Organizing principles in networking

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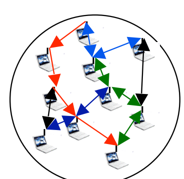
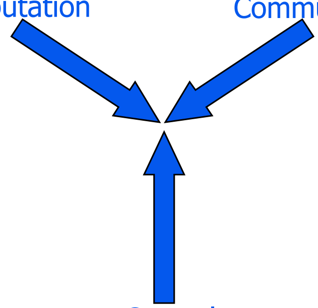
From wireless to sensor networks and control

Wireless networks
Ubiquitous communications



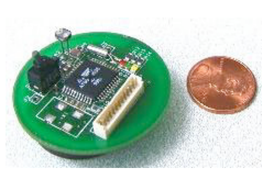
Computation

Communication

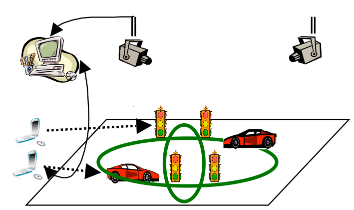


Control

Can actuate as well as sense



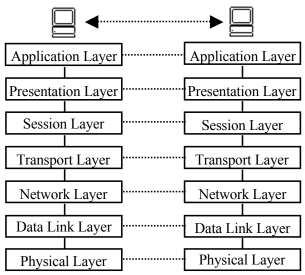
Berkeley Motes : "Smart Dust"
Can sense



- Interaction with the physical world through sensing and actuation
  - Convergence of Control with Communication and Computation

Architecture and abstractions

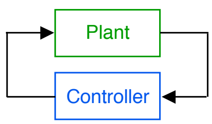
OSI



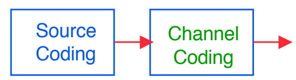
Serial computation

von Neumann Bridge

Control systems

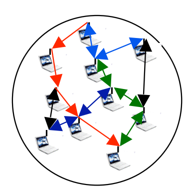


Digital Communication

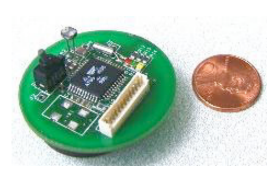


Outline of talk

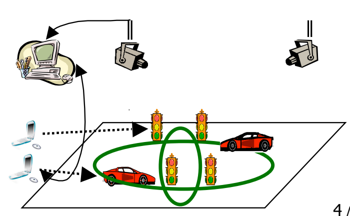
- Wireless networks
  - How to organize data transfer



- Sensor networks
  - Theory for in-network processing



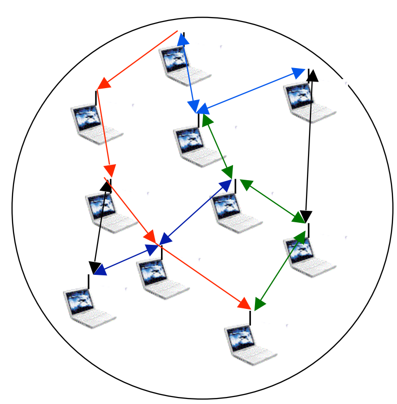
- Convergence with control
  - Middleware and multi-technology integration



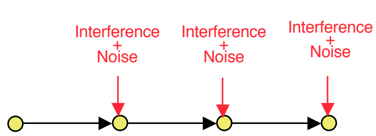
Capacity and Architecture of Wireless Networks

Ad Hoc Wireless Networks

- Communication networks formed by nodes with radios
  - Ad Hoc Wireless Networks

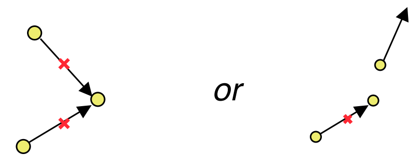


- Current proposal for operation:
  Multi-hop transport
  - Nodes relay packets until they reach their destinations
  - Fully decode packets at each stage treating all interference as noise

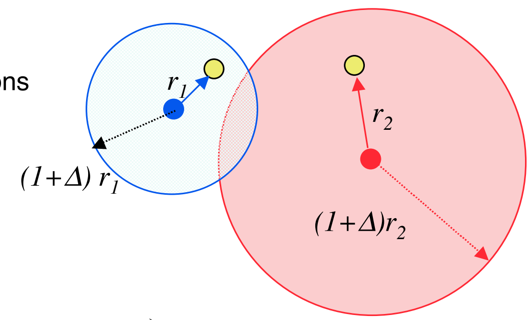


When all interference is regarded as noise …

- Packets can collide destructively



- <u>Several Models</u>
  - Reception is successful if
    - » Receiver not in vicinity of two transmissions

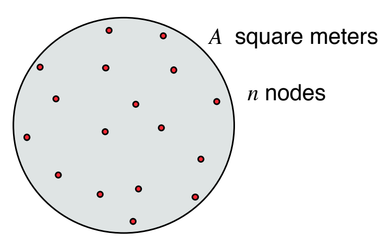


» Or $\text{SIR Ratio} = \dfrac{P_i r_i^{-\alpha}}{N + \sum_{j \neq i} P_j r_j^{-\alpha}} \geq \beta$

» Or Rate depends on SIR: $\text{Rate} = B \log\left(1 + \dfrac{P_i r_i^{\delta}}{N + \sum_{j \neq i} P_j r_j^{\delta}}\right) \text{bps}$

Scaling laws under interference model

- <u>Theorems</u> (Gupta & K 2000)
  - Disk of area A square meters
  - n nodes
  - Each can transmit at W bits/sec
  - Packets interfere/collide with each other

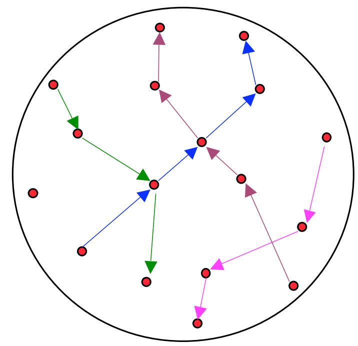


- Best Case: Network can transport $\Theta\left(W\sqrt{An}\right)$ bit-meters/second

- Square root law
  - Transport capacity doesn't increase linearly, but only like square-root
  - Each node gets $\frac{c}{\sqrt{n}}$ bit-meters/second

Random Network Scenario

- n nodes randomly located in disk of unit area
  - Each node chooses random destination
  - Equal throughput λ bits/sec for all OD pairs
  - Each node chooses same range r



- Each node can send $\Theta\left(\frac{1}{\sqrt{n \log n}}\right)$ bits/sec even with
  - With best choice of spatio-temporal scheduling, ranges and routes

- Definition of capacity

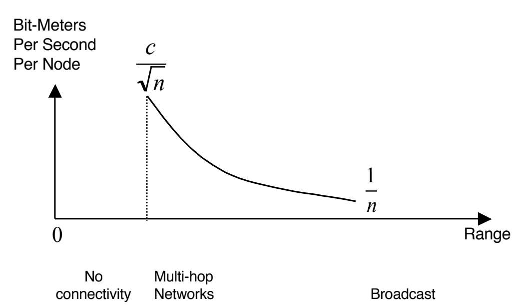
$$\lim_{n\to\infty} \Pr\left(\lambda(n) = \frac{c}{\sqrt{n \log n}} \text{ is feasible}\right) = 1, \text{ and}$$

$$\lim_{n\to\infty} \mathrm{P}\left(\lambda(n) = \frac{c'}{\sqrt{n \log n}} \text{ is feasible}\right) = 0$$

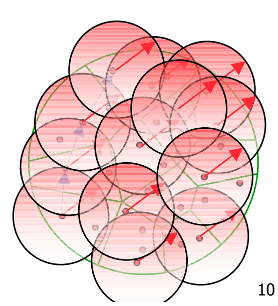
} Sharp cutoff phenomenon

Order optimal operation under "collision" model

- Optimal operation is multi-hop
  - Transport packets over many hops of distance $\frac{c}{\sqrt{n}}$



- Optimal multi-hop architecture
  - Group nodes into cells of size log n
  - Choose a common power level for all nodes
    - » Nearly optimal
  - Power should be just enough to guarantee network connectivity
    - » Sufficient to reach all points in neighboring cell
  - Route packets along nearly straight line path from cell to cell

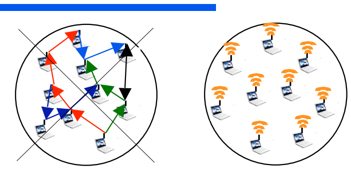


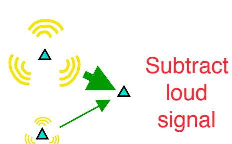
But are these fundamental limits?

Is this the right architecture for data transfer?

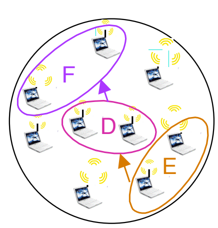
Wireless networks are not wired networks …

- Wireless networks are formed by nodes with radios
  - Maxwell rather than Kirchoff
- Nodes can cooperate in many complex ways





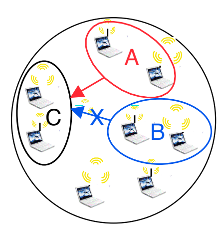
No collisions
Interference is not interference
Interference is information



Amplify and forward
Why digital?

$$\frac{\text{Signal}}{\text{Interference} + \text{Noise}}$$

Reduce by cancellation

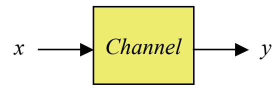


"There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy."
— Hamlet

Goal
- A strategic theory to determine basic architecture
- Specify what functionalities needed
- Then develop protocols to implement the architecture

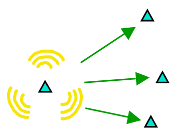
Network information theory

- Shannon's original work was for a single link

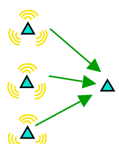


Triumphs

Gaussian broadcast channel

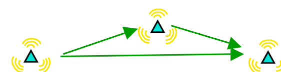


Multiple access channel

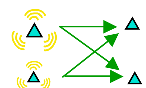


Unknowns

The simplest relay channel



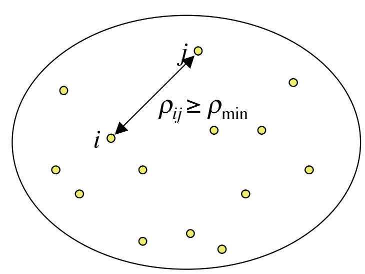
The simplest interference channel



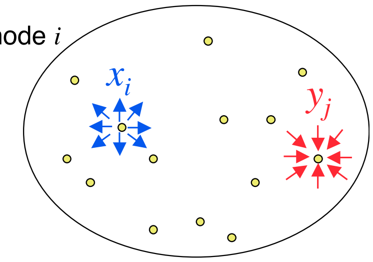
- Networks being built (ad hoc networks, sensor nets) are much more complicated

Model of system: A planar network

- Introduce node locations, distances between nodes, and attenuation as a function of distance
- n nodes in a plane
- ρ_{ij} = distance between nodes i and j
- Minimum distance $\rho_{\min}$ between nodes
- Signal attenuation with distance ρ: $\frac{e^{-\gamma\rho}}{\rho^{\delta}}$
  - $\gamma \geq 0$ is the absorption constant
    - Generally $\gamma > 0$ since the medium is absorptive unless over a vacuum
    - Corresponds to a loss of $20\gamma \log_{10} e$ db per meter
  - $\delta > 0$ is the path loss exponent



Transmitted and received signals



- W_i = symbol from some alphabet $\{1,2,3,\ldots,2^{TR_{ik}}\}$ to be sent by node i
- $x_i(t) = f_{i,t}(y_i^{t-1}, W_i)$ = signal transmitted by node i time t
- $y_j(t) = \sum_{\substack{i=1 \\ i \neq j}}^{n} \frac{e^{-\gamma \rho_{ij}}}{\rho_{ij}^{\delta}} x_i(t) + z_j(t)$ = signal received by node j at time t ($z_j(t)$: $N(0,\sigma^2)$)
- Destination j uses the decoder $\hat{W}_i = g_j(y_j{}^T, W_j)$
- Error if $\hat{W}_i \neq W_i$
- $(R_1, R_2, \ldots, R_l)$ is feasible rate vector if there is a sequence of codes with

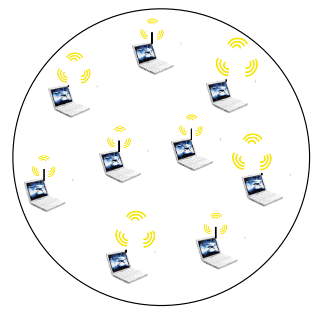
$$\underset{W_1,W_2,\ldots,W_l}{Max} \Pr(\hat{W}_i \neq W_i \text{ for some } i \mid W_1, W_2, \ldots, W_l) \to 0 \text{ as } T \to \infty$$

- **Individual power constraint** $P_i \leq P_{ind}$ for all nodes I. **or Total power constraint** $\sum_{i=1}^{n} P_i \leq P_{total}$
- **Transport Capacity** $C_T = \sup_{(R_1, R_2, \ldots, R_{n(n-1)})} \sum_{i=1}^{n(n-1)} R_i \cdot \rho_i$ bit-meters/second or bit-meters/slot

The Results

Power cost of transport capacity

- Theorem: Bit-meters per Joule bound (Xie & K'02)
  - Suppose $\gamma > 0$, there is some absorption,
  - Or $\delta > 3$, if there is no absorption at all
  - Then for all Planar Networks



$$C_T \le \frac{c_1(\gamma, \delta, \rho_{\min})}{\sigma^2} \cdot P_{total}$$

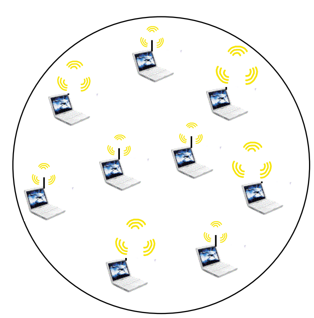
where

$$c_1(\gamma, \delta, \rho_{\min}) = \frac{2^{2\delta+7}}{\gamma^2 \rho_{\min}^{2\delta+1}} \frac{e^{-\gamma\rho_{\min}/2}(2 - e^{-\gamma\rho_{\min}/2})}{(1 - e^{-\gamma\rho_{\min}/2})} \quad \text{if } \gamma > 0$$

$$= \frac{2^{2\delta+5}(3\delta - 8)}{(\delta-2)^2(\delta-3)\rho_{\min}^{2\delta-1}} \quad \text{if } \gamma = 0 \text{ and } \delta > 3$$

O(n) upper bound on Transport Capacity

- Theorem: Transport capacity is $O(n)$ (Xie and K'02)
  - Suppose $\gamma > 0$, there is some absorption,
  - Or $\delta > 3$, if there is no absorption at all
  - Then for all Planar Networks



$$C_T \le \frac{c_1(\gamma, \delta, \rho_{\min}) P_{ind}}{\sigma^2} \cdot n$$

- Same as square root law based on treating interference as noise
  - $\Theta(\sqrt{An}) = \Theta(n)$ since area A grows like $\Omega(n)$
- So multi-hop with decode and forward with interference treated as noise is order optimal architecture whenever $\Theta(n)$ can be achieved { No need for network coding, multi-user detection, etc.

From scaling laws to architecture

- Explicitly incorporated *distance* in model
  - » Distances between nodes
  - » Attenuation as a function of distance
  - » Distance is also used to measure transport capacity

- Studied networks with *arbitrary numbers of nodes*

- Make progress by asking for less
  - – Instead of studying capacity region, study the *transport capacity*
  - – Instead of asking for exact results, study the *scaling laws*
    - » The exponent is more important
    - » The preconstant is also important but is secondary - so bound it
  - – Draw some broad conclusions about *order-optimal architecture*
    - » Optimality of multi-hop when absorption or large path loss
    - » Optimality of coherent multi-stage relaying with interference cancellation when no absorption and very low path loss

What about pre-constants?

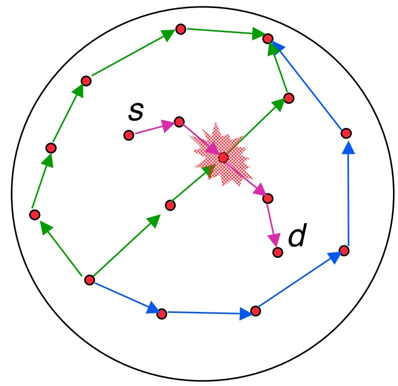
From pre-constants to architecture:
Ideas for protocol design

Traffic adaptive routing:
STARA

(Gupta & K 1998,
Borkar & K 2003,
Raghunathan & K 2004)

Traffic adaptive routing protocols

- Routing protocol based on Minimum Hop routing
- However Min Hop paths can mutually interfere
- Moreover we may want to use multiple paths
- How to quantify the possible improvement in the preconstant?

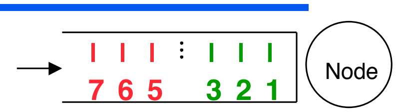


- Few Sources Theorem: A 4x improvement (Raghunathan & K '04)
  - If Number of sources = $o(n^{1/6})$
  - There exist flow avoiding, multiple paths so that

$$\liminf_{n\to\infty} \frac{\text{Thpt of Flow Avoiding Multipath routing}}{\text{Throughput of Minimum Hop Routing}} \geq 4$$

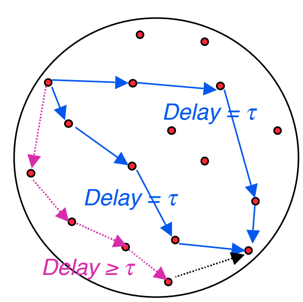
Delay Equalizing solution

- And we may want low delay



- Goal: Route traffic from origin to destination such that
  - All utilized routes have the same mean delay
    All unutilized routes have larger mean delay

The *Wardrop equilibrium*:
"The journey times on all the routes actually used are equal, and less than those which would be experienced by a single vehicle on any unused route."
J. G. Wardrop, "Some Theoretical Aspects of Road Traffic Research," *Proc. Inst. Civil Engineers*, Part 2, pp. 325-378, 1952.



- Delay Estimation Algorithm
  - D_{ij}^d = Estimate of delay from i to d via j
  - D_{ij}^d(new) = $(1-\theta)$ D_{ij}^d(old) + θ (Latest D_{ij}^d)
  - D_i^d = Average i to d delay over *all* routes
  - D_i^d (new) = $\sum_j p_{ij}^d$(new) D_{ij}^d(new)

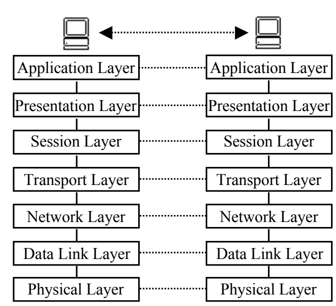
- Route Adaptation Algorithm
  - p_{ij}^d = Proportion of traffic from i to d routed via j
  - p_{ij}^d(new) = p_{ij}^d (old) + $\alpha\, p_{ij}^d$ (old) (D_i^d(new) - D_{ij}^d(new))
  - Note: Subtraction eliminates clock offsets!
  - Also we are equalizing delays!

The COMPOW Protocol for Power Control

(Narayanaswamy, Kawadia, Sreenivas & K '00)

Power Control problem: How to choose transmissions power levels?

- Conceptualization problem: Which Layer?
  - Physical layer: Quality of reception
  - Network layer: Impact on routing
  - Transport layer: Higher power impacts congestion

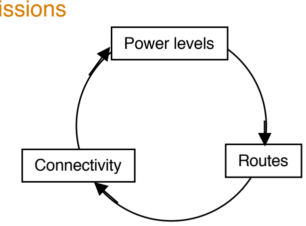


- COMPOW Solution
  - All nodes use common power chosen just large enough for network connectivity - or larger

Distance-rate product $\approx r \times \frac{1}{r^2} = \frac{1}{r}$

Transmission range (r) — Number of simultaneous transmissions ($\frac{1}{r^2}$)

- This is a Network Layer problem
  - Interdependence of Power Control, Routing, Connectivity

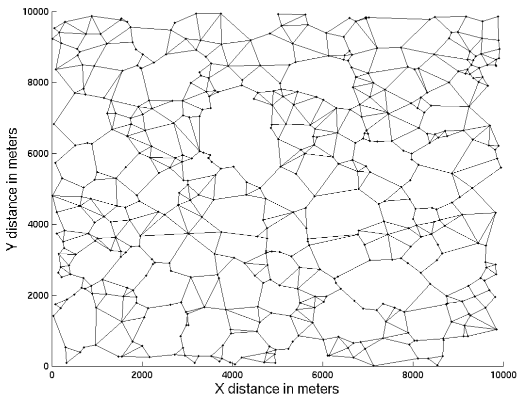


- So joint solution for Power Control and Routing situated at the Network Layer

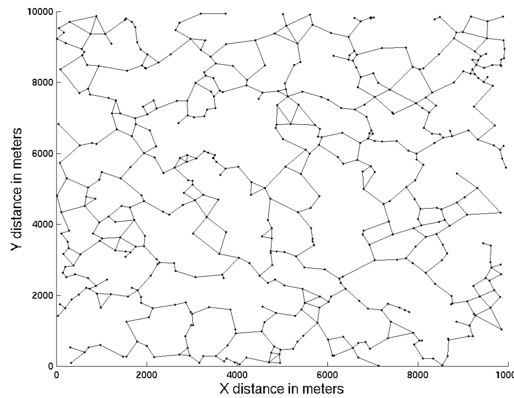
Low common power level also yields transmission power efficient routes

- Theorem
  - For propagation path loss $1/\rho^{\alpha}$ with $\alpha \geq 2$ the minimum power routes give a planar graph with straight line edges that do not cross.
  - The graph for $\alpha > 2$ is a subgraph of that for $\alpha = 2$.

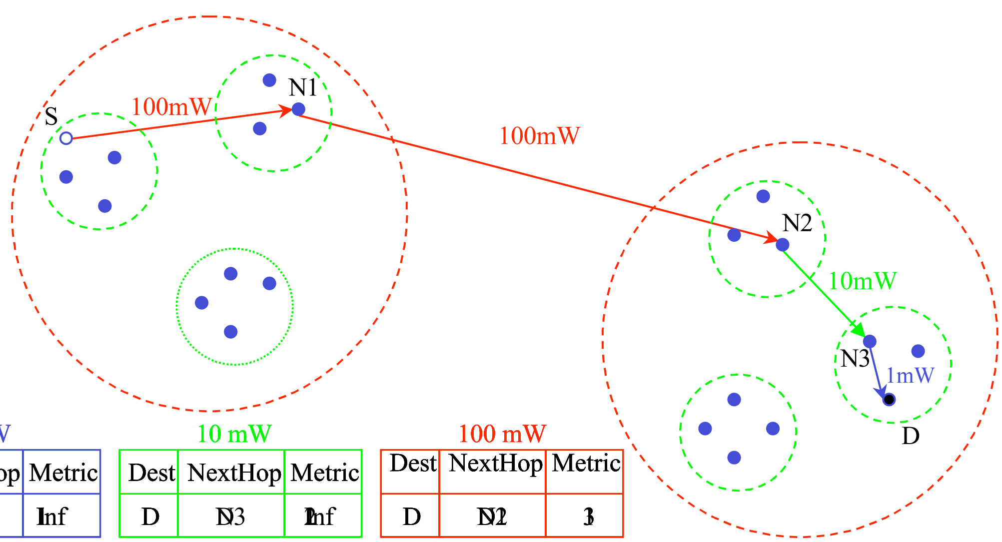
$\alpha = 2$



$\alpha = 4$



Routing Table at N1 / N2 / N3



1 mW

Dest	NextHop	Metric
D	D	Inf

10 mW

Dest	NextHop	Metric
D	N3	Inf

100 mW

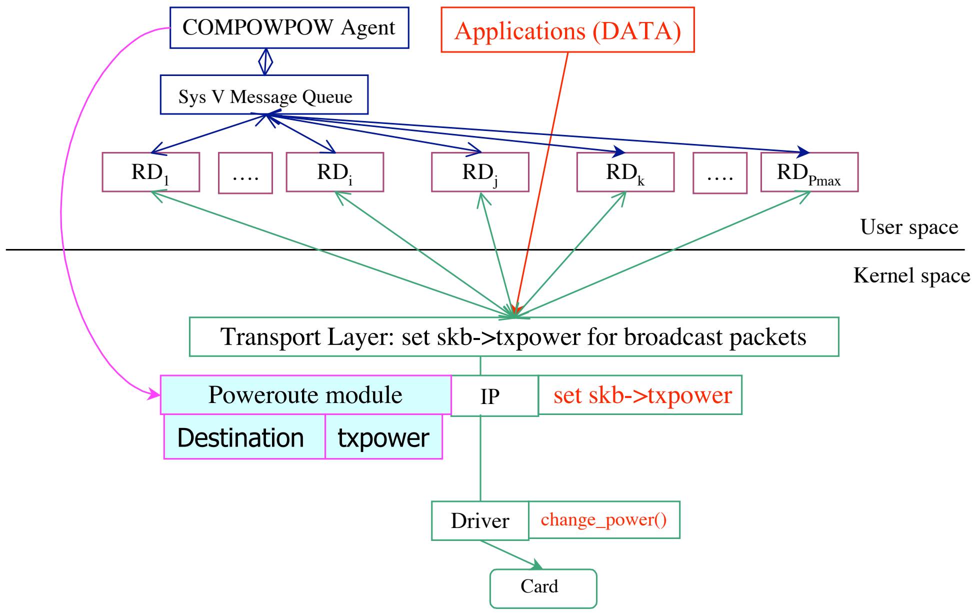
Dest	NextHop	Metric
D	N2	3

Kernel IP Routing Table

N1 / N2 / N3

Dest	NextHop	Metric	TxPower
D	N2	3	100mW

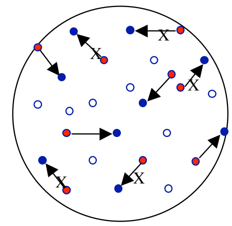
Software Architecture for Power Control: COMPOW



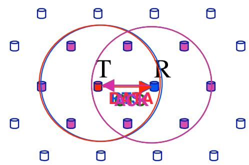
The SEEDEX Protocol for Media Access Control

(Rozovsky & K 2000)

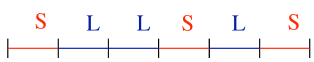
The Media Access Control problem

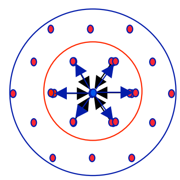


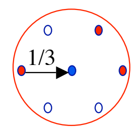
- Wireless is a shared medium
  - Neighbors of receiver should not transmit
  - Circular problem: Communication ↔ Coordination
  - How to resolve in asynchronous distributed real time fashion?
- IEEE 802.11 solution
  - Two neighborhoods silenced
  - Backoff
  - Wasteful?



- SEEDEX Solution
  - Random Bernoulli schedule: p, $1\text{-}p$







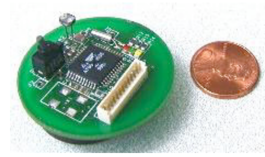
  - Seed Exchange with two hop neighbors

Sensor Networks: Towards a theory of in-network processing

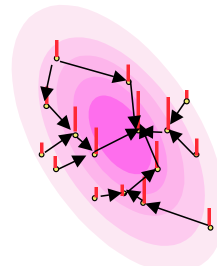
(Giridhar & K 2004)

The oncoming convergence: Harvesting statistics from sensor networks

- Sensor networks
  - Example: Berkeley Motes
    - Can sense, wirelessly communicate, compute



- Examples of Tasks
  - Environmental monitoring
    - n nodes take temperature measurements $x_1, x_2, \ldots, x_n$
    - Determine the Mean temperature: $(x_1 + x_2 + \ldots + x_n)/n$
  - Alarm networks
    - Determine the Max temperature: Max x_i



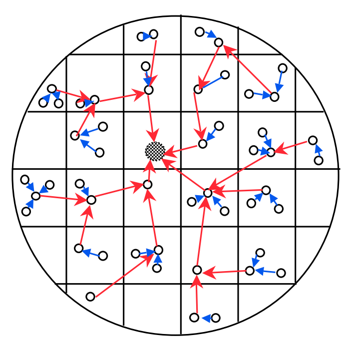
- More generally: Consider a symmetric function $F(x_1, x_2, \ldots, x_n)$
  - Eg. Max, Mean, Mode, Median, Percentile, Frequency Histogram

- How should we process information in-network to compute and collect functions of interest?

Computing symmetric functions: Harvesting the *type* (Giridhar & K '03)

- Value of symmetric function depends only on the *type* of the measurement set
  - *Type* = Frequency histogram

- <u>Theorem</u>: The maximum frequency at which types can be harvested at a fusion node in a random multihop network is $\Theta(\frac{1}{\log n})$
  - Strategy
    - Tessellate
    - Fuse locally
    - Compute along a rooted tree of cells



- Different architecture for "Max" function
  - Block coding

Summary: Order of difficulty of computations

$\Theta(1/n)$

Collocated network: *Mean, Mode, Type*

Data downloading

$\Theta(1/\log n)$

Random planar network: *Mean, Mode, Type*

Collocated network: *Max*

$\Theta(1/\log\log n)$

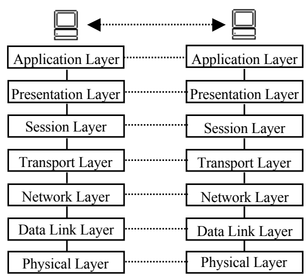
Random planar network *Max*

The convergence of control with communication and computing

(Graham & K '03,04, Baliga & K '03,Giridhar & K '03, Huang, Graham & K '03, Graham, Baliga & K '04)

Challenge of architecture and abstractions for convergence

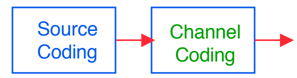
Internet



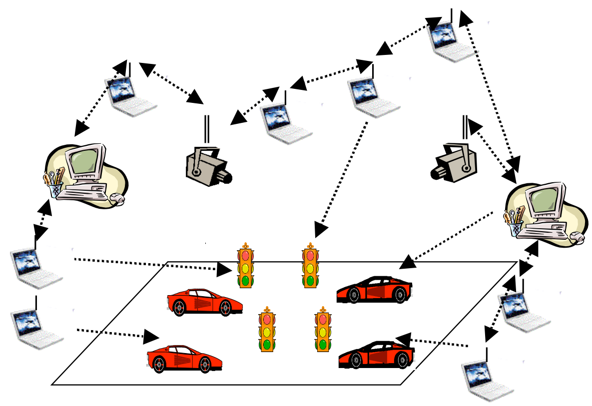
Serial computation

von Neumann Bridge

Digital Communication

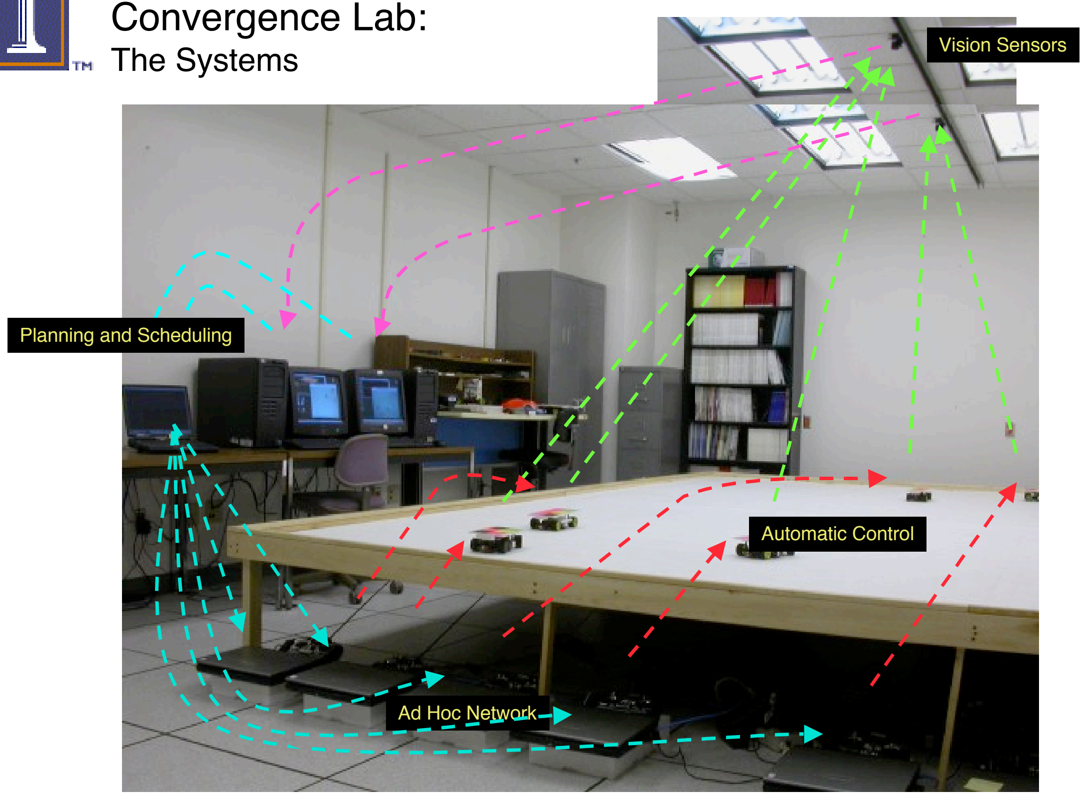


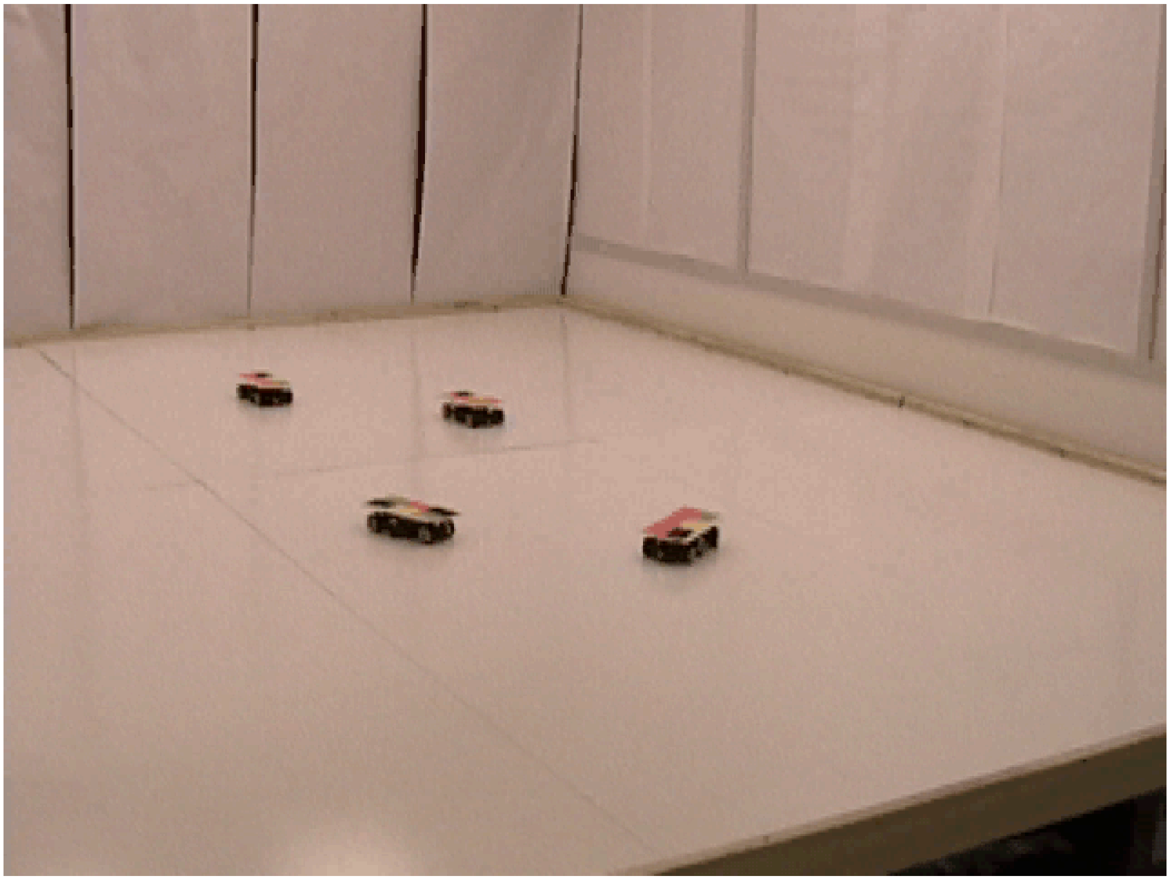
- What are the abstractions and architecture for convergence with communication and computing?



Information Technology Convergence Lab:

The Systems



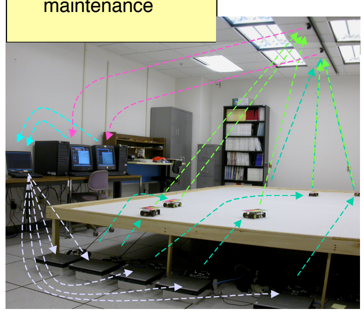


Subsystems

Control law development
- Time scale decomposition
- State estimation
  - Asynchronous measurement
  - Lossy measurement
  - Sensor errors
- Robustness
- Vision based control

System integration
- Hardware development
- Software development
- System maintenance

Subsystems
- Ad hoc wireless network
  - Cisco Aironet 802.11b pcmcia cards
- Vision and sensor network
  - Matrox Imaging frame grabber and library
- Planning and scheduling
  - Centralized and distributed
- Predictive controller



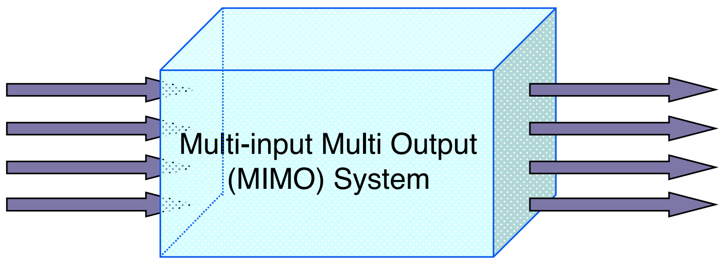
Distributed application development
- Feature bloat environment
- Rapid
- Reliable
- Evolvable

Software
- Middleware
- Services

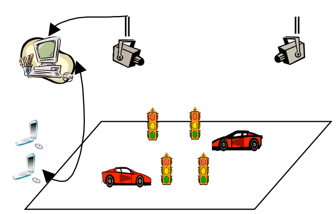
Optimizing at run-time
- On-line identification and adaptation
- Reactive planning and scheduling
- Migration for communication vs. computation load balancing

Measuring and managing time in a distributed system
- Measurement latencies
- Clock synchronization
- System performance related to timing accuracies

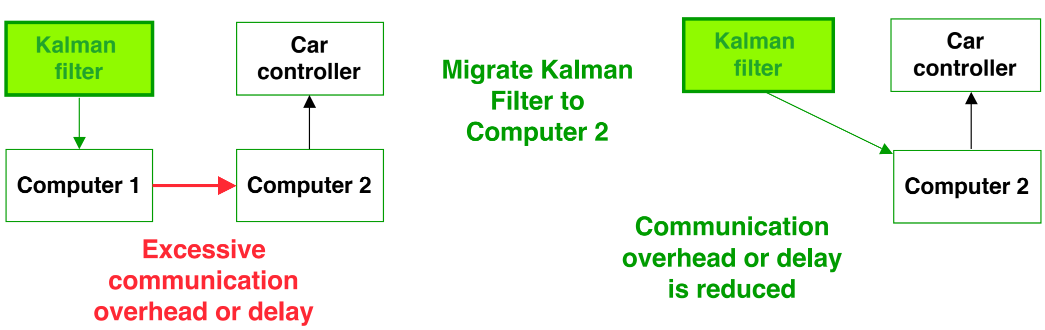
Abstraction of virtual collocation

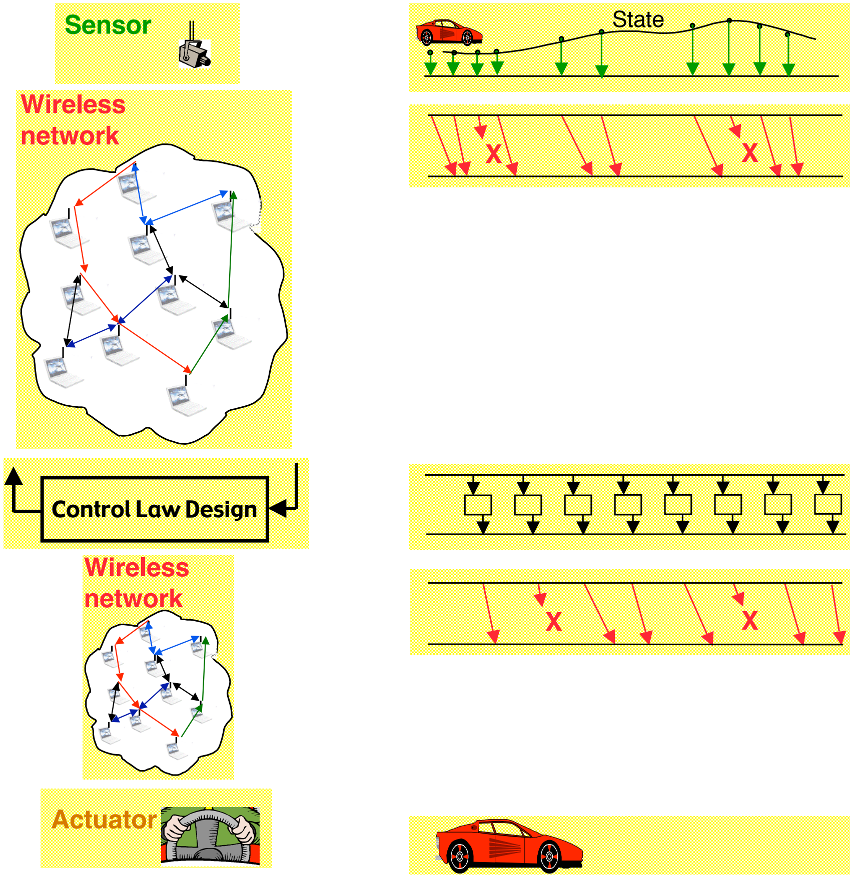


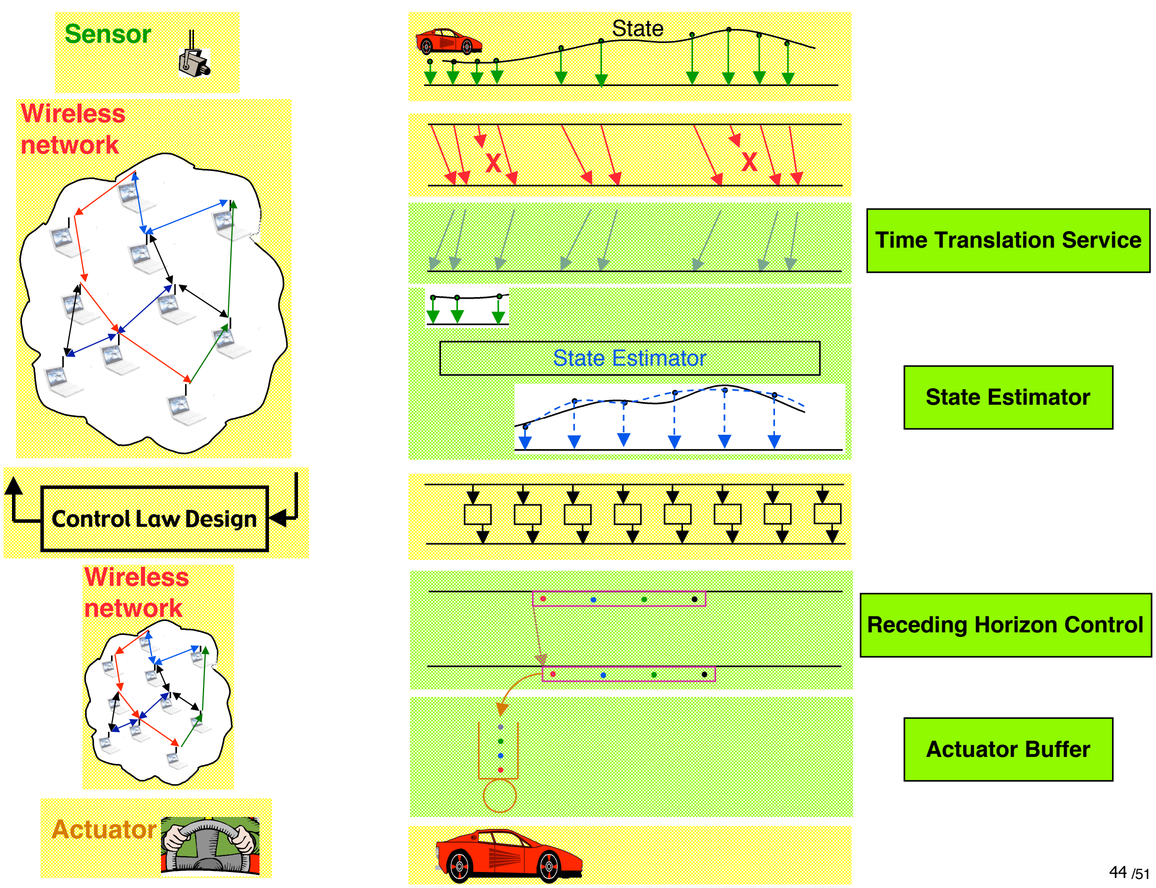
Middleware: EtherArch Software (Baliga & K'03)



- Component architecture
- Location independence
- Semantic addressing of components
- System startup and upgrade during execution
- Time translation
  - Knowledge of per-packet delay important for control
- Automatic migration of components for performance




Sensor
Wireless network
Control Law Design
Wireless network
Actuator
State


Sensor
Wireless network
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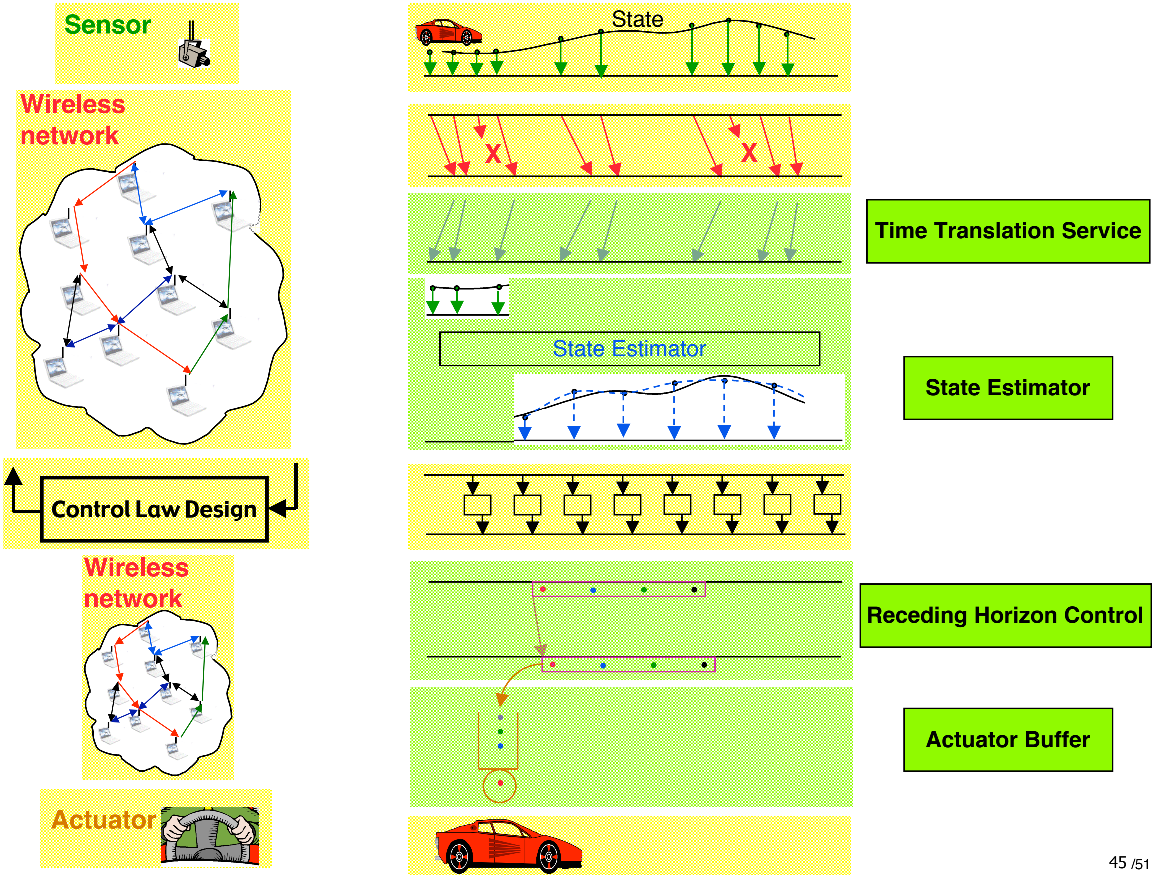
Wireless network
Actuator
State
Time Translation Service
State Estimator
State Estimator
Receding Horizon Control
Actuator Buffer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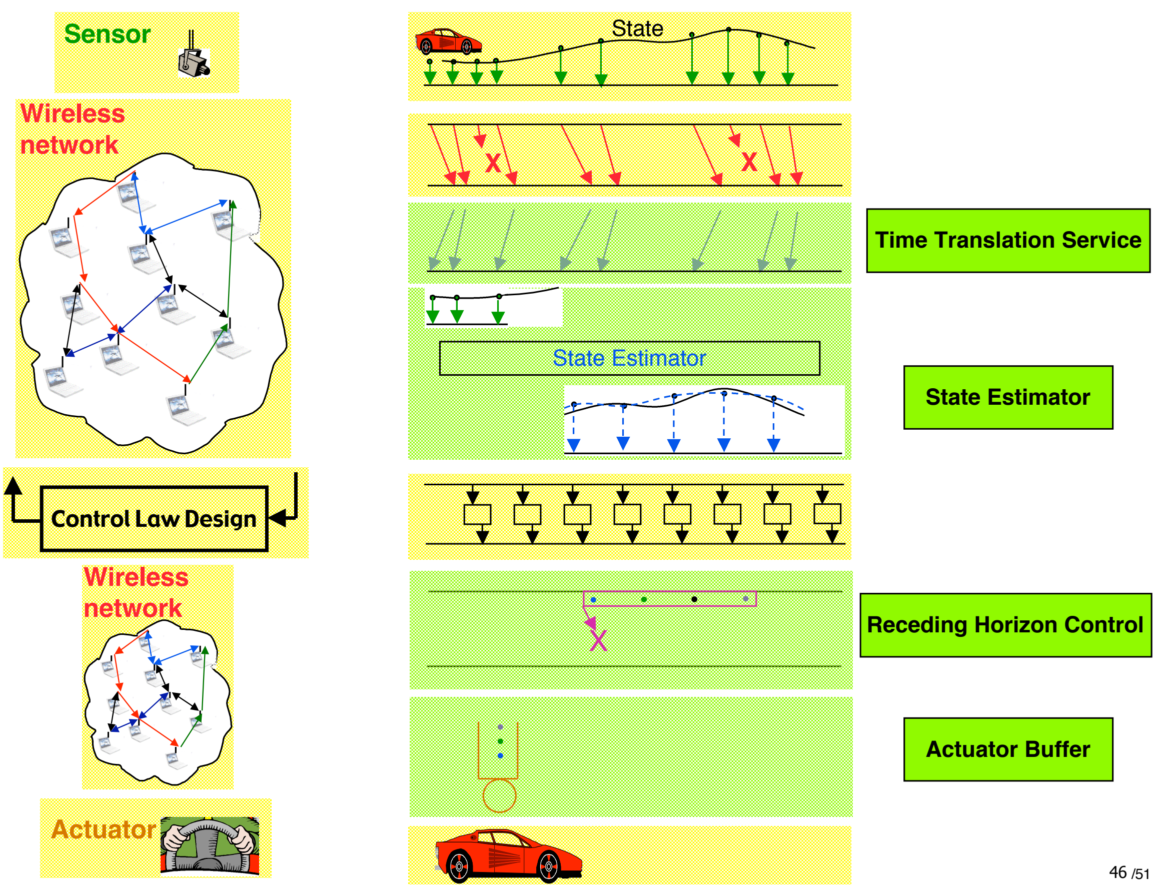
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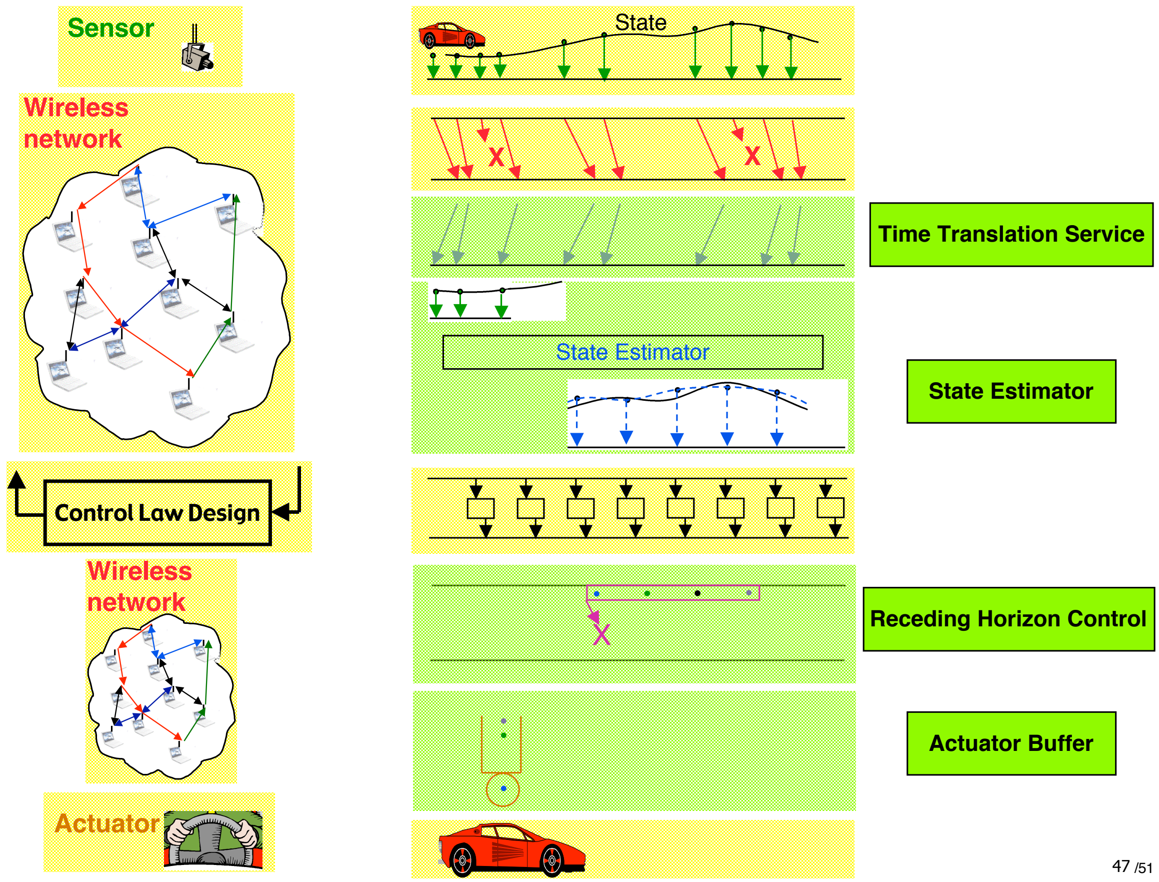

Local Temporal Autonomy

- Components able to tolerate failures of other components for some time
- Example: Insulating Controller from Sensor and Communication Network

  Sensor → State Estimator → Controller — Now controller has Local Temporal Autonomy

- Example: Insulating Actuator from Controller and Communication Network

  Controller → Block Computation → Actuator Buffer → Actuator — Now Actuator has Local Temporal Autonomy

- Converts *Dependency* relationships to *Use If Available* relationships
- Makes possible other facilities such as
  - *Automatic Restart of Failed Components*
  - *Migration of Components*
  - *Component Upgrade at Runtime*

{ Reliability, robustness
System integration, Initialization
Evolution and Scalability

The oncoming theoretical convergence

Post Maxwell,
von Neumann,
Shannon,
Bardeen-Brattain world

- Sensor/Actuator networks
  - Nodes can compute
  - Nodes can communicate
  - Nodes can actuate
  - Nodes can sense

- 1950 — 2000 and continuing: Substantial progress in several individual disciplines
  - Computation: ENIAC (1946), von Neumann (1944), Turing,..
  - Sensing and inference: Fisher, Wiener (1949),…
  - Actuation/Control: Bode, Kalman (1960),…
  - Communication: Shannon (1948), Nyquist,…
  - Signal Processing: FFT, Cooley-Tukey (1965),…

- Larger grand unification of sensing, actuation, communication and computation

- ~ 2000 — onwards
  - A gradual fusion of all these fields
  - But still knowledge of all these fields may be important

To obtain papers

- <u>Papers can be downloaded from</u>

  http://black.csl.uiuc.edu/~prkumar

- <u>For hard copies send email to</u>

  prkumar@uiuc.edu