



# Cross-Layer Design For Large-Scale Sensor Networks

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# Network Overhead is Costly!

- Network Functions Are Dominant Users of Bandwidth
- Fixed Overhead Increasingly Less Efficient as Duty Cycle Decreases
- Closed Loop Mechanisms Require Duplex Operation
- Much of Bandwidth Provides Redundant/Unnecessary Information

- Headers for Each Level
- Timing
- Status

*Redundant since information exists in the Integrated system*

**SUOSAS Aggregate 200 Mbps Capability**

512 byte packet, 32 mpps & FEC = 1/2 @ 4000 kbps maximum burst

	Bits (in K)	Reduction %	Payload
Transmission Capacity of 50 Radios	200,000		
Half-Duplex Operation	100,000	100,000	
Channel Contention @ 5 Radio Density	40,000	60,000	
UDP Header	39,385	615	34%
IP Header	37,647	1,738	95%
COMSEC Header	36,571	1,076	59%
Radio Network Header	36,120	451	25%
Radio Link Layer Header	35,679	441	24%
Modem Framing & CRC	35,068	611	34%
Forward Error Correction	17,534	17,534	
Waveform Framing	17,491	43	2%
Synchronization Probe Overhead	13,378	4,113	226%
Slot Quantization @ 1.2 ms per Slot	11,378	2,000	110%
Channel Acquisition (RTS/CTS)	6,827	4,551	250%
Frame Acknowledge	5,689	1,138	62%
Average Contention Interval (1.44 slots)	4,588	1,101	60%
Average Number of Transmissions per packet	1,821	2,767	
Candidate Packet Overhead			982%

From SUO SAS TIM, June 12 & 13 2001

**Actual Application Data 1.8 Mbps ≈ 0.9 %**

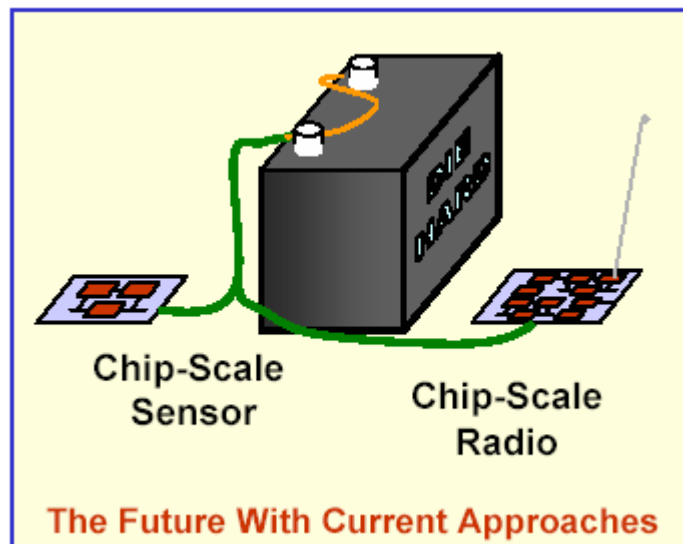
- Does Not Include Initial Acquisition, Other Entry Requests, TCP, Routing Table, and Related Bandwidth Requirements
- 10 Second Set-up Time Represents Opportunity Cost of 2 Gigabits of Throughput

(DARPA Connectionless Networks)

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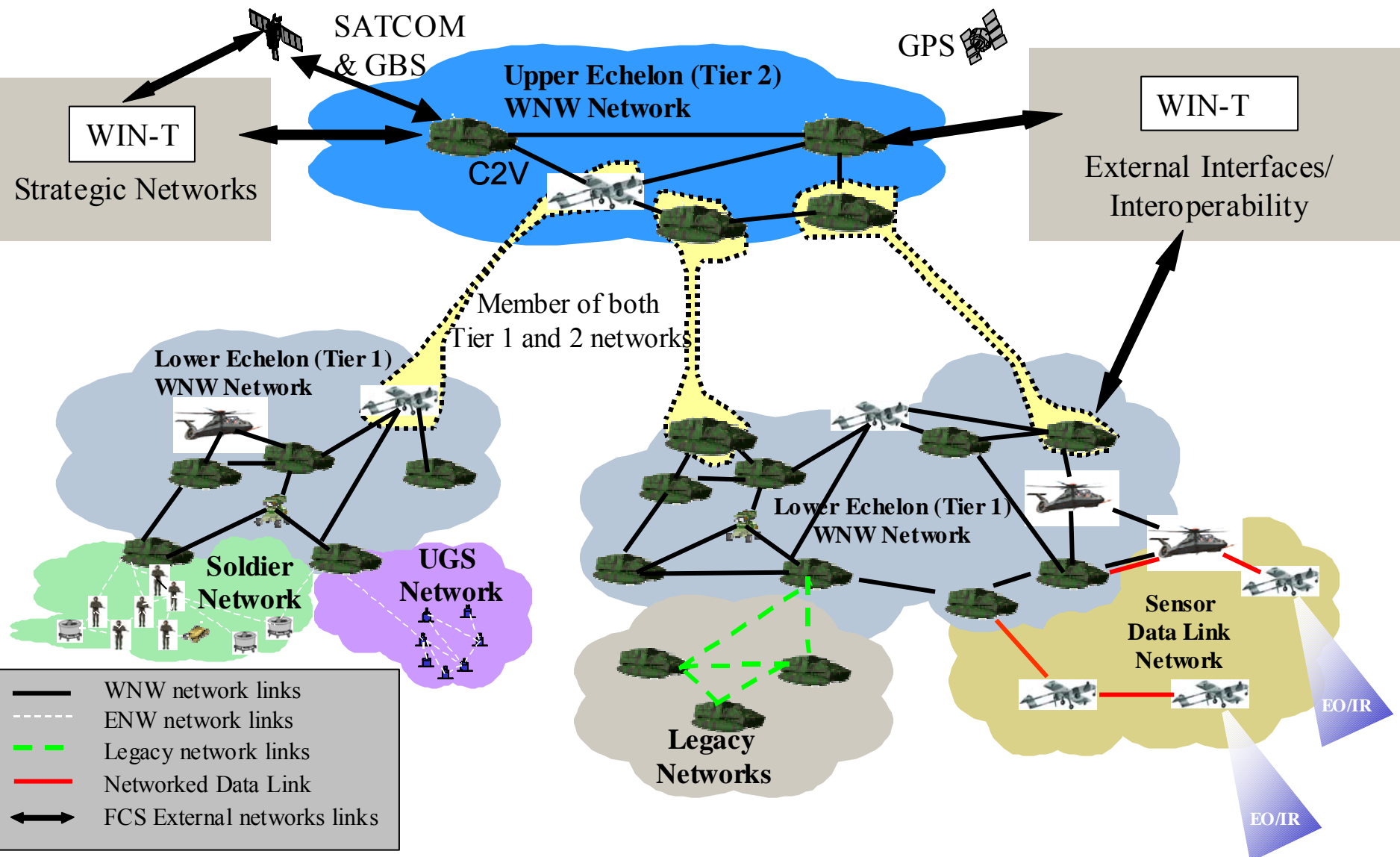
→ Motivates cross-layer design  
→ Architecture vs. Performance

# Low Duty-Cycled Sensor Network Demands Different Kind of Radio



- ✓ Energy consumed in “staying awake”
- ✗ Moore’s “law” does not extend to Shannon / Maxwell
- Motivates cross-layer design

# FCS (UOA) Network Communications Architecture



# Outline

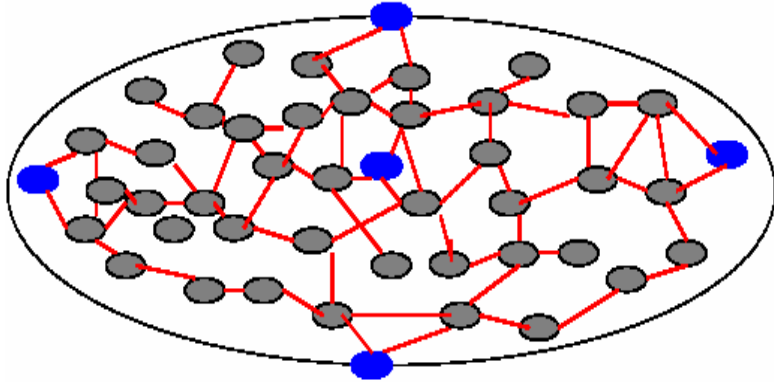
- **Basic sensor network problems**  
Distributed Detection  
Estimation  
PHY-MAC

## Some Questions:

- What makes a sensor network different?
- Current methodologies / architectures adequate?
- What are the challenges ?
- Who owns / controls the sensor ?
- Who has access to the sensor ?
- How many sensors are alive? For how long?
- Should sensors talk to each other : how much ?
- **MAC issues:**
  - Nodes may have only one packet to send (no stability issue)
  - Nodes have finite battery : listening consumes energy
  - ‘Send when the channel is good’
  - How to control sensors

➤ **Motivates judicious cross-layer design**

# Large Scale Sensor Networks



## Applications:

- Infrastructure security / area denial
- Traffic control
- Habitat monitoring
- Target detection / tracking
- Chem-bio-Rad detection
- DSN, SensIT, Rembass, TRSS, CEC, FDS, ADS, SoSuS

## Nodes:

- Randomly deployed
- Many nodes, wide area
- Low power, low duty cycle
- Low cost and complexity
- Asynchrony

## Channel :

- Fading, path loss; NLOS
- CCI / CSI; Jamming

## Network:

- Peer-to-peer or Hierarchical ?
- Packets to/from gateway nodes
- Gateways may be mobile
- Correlated / asymmetric traffic

- **Interplay between sensing, SP, comms and control**
- **Data-centric paradigm**

# One Hop or Multi-Hop

Transmitting one bit:  $E_{\text{tx}}(r) = e_{\text{tx}} + \max\{e_{\text{min}}, e_{\text{out}} r^{-\alpha}\}$ .

Hardware limit on  $r$ :  $r \geq r_0 = \left(\frac{e_{\text{min}}}{e_{\text{out}}}\right)^{\frac{1}{\alpha}}$

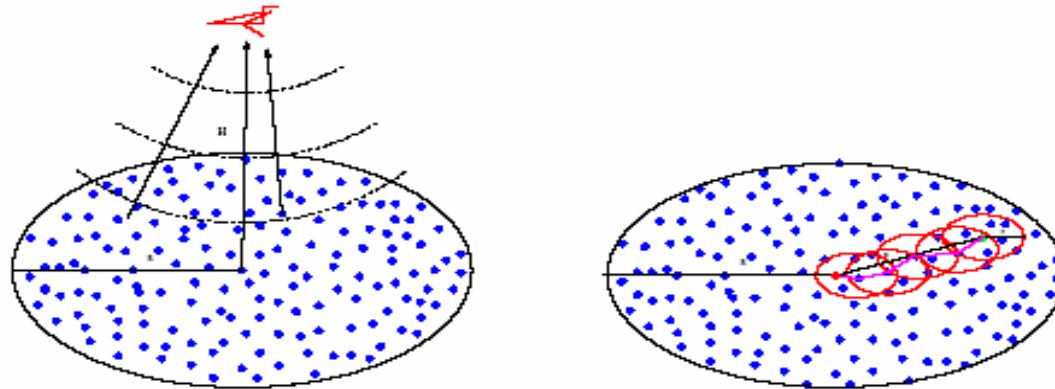
Energy consumption in one hop

$$\mathcal{E}_1(r) = E_{\text{tx}}(r) + \left(\frac{r^2}{R^2}(N - 1)\right)E_{\text{rx}}$$

Minimum Transmission Range

$$r \geq r_{\text{min}} \triangleq \max\left\{r_0, R\sqrt{\frac{\log N}{N}}\right\}$$

# Energy efficiency: a case for mobility



$$\mathcal{E}_{\text{SENMA}} = E_{\text{tx}}(H) = \mathcal{O}(1)$$

$$\mathcal{E}_{\text{AdHoc}} = \begin{cases} \mathcal{O}(\sqrt{N \log N}) & \rho \uparrow, r_0 = 0 \\ \mathcal{O}(N) & \rho \uparrow, r_0 > 0 \\ \mathcal{O}(\sqrt{N(\log N)^{\alpha-1}}) & R \uparrow \end{cases}$$

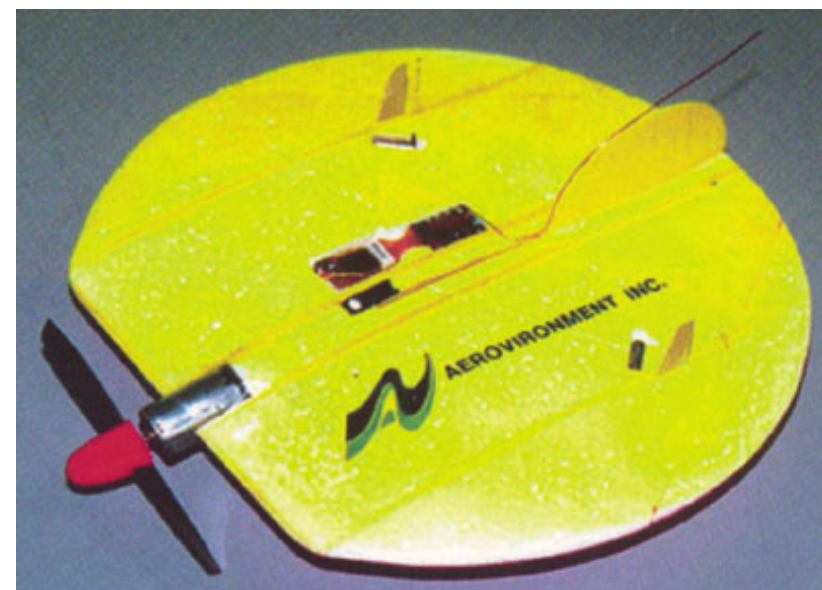
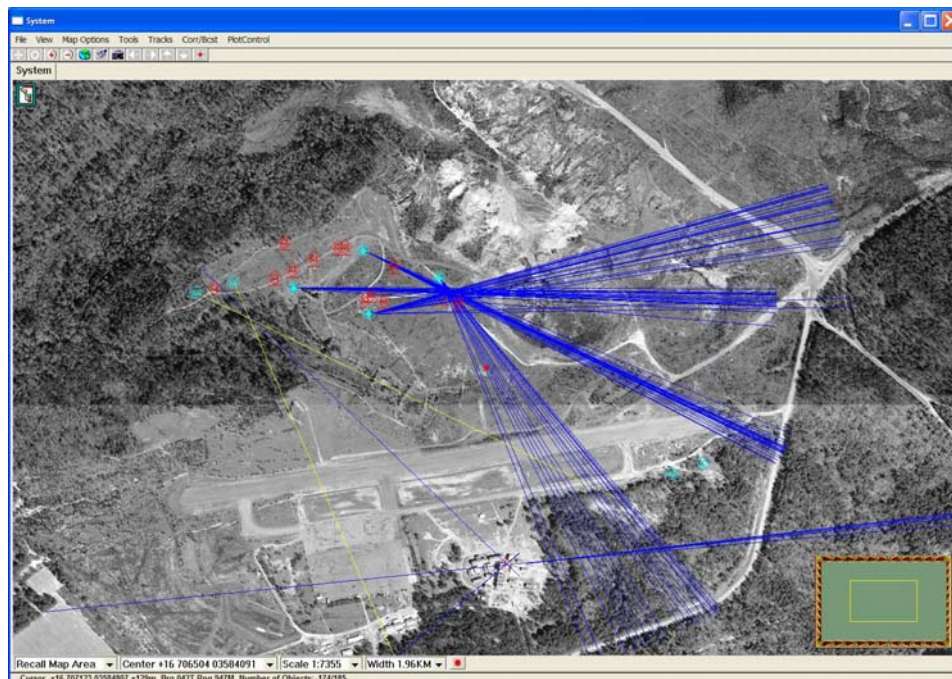
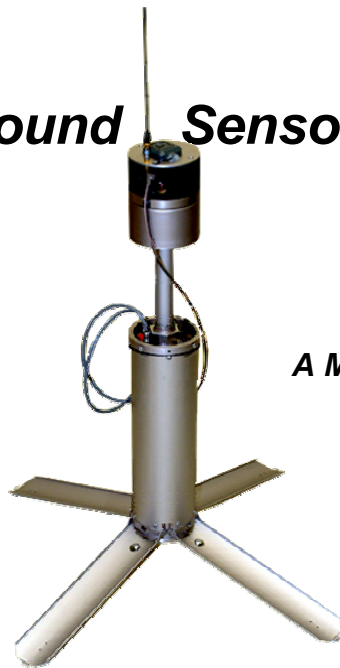
## Remark

If  $\mathcal{O}(\sqrt{N})$  number of packets are to be extracted, then **energy consumption per node** is unbounded as  $N \rightarrow \infty$  without perfect scheduling!

→ Listening / Routing dominates energy consumption

# UGS: Unattended Ground Sensor Array

SOME SENSORS



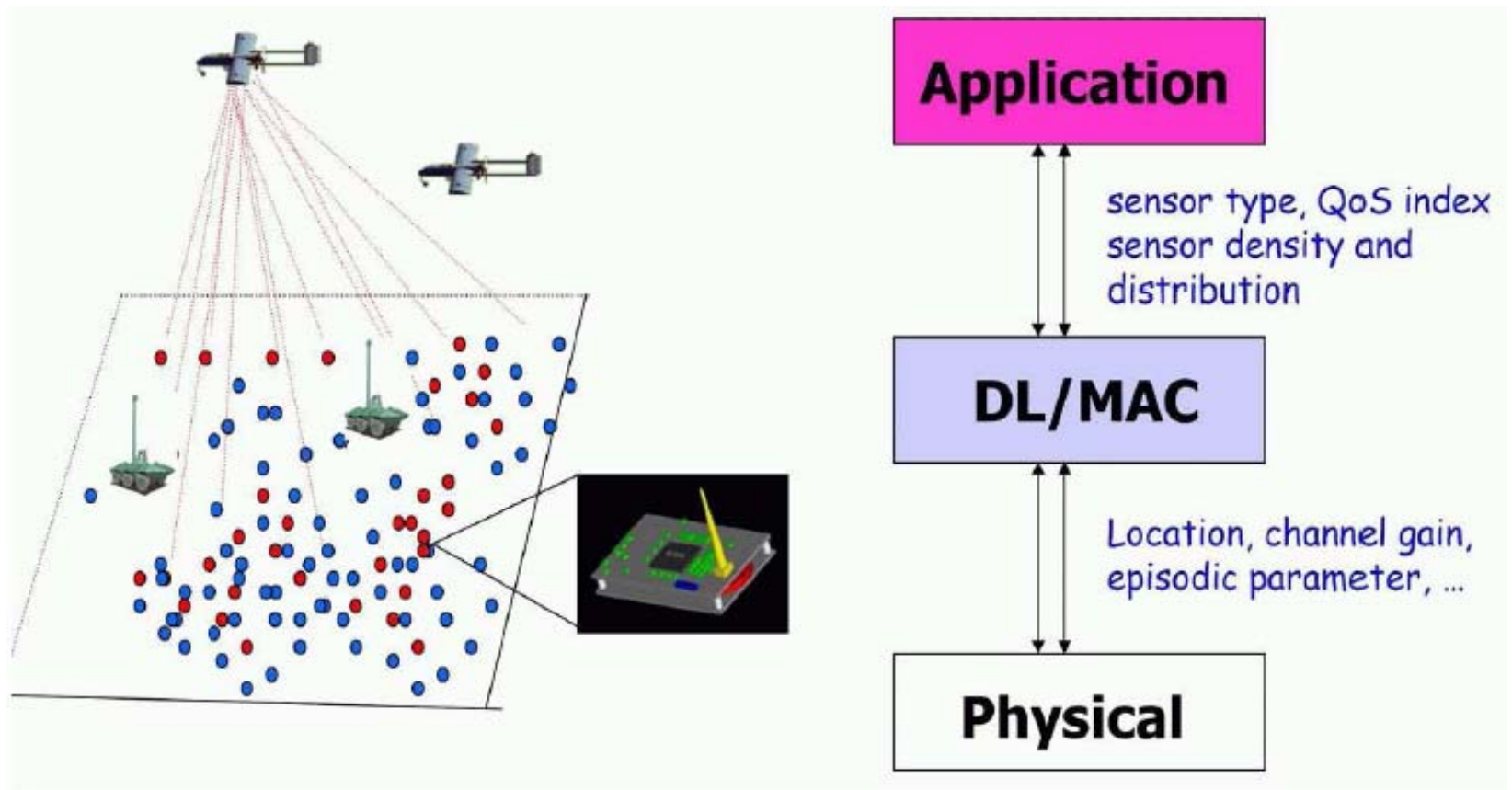
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An UGS array of IR and acoustic sensors track a convoy.

PACBOT



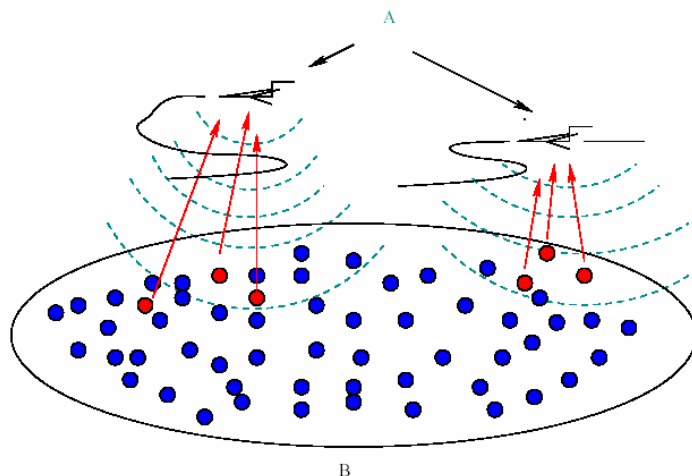
# Cross-Layer Design with Mobility



# Outline

- Basic sensor network problems
  - Distributed Detection**
  - Estimation
  - PHY-MAC

# Example 1: (Distributed) Detection



- ✓ Optimal fusion rule?
- ✓ Optimal local threshold?
- (APP-MAC-PHY interaction)
- ✗ How many bits per sensor ?
- ✗ Identical sensors?
- ✗ With correlated data?

- $Y_i = W_i + \theta s(X_i)$  :  $W$  iid
- Binary sensors
- RA channel

## Approach:

- *Local* problem:  $\theta \sim 0$
- *Asymptotic*: Many sensors
- *Randomly* distributed sensors
- *Marked thinned IPP*

[STS, 2004]

# Non-Randomized ALMP Global Detector

- **Optimal Fusion Rule:** Decide  $H_1$  ( $\theta > 0$ ) if  $\Delta_{n,o} > Q^{-1}(\alpha)$

$$\Delta_{n,o} = [ \sum_A s(x_i) - n \lambda_o \int_A s(x) dx ] / [ n \lambda_o \int_A s^2(x) dx ]^{1/2}$$

- **Power under fixed global size:**

$$\rightarrow Q( Q^{-1}(\alpha) - \theta [ n \lambda_h p_m [\beta'(0; \tau_o)]^2 / \beta(0; \tau_o) \int_A s^2(x) dx ]^{1/2} )$$

- **Optimal local threshold:**  $\tau_{opt} = \arg \max \{ [\beta'(0; \tau)]^2 / \beta(0; \tau) \}$

- **For AWGN channel:**  $\tau_{opt} = 0.612 \sigma_w$

**$\rightarrow$  local size = 0.27 : 'poor' sensors**

- Error decreases exponentially in "SNR"
- Build a better MAC? Increase sensor density?

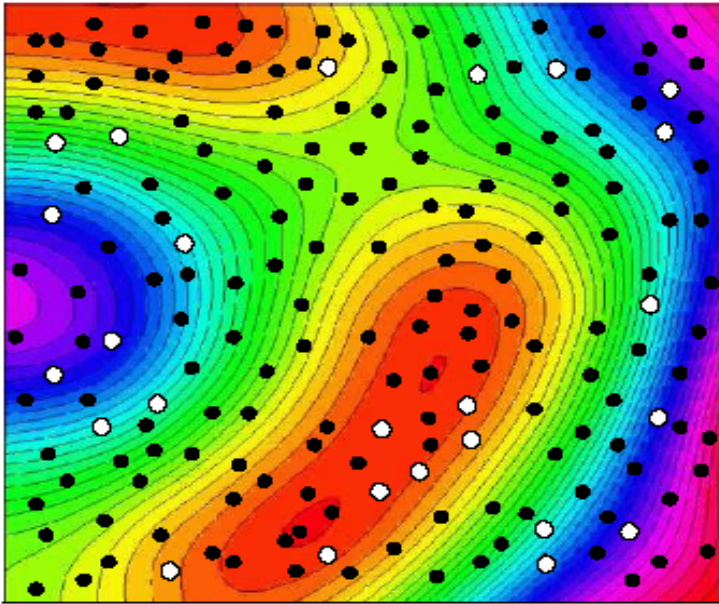
$$\lambda_o = \lambda_h p_m \beta(0; \tau_o)$$

- $\rightarrow n p_m$  must increase with  $n$  :

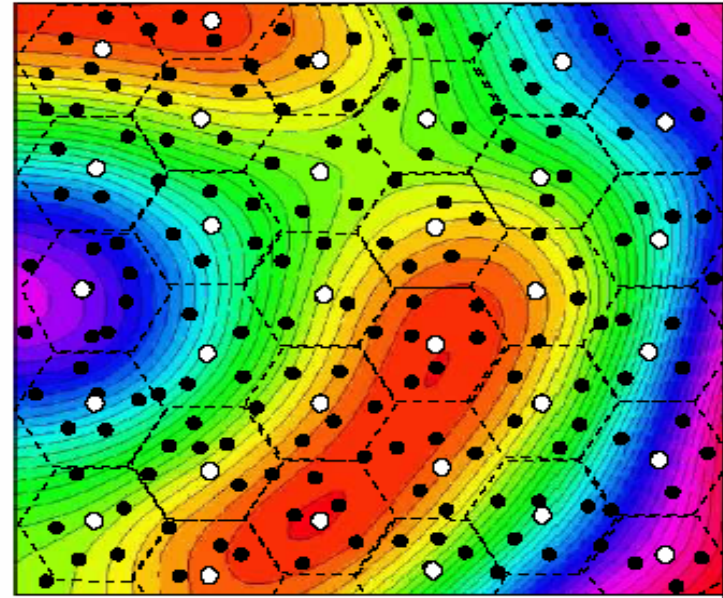
# Outline

- Basic sensor network problems
  - Distributed Detection
  - Estimation**
  - PHY-MAC

# Impact of MAC on Estimation



Random Access



Deterministic Scheduling

Which MAC is preferable?

# Random or Regular Sampling ? Random Access or Scheduling ?

## Assumptions:

- Dense network; sensors know locations
- AR(1) model for data : `interpolation`
- Metric: Expected Maximum Distortion
- Random access needs  $O(\log K)$  more packets;  
has  $O(\log K)$  higher excess MSE:

$$\mathbf{M}_D = \mathbf{O} ( \mathbf{M}_R / \ln \mathbf{M}_R )$$

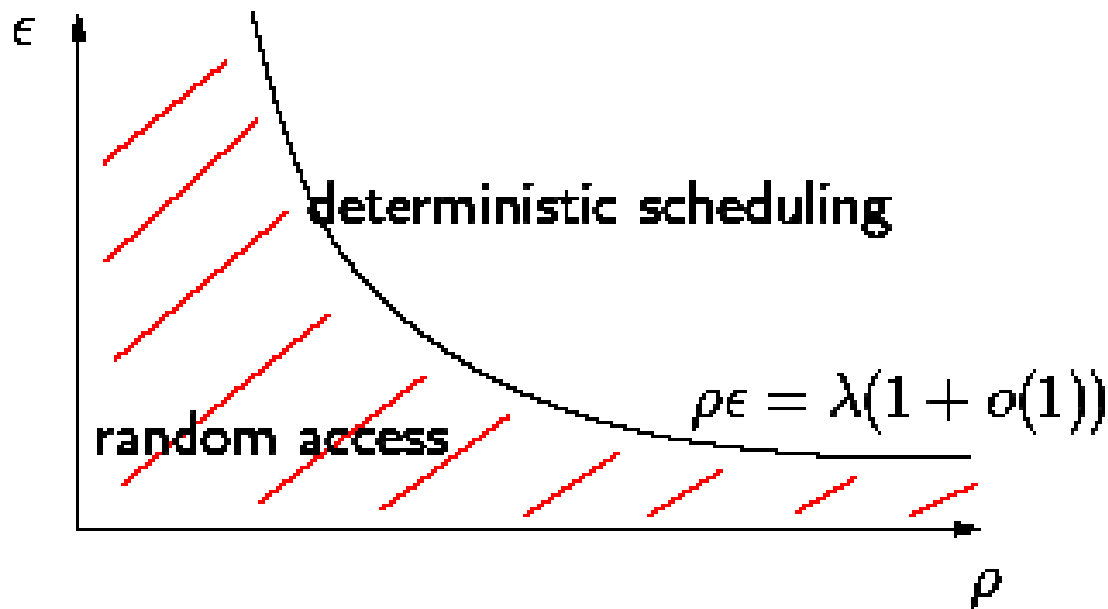
$$\mathbf{r}(\mathbf{K}, \mathbf{SNR}) = \ln (\mathbf{K}) + \mathbf{O}( .. )$$

*Should we always schedule ?*

[DTS, 2003]

### 3. Estimation: Finite Density Networks

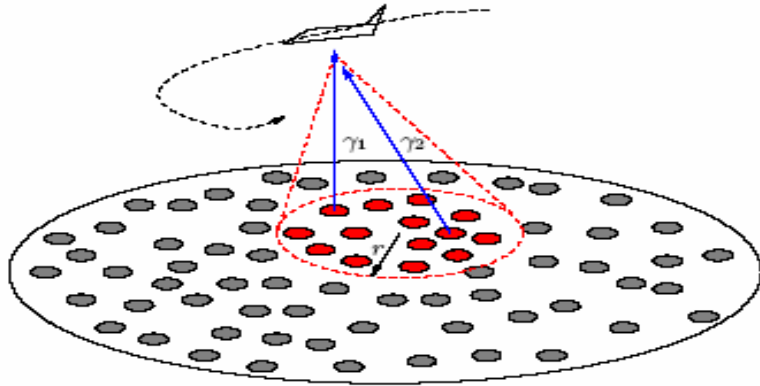
- DS: sensor may not exist
- RA: Collision channel



# Outline

- Basic sensor network problems
  - Distributed Detection
  - Estimation
  - PHY-MAC**

# Opportunistic MAC



- Mobility induces fading
- Wait for a good channel

## Distributed Opportunistic MAC

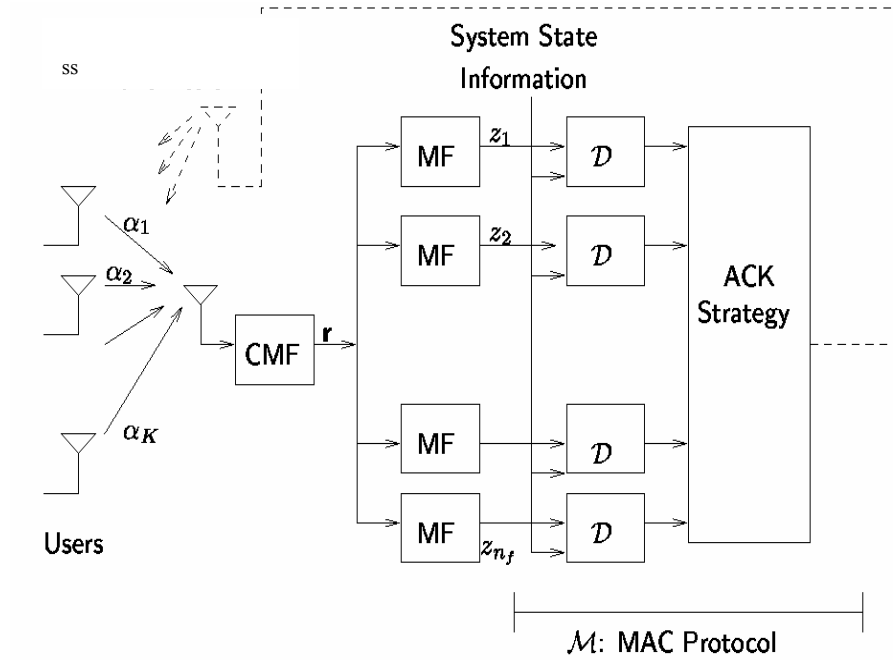
- **Channel Acquisition**  
Estimate  $\gamma$  from beacon.
- **Opportunistic ALOHA**  
Transmit with probability  $s(\gamma)$ .
- **Opportunistic CSMA**
  - Sense carrier with backoff  $\tau(\gamma)$ .

## Advantages

- Simplicity. □ Scalability.
- Energy Efficiency.

- Transmit with probability based on CSI : O-ALOHA

# Example 4: Optimal Detection for MAC

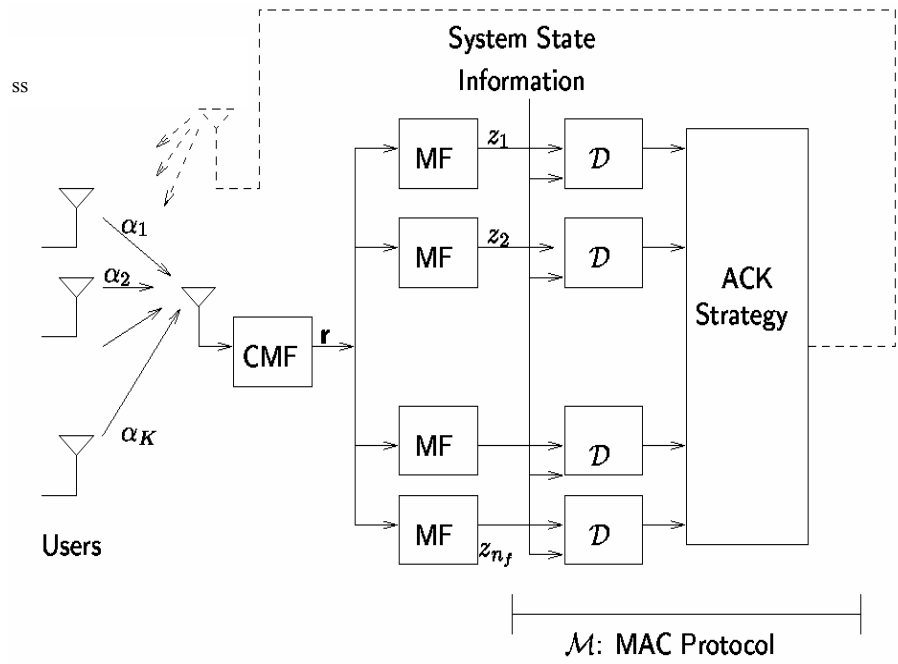


## Optimal Detection at the Receiver:

- MAC assumes accurate detection of requests.
  - RTS-CTS exchanges. Busy-tone detection.
- Missed detections and false alarms likely in interference-rich environment
  - What is the impact on the MAC?
  - How do we model PHY / MAC interaction ?
- What is the detector that optimizes the MAC performance (throughput and delays)?
- Markov chain formulation / Optimal Bayesian detector

[MTS, 2003]

# Signal Model



Users select random codes  
Unknown fades

$N = \#$  orthogonal codes  
 $f = \#$  free codes  
 $L =$  packet length  
 $\lambda =$  arrival rate

MF output is a sufficient statistic:  $\sim \text{CN}(0, K_i \sigma^2 + \sigma_v^2)$   $K$  is unknown.

Traffic: Poisson w aggregate rate  $\lambda \rightarrow K$  is Poisson ( $\lambda / f$ )

PHY-MAC problem:  $K = 1 ?$  Metric ?

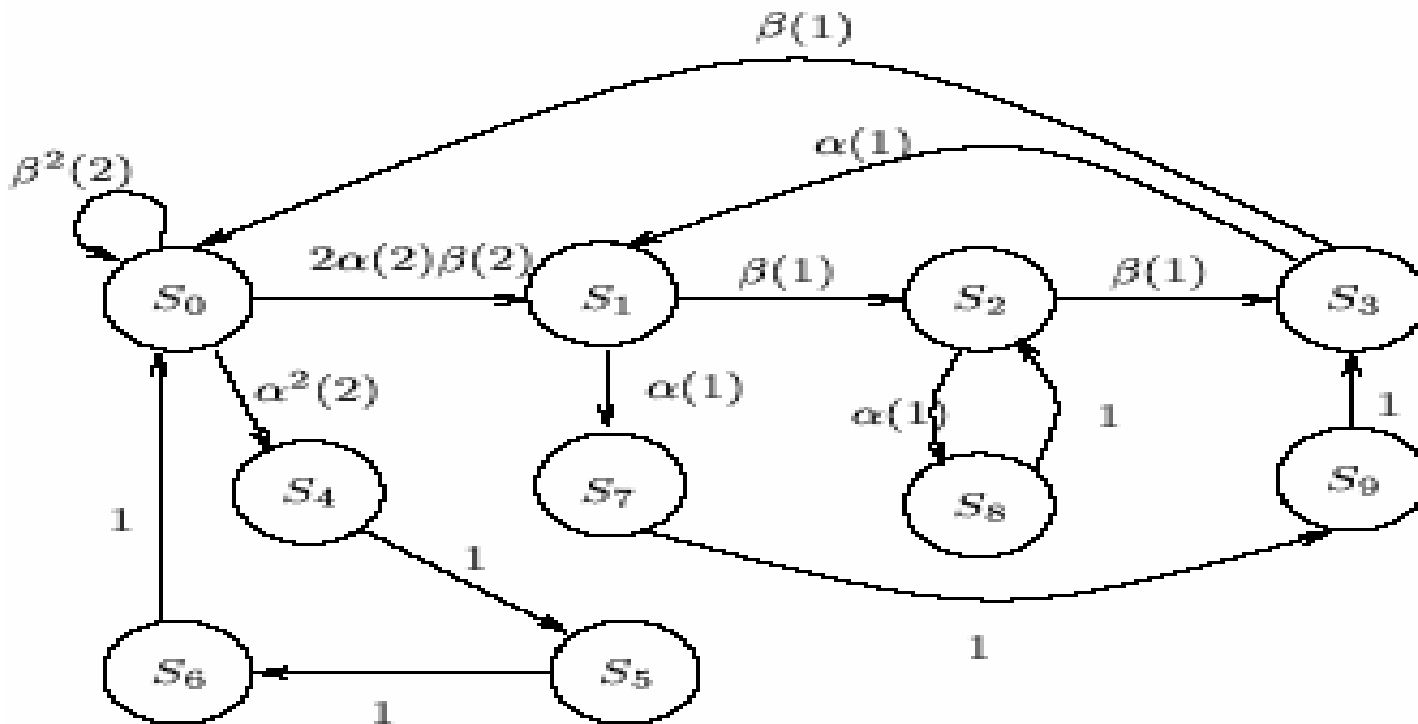
Two Approaches:

- Optimal detection + optimal scheduling
- Joint optimization to maximize throughput

# Markov Chain for N=2, L=3

$\alpha(f)$  = Prob of ACK'ing a channel, given  $f$  free channels

$$\beta(f) = 1 - \alpha(f)$$

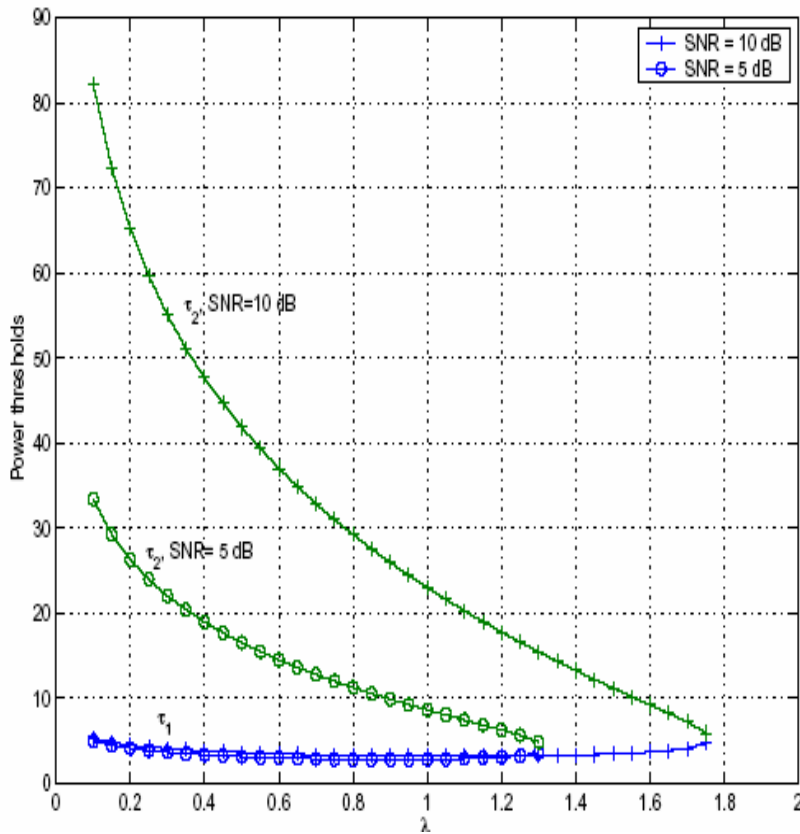


Symbol	State	$f_i$
$S_0$	[0 0 0]	2
$S_1$	[0 0 1]	1
$S_2$	[0 1 0]	1
$S_3$	[1 0 0]	1
$S_4$	[0 0 2]	0
$S_5$	[0 2 0]	0
$S_6$	[2 0 0]	0
$S_7$	[0 1 1]	0
$S_8$	[1 0 1]	0
$S_9$	[1 1 0]	0

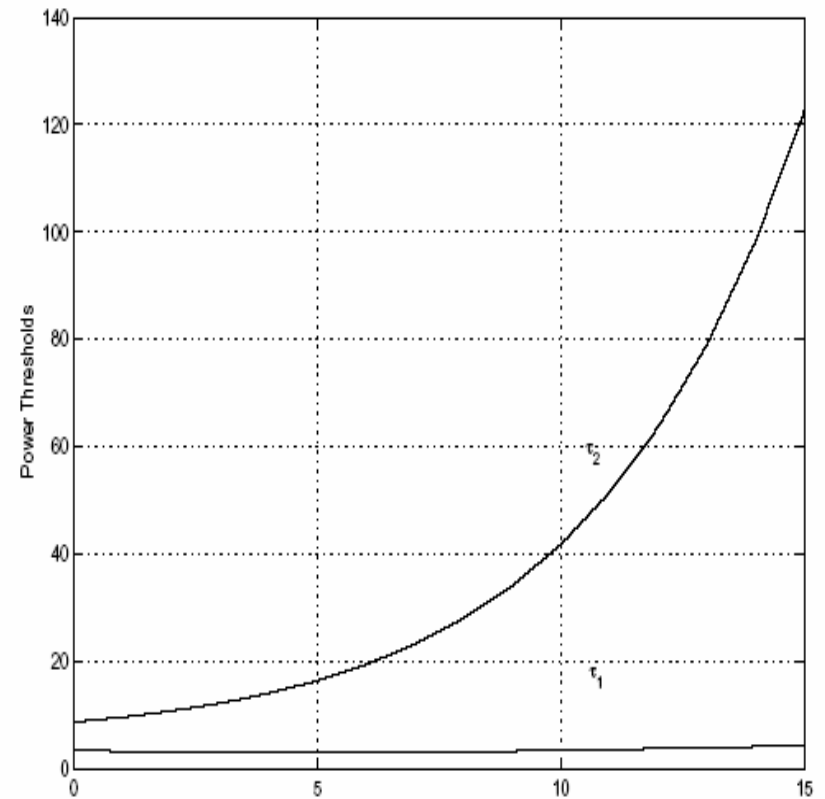
\*  $\forall N, L$ , Markov chain is finite, aperiodic, and irreducible  $\rightarrow$  Steady state distribution  $\pi_{\delta}$  exists

# Optimal Decision Regions

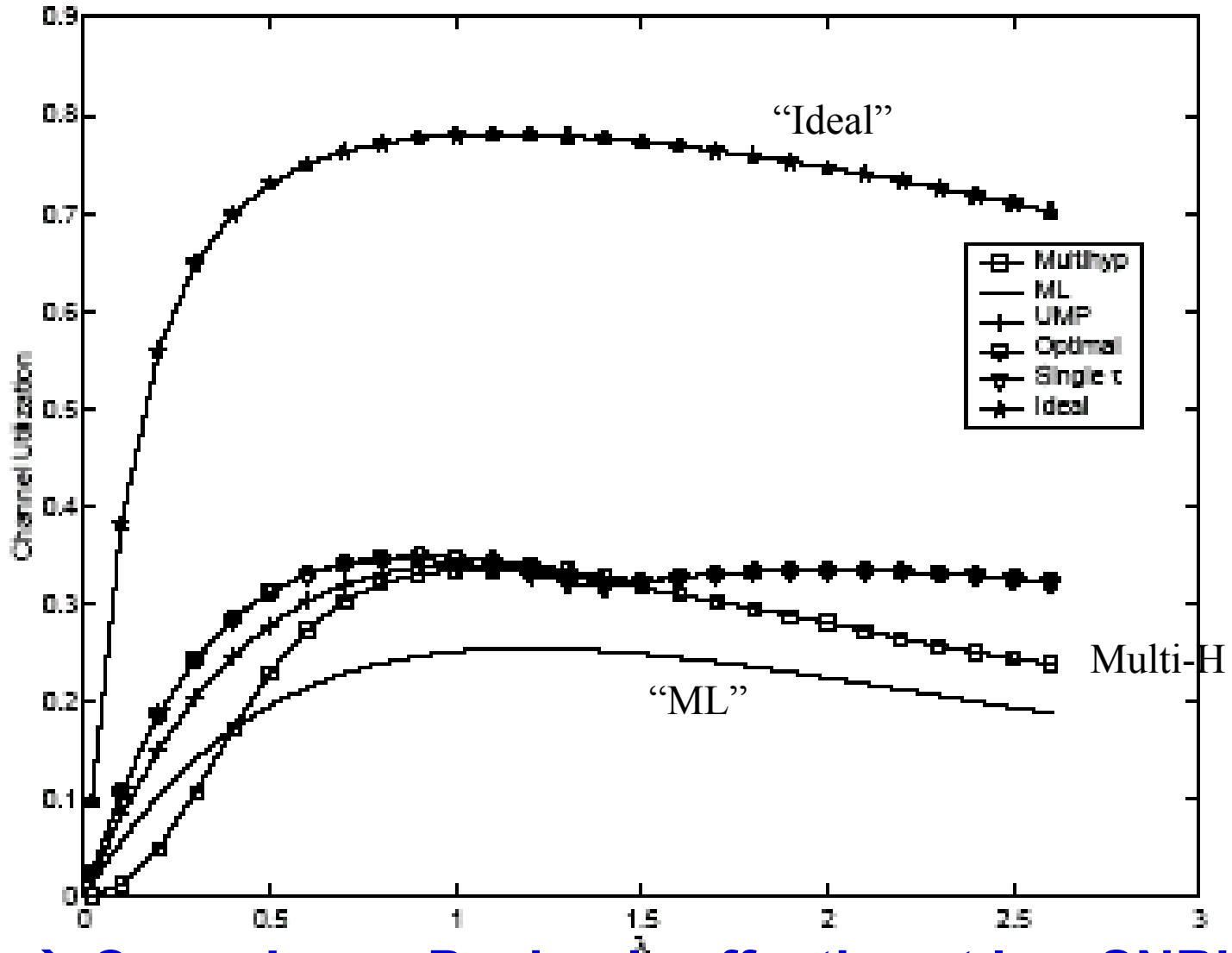
vs. arrival rate



vs. SNR

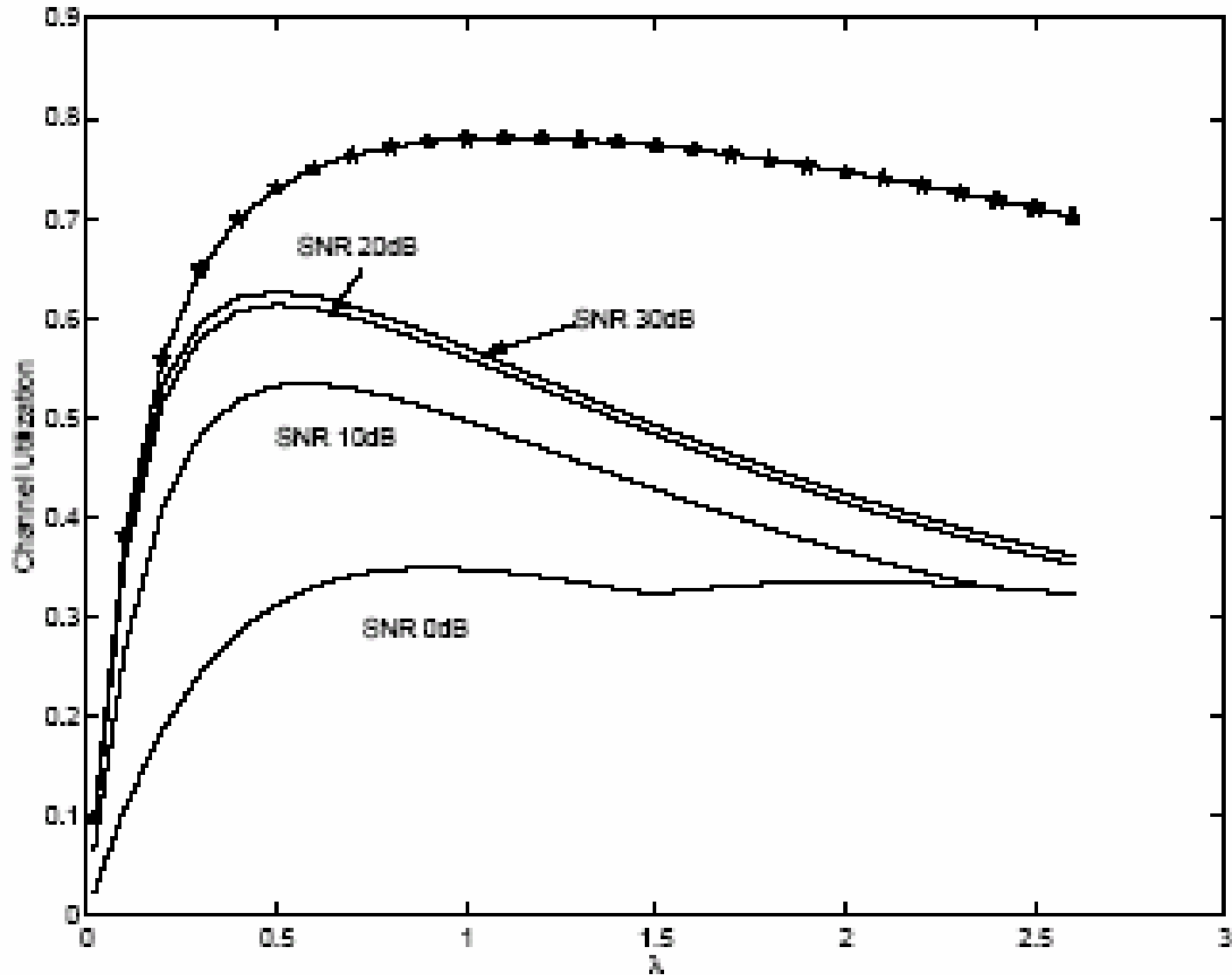


# Utilization vs. Traffic Rate



→ Cross-Layer Design is effective at low SNR's

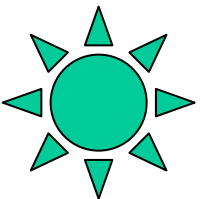
# Utilization Curves



→ A Gap still exists

# Cross-Layer Design

- promises adaptability, agility, efficiency.
- Does not always imply improved performance.
- Potential for instability
- Sensor networks are application specific; PHY+MAC+APP cross-layering natural.



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