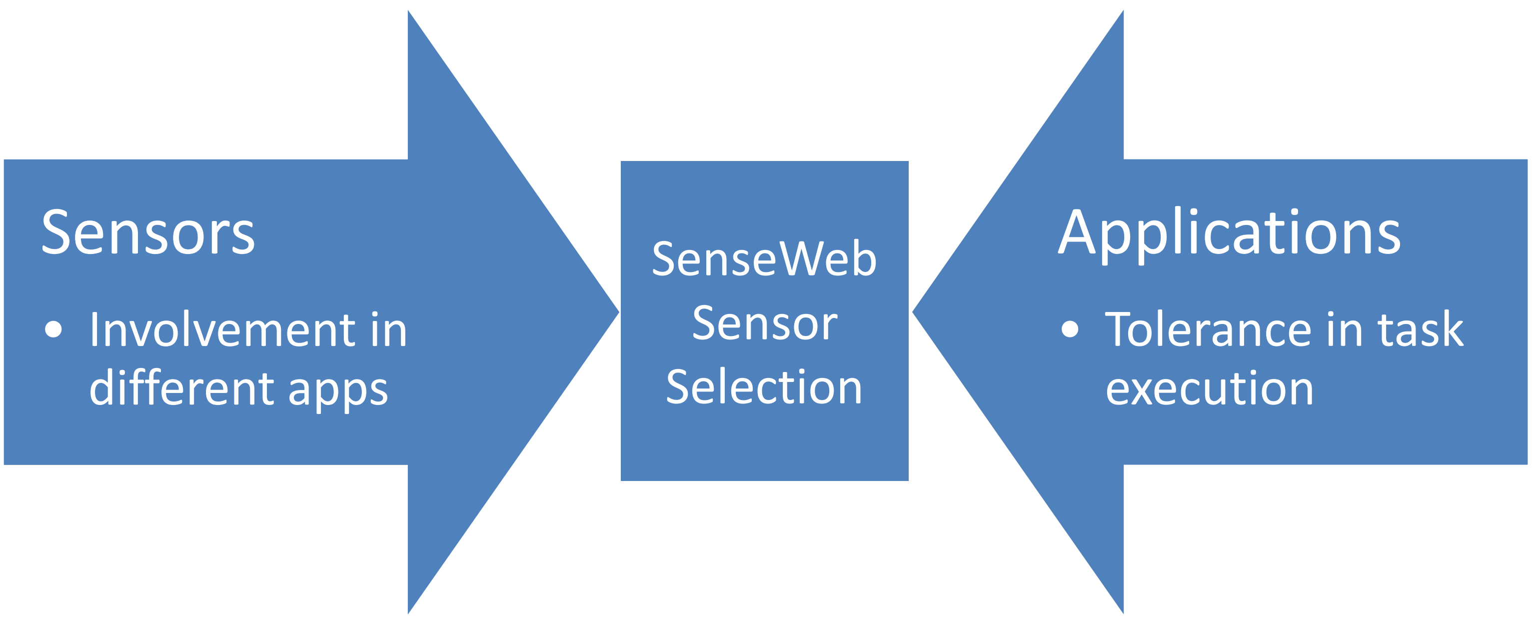
COLR-Tree Evaluation

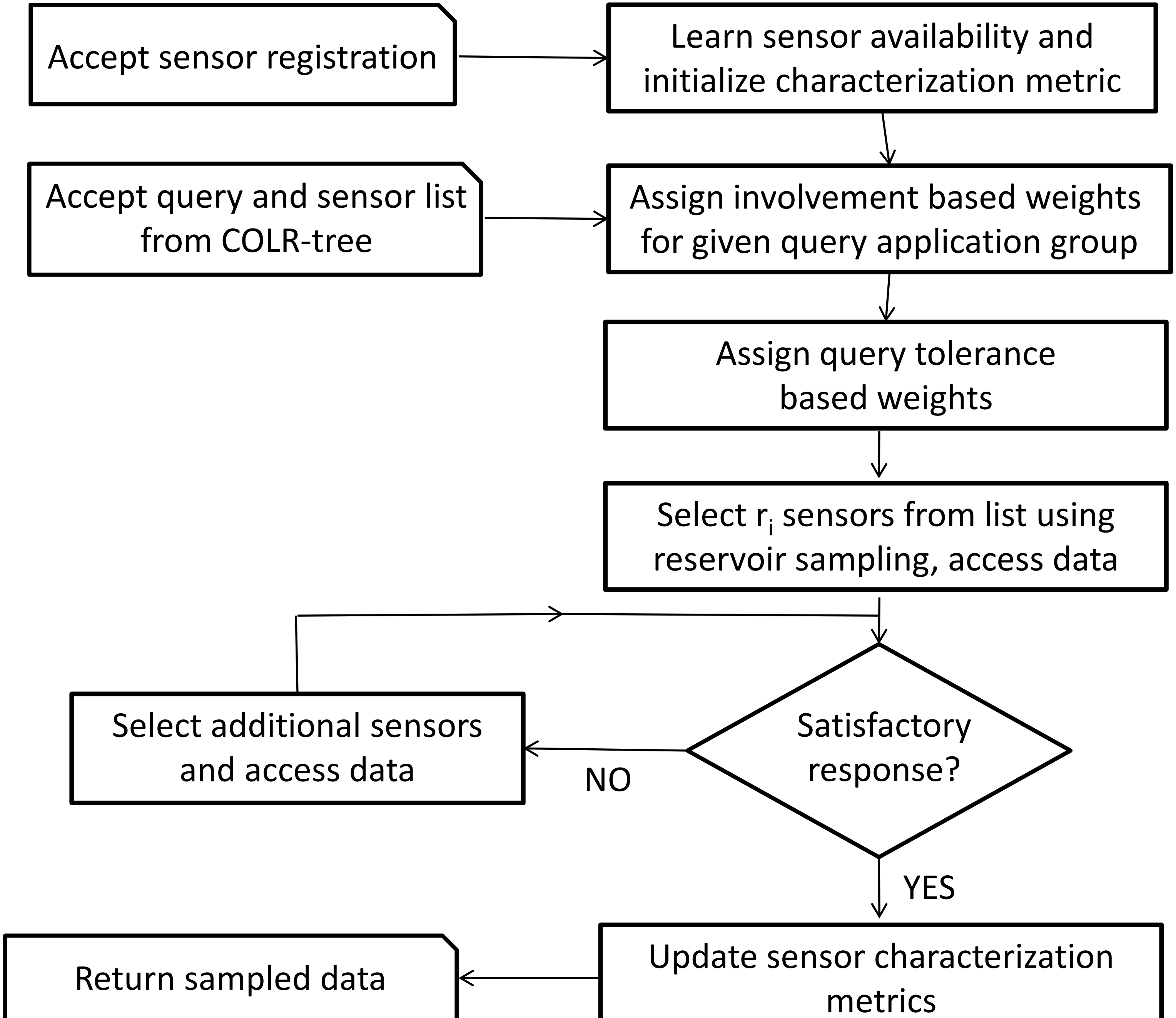
- Test data
  - 400K points from VE Yellow Pages
  - Regions queried: Virtual Earth usage trace



Tasking Heterogeneous Sensors

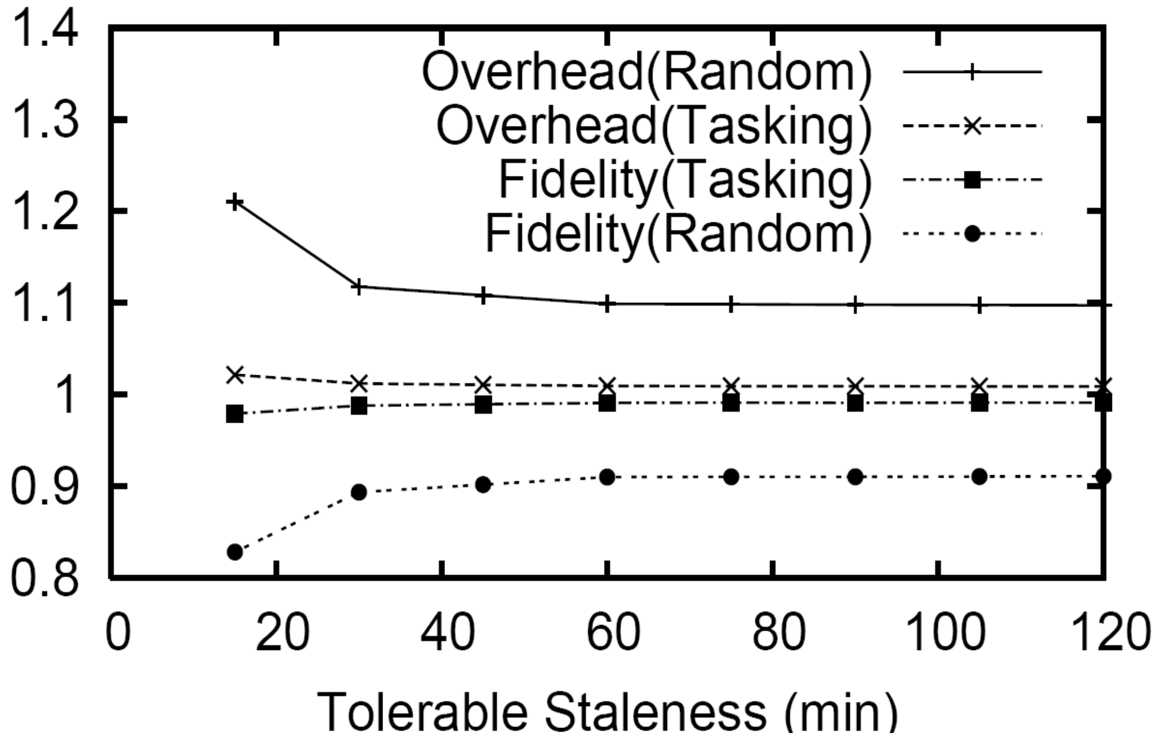
- Select uniformly rather than overloading the best sensors
- Leverage lower capability sensors when usable for a query
- Learn and adapt to sensor characteristics: availability, bandwidth
- Weighted reservoir sampling
  - Weighted random selection, with desired number of sensors




Accept sensor registration
Learn sensor availability and initialize characterization metric
Accept query and sensor list from COLR-tree
Assign involvement based weights for given query application group
Assign query tolerance based weights
Select r_i sensors from list using reservoir sampling, access data
Select additional sensors and access data
NO
Satisfactory response?
YES
Return sampled data
Update sensor characterization metrics

Tasking Algorithm Performance

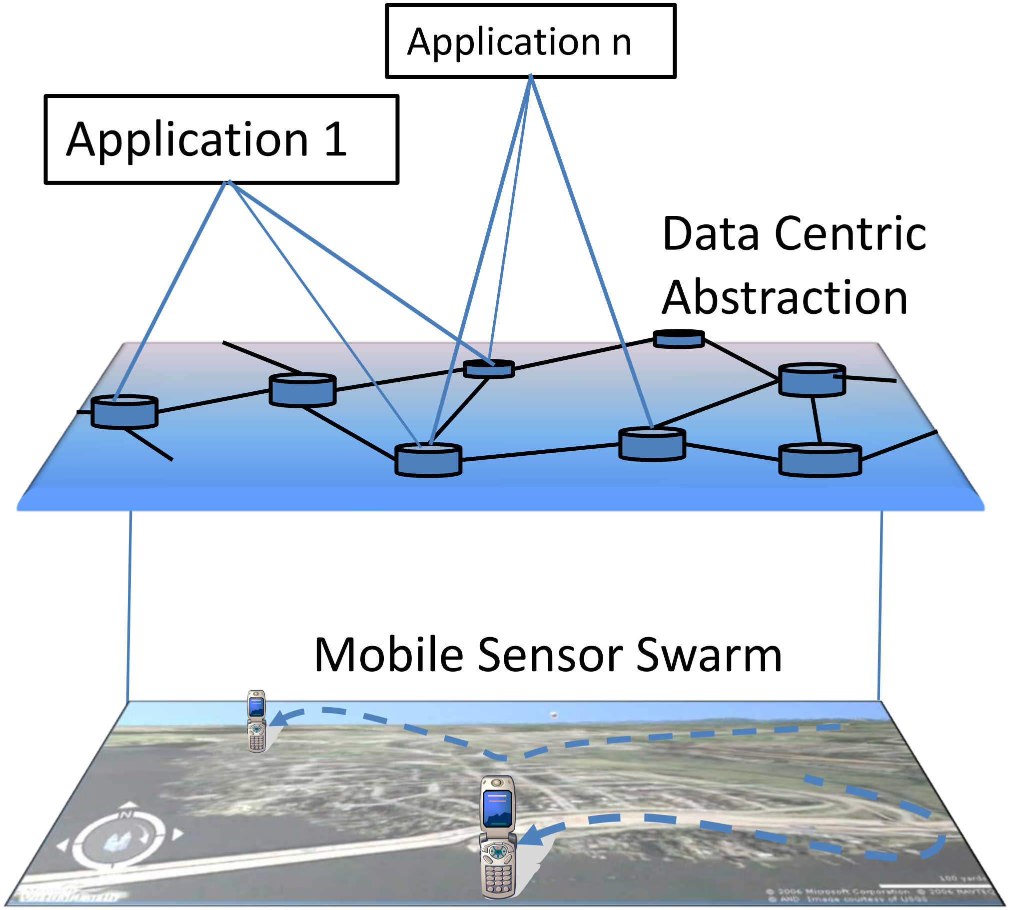
- Test on USGS stream water sensors
  - Random selection vs. Weighted reservoir sampling



Mobile Contributors in SenseWeb

+ More coverage
- Hard for application to track relevant devices

- **Solution:** data centric abstraction
  - Location based indexing
    - using GPS, cell-tower triangulation, content based location



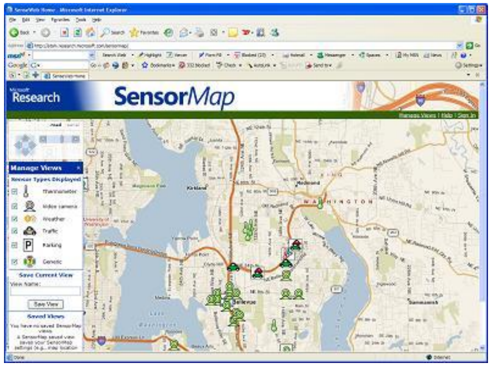
Implementation: “Demo: Building a Sensor Network of Mobile Phones," IPSN 2007.
Details: “Location and Mobility in a Sensor Network of Mobile Phones,” ACM NOSSDAV 2007.

Peer Production Summary

- Peer production can make low cost sensor networks possible for many apps.
- Design system to work with highly heterogeneous resources and dynamically varying availability
  - Adaptively allocate resources to tasks and services

Networked Embedded Computing

http://atom.research.microsoft.com/sensormap/



SenseWeb

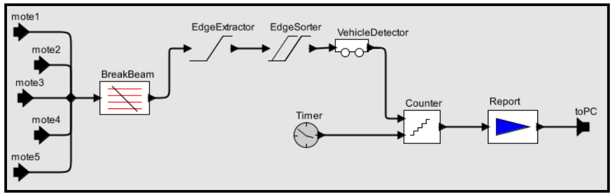
Shared sensor networks

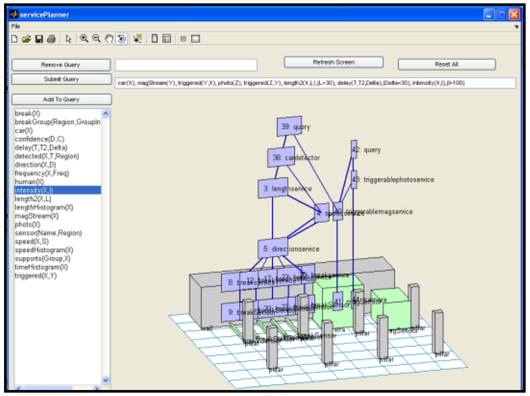
mPlatform

reconfig proc., comm, storage

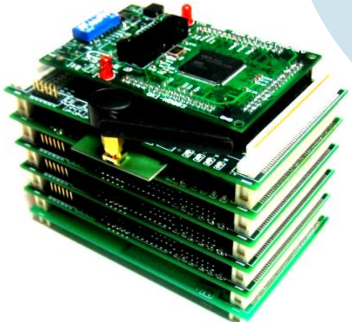
MSRSense

Composing apps on sensor streams





(open source. Download from http://research.microsoft.com/nec/msrsense/)



ftp://ftp.research.microsoft.com/pub/tr/TR-2006-142.pdf