Networked Signal Processing

Netted Sensors Community Workshop
Mitre-DC 25 Oct 2005

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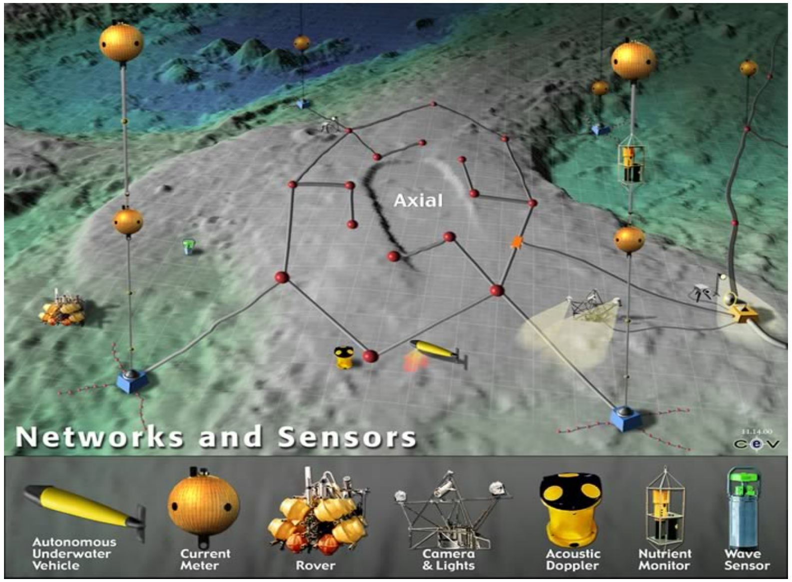
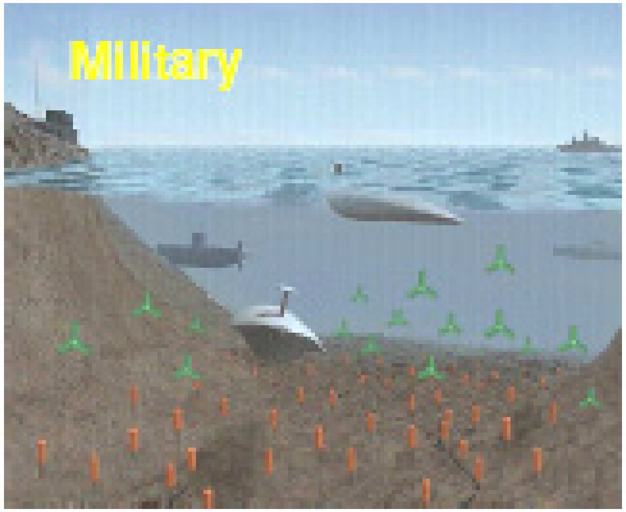
AEROVIRONMENT INC.


Environment


Axial
Networks and Sensors
Autonomous Underwater Vehicle
Current Meter
Rover
Camera & Lights
Acoustic Doppler
Nutrient Monitor
Wave Sensor


Military

Sensor Networks are not MANET'S

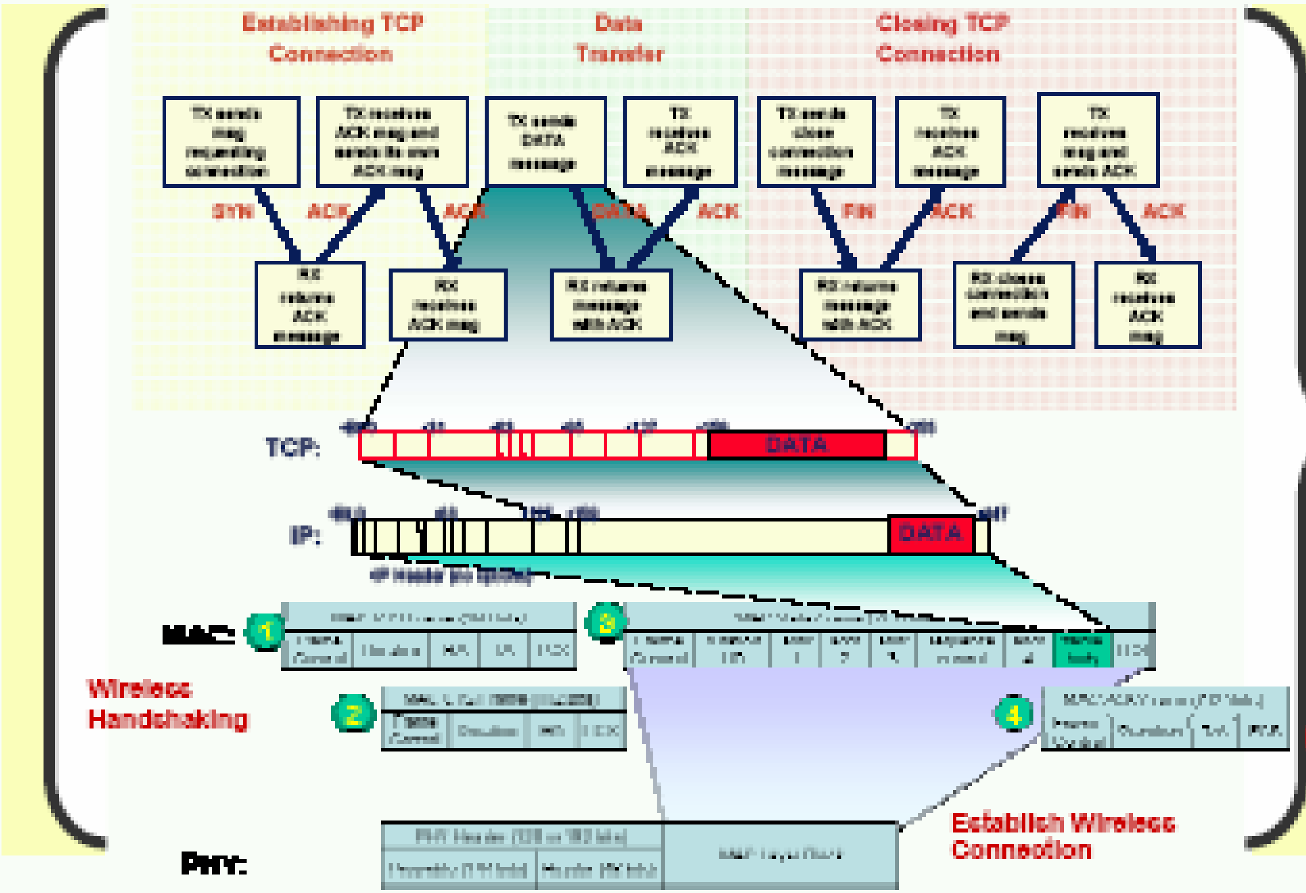
- **Limited energy and large networks:**
  - Duty cycling → synchronization & self-localization issues
  - Limited data to send → metrics must be tied to application
  - Novel protocol stack decompositions; impacts hardware
  - Scalable energy-efficient protocols
- **Application dictates metrics → architecture & protocols**
  - distributed detection, estimation, tracking, monitoring, …. ?
  - MAC and routing impact estimation & detection accuracy and design of local sensors
  - Short hops or long hops ?
  - ➢ Fundamental interplay of MAC, Routing, and Application
- **Wireless is Broadcast → cross-layer design inevitable**

Scaling Issues and Energy Constraints are critical.
Cannot graft `wired approaches' onto wireless medium

Existing Network Protocols Are Not Always Efficient

EXAMPLE #1 (Cont'd): TCP/IP/RTS-CTS – Transfer Inefficiencies, Excessive Overhead, Single 80-bit Payload

CB-MANET: Chris Ramming



TCP/IP Protocols:
Payload: 80 Bits
Total Sent: 2,000 Bits
Transmissions: 6*

% Effective: 4 %

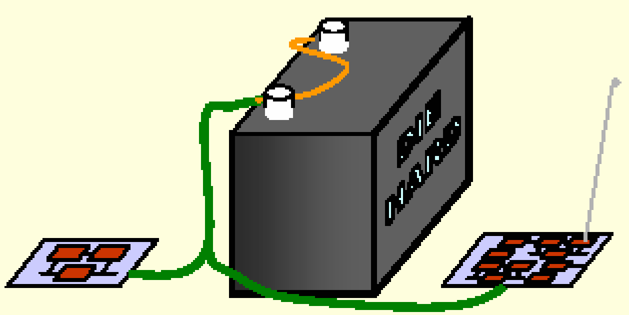
*could be 7 if receiver is not ready to close the connection

Wireless Protocols:
(802.11b)
Wireless Sent: 10,554 Bits
Transmissions 24

BW Efficiency: 0.75 %

It is possible that we need to completely rethink wireless network protocols

Low Duty-Cycled Sensor Network Demands
Different Kind of Radio



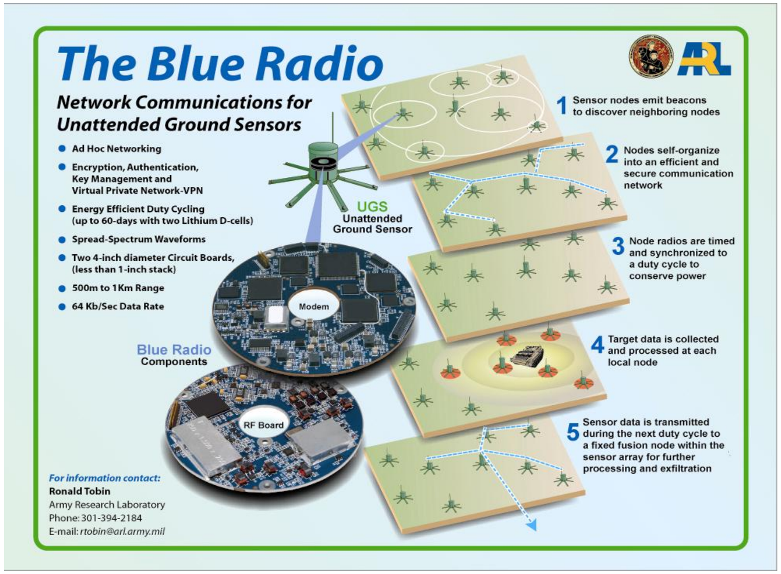
The Future With Current Approaches

DARPA CN:
Preston Marshall

- ✓ DARPA chip-scale atomic clock
  - -30 mW: 100 hrs with 1 AA battery
- ✓ Energy consumed in ``staying awake''
- ✘ Moore's "law" does not extend to Shannon / Maxwell
- ➢ Energy harvesting ?
- ➢ Cross-layer design critical for energy savings

ARL Blue Radio

Survivable energy-efficient communications for distributed, unattended sensor nodes.

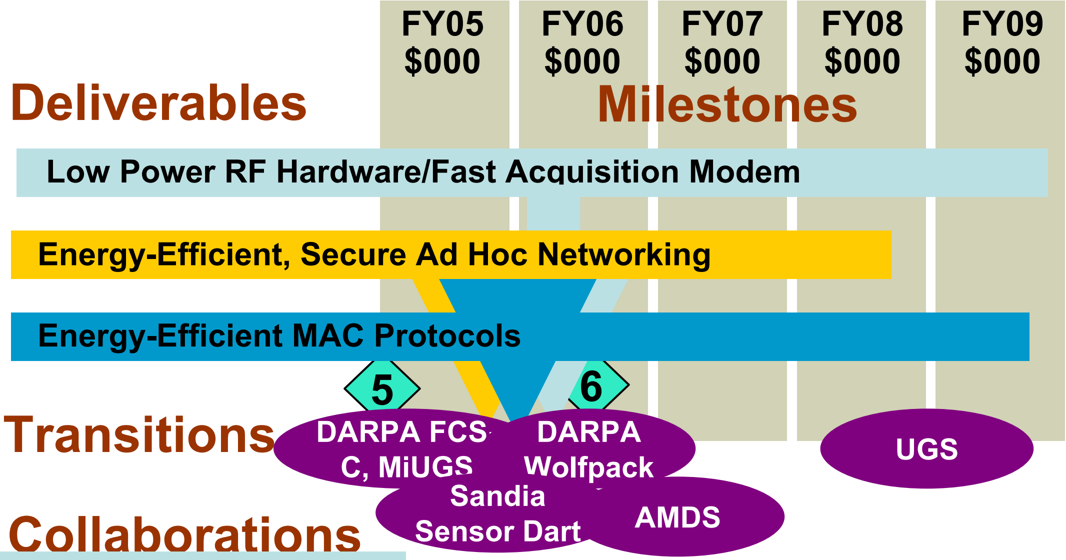


Challenges / Problem

- Extreme bandwidth, power, energy, and computational constraints
- Severe near-earth propagation effects ($1/R^4$ versus $1/R^2$)
- Self-organization under a variety of delivery mechanisms
- Jam-resistant, LPI/LPD operation
- Low cost

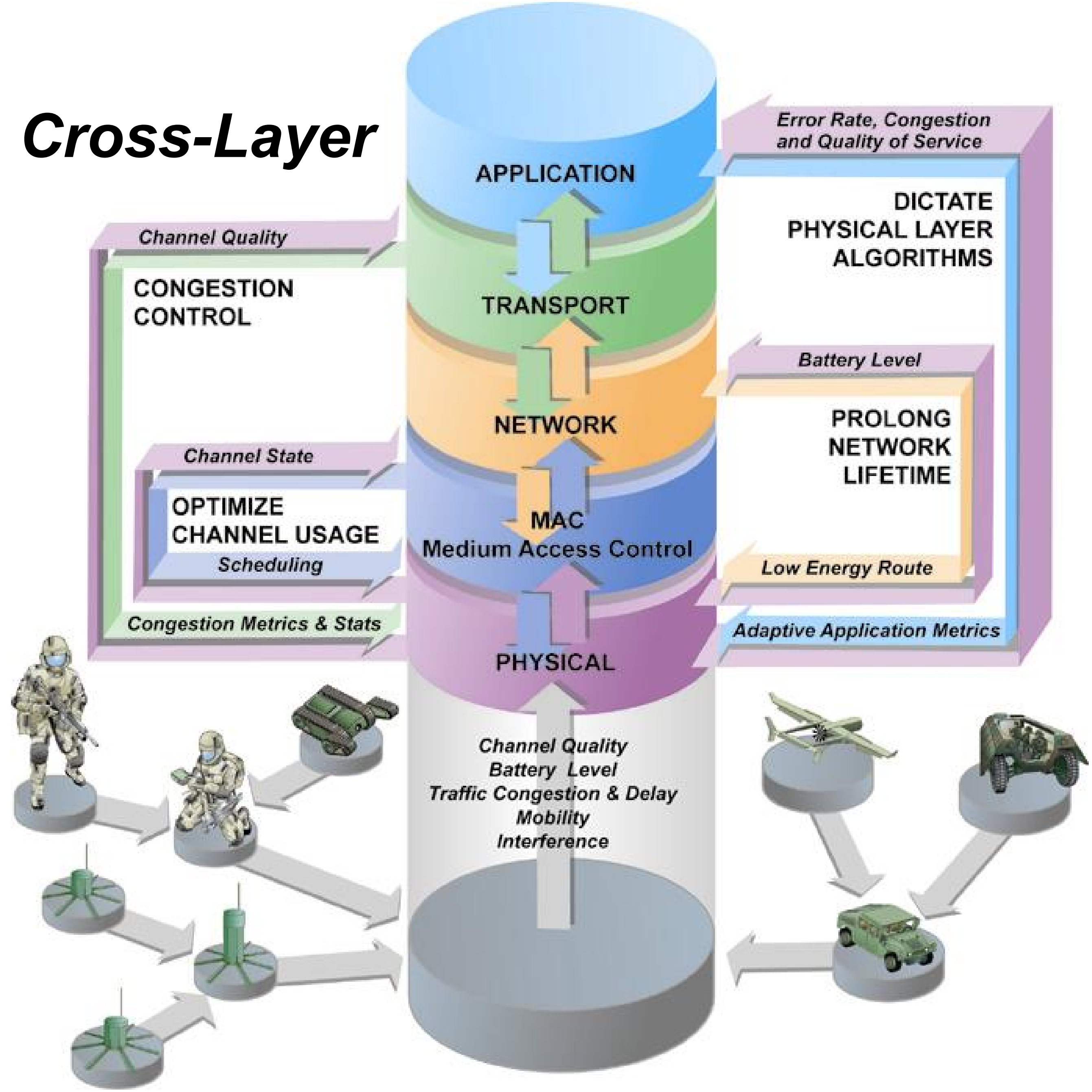
Approach

- Duty cycling to conserve energy
- Robust, high PG waveforms that are fast-acquisition to allow duty cycling
- Low overhead, reactive ad hoc routing
- Energy-efficient MAC including duty cycling, power control, and multi-user detection
- Leveraging commercial wireless radio components (A/D, DSP, etc)



Ron Tobin: rtobin@arl.army.mil

Cross-Layer



APPLICATION
TRANSPORT
NETWORK
MAC
Medium Access Control
PHYSICAL
Channel Quality
CONGESTION
CONTROL
Channel State
OPTIMIZE
CHANNEL USAGE
Scheduling
Congestion Metrics & Stats
Error Rate, Congestion
and Quality of Service
DICTATE
PHYSICAL LAYER
ALGORITHMS
Battery Level
PROLONG
NETWORK
LIFETIME
Low Energy Route
Adaptive Application Metrics
Channel Quality
Battery Level
Traffic Congestion & Delay
Mobility
Interference

SP for Networking

- Channel State Information
  - Power control (Knopp-Humblet ICC'95)
  - Opportunistic MAC (Cheng'96, Tse-Hanly'98, Qiu-Berry'03, Zhao-Tong'05)
  - Multi-channel reservation MAC (Maharshi-Tong-Swami'03)
  - Channel-aware routing (Dube'97, Souryal'05, Lin '05).
- Residual Energy Information
  - Sensor placement (Cheng &'04, Ganesan & '04, Chen &'05)
  - Routing (Chang &'00, Shankar &'04, Kannan &'04, Srinivasan &'04)
  - Network lifetime (Chen &'05, Bhardwaj &'02, …. ….)
- Sensor sync and localization
  - Duty cycling, scheduling, routing
- Traffic estimation & change detection (He &'05)
- Network energy profile & density monitoring (Leshem &'05)

Zhao-Swami-Tong, SPM'06

Networking for Signal Processing

- Protocol design for detection, estimation & tracking
  - Data-centric MAC (Liu &'04, Mergen &''04)
  - Energy & data-aware routing (Sung &'05)
  - Distributed detection (Sung-Tong-Swami'05)

- Reconstruction of correlated fields
  - Distributed source compression (Pradhan'02, Xiong'04)
  - Aggregation (Esterin & '00, '02)
  - Sampling (Dong &'04, Iyer &'03)

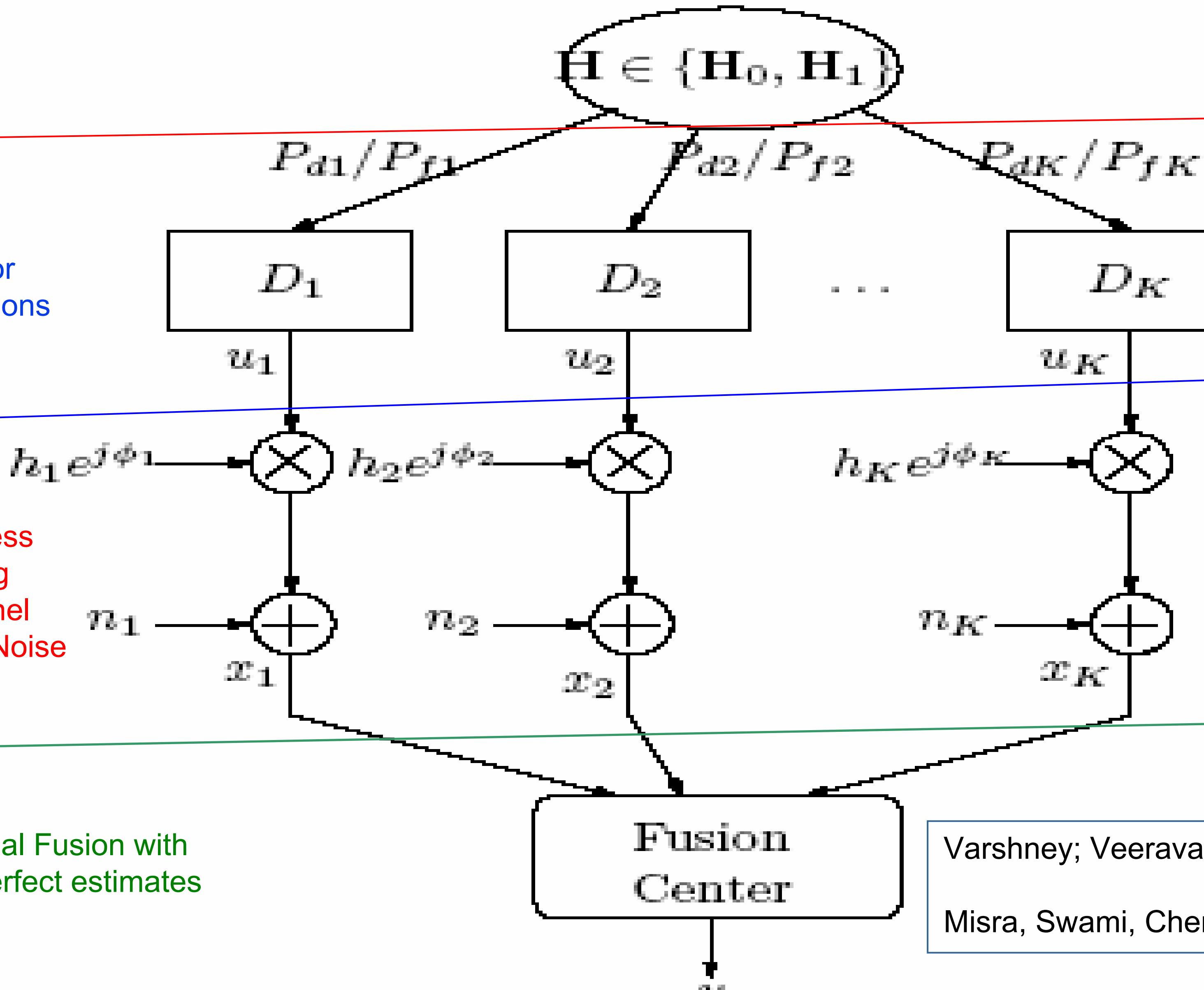
Zhao-Swami-Tong, SPM'06
Swami-Tong, SPM'04

Parallel Fusion Model

Local Sensor Decisions

Wireless Fading Channel MAI+Noise

Global Fusion with imperfect estimates

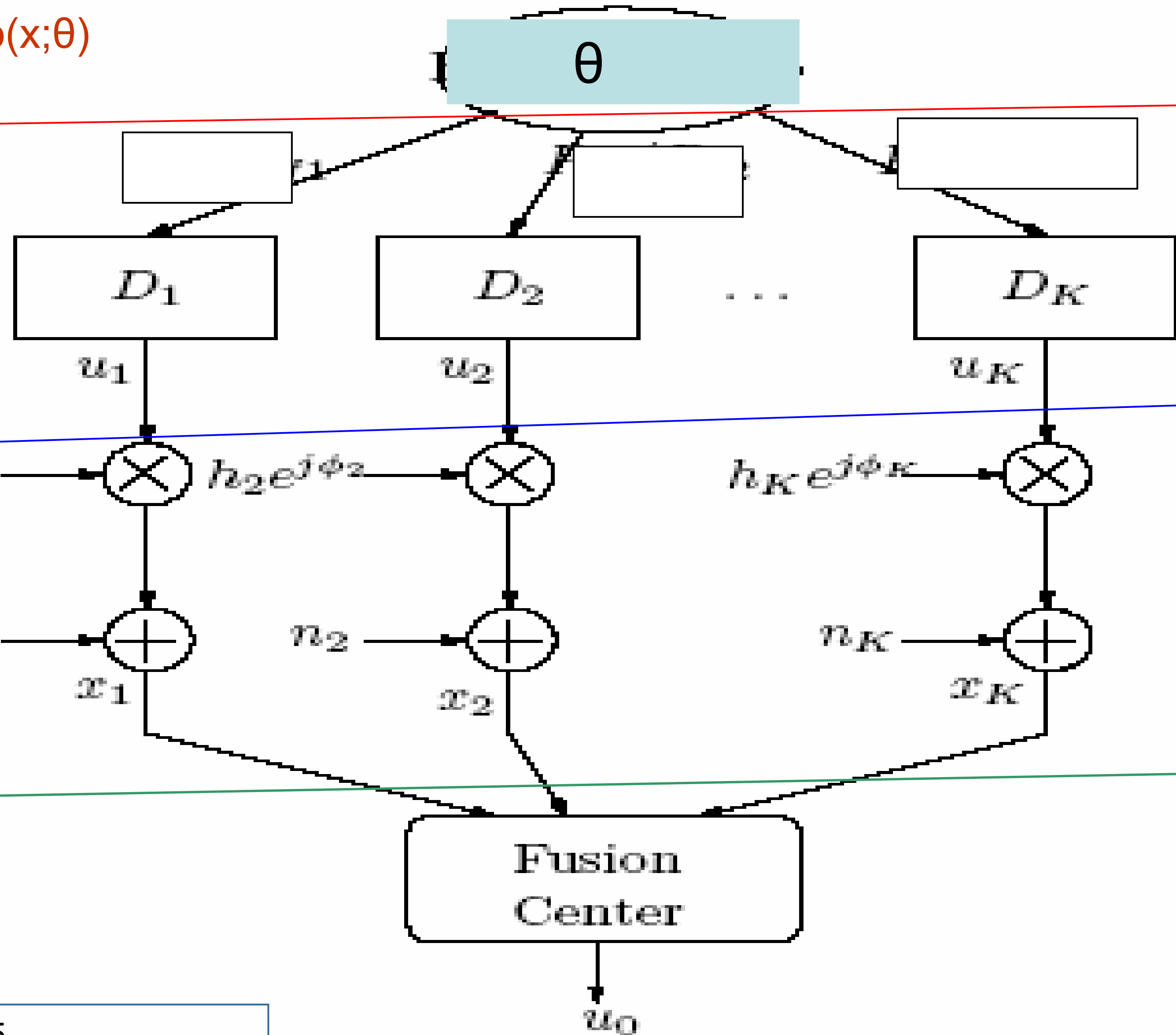


Varshney; Veeravalli (….)

Misra, Swami, Chen, MILCOM'05

Parameter Estimation

M-ary data; p(x;θ)



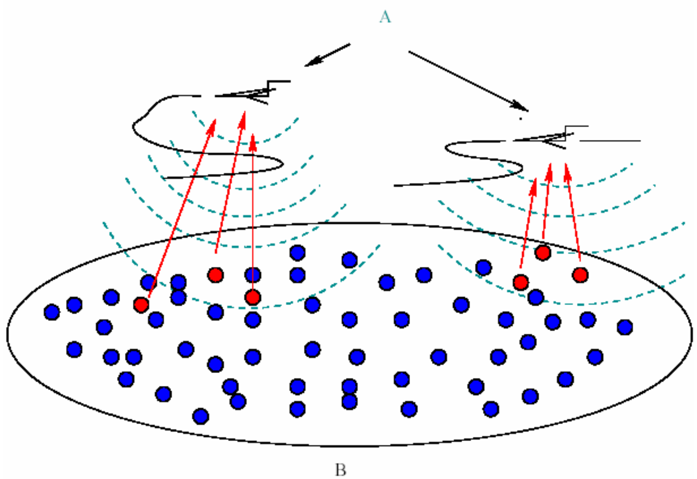
Local Sensor Encoding

Wireless Fading Channel MAI+Noise

Global Estimate

Mergen-Tong 05

(Distributed) Detection over the Network



- ☑ Optimal fusion rule?
- ☑ Optimal local threshold?
- ➢ (APP-MAC-PHY interaction)

Approach:

- *Local* problem: θ ~ 0
- *Asymptotic:* Many sensors
- *Randomly* distributed sensors
- *Marked thinned IPP*

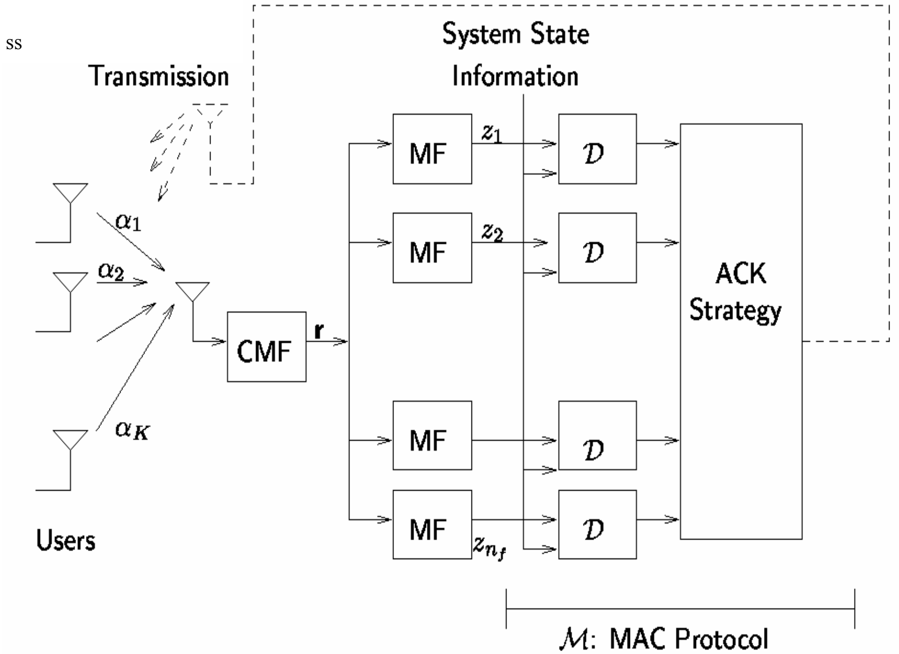
- $\mathbf{Y_i = W_i + \theta\, s(X_i)}$: W *iid*
- *Binary identical* sensors
- Random access channel

- Derived optimal fusion rule
- Derived optimal local threshold

Sung, Tong, Swami: IEEE-TSP 2005

Network Impacts Design of Local Sensor (application)

Optimal Detection for the MAC



Sensors select random codes
Unknown fades

N = # orthogonal codes
f = # free codes
L = packet length
λ = arrival rate

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

Traffic: Poisson w aggregate rate λ → K is Poisson (λ /f)

PHY-MAC problem: K = 1 ? (RTS-CTS) K=0 ? (CSMA) Metric ?

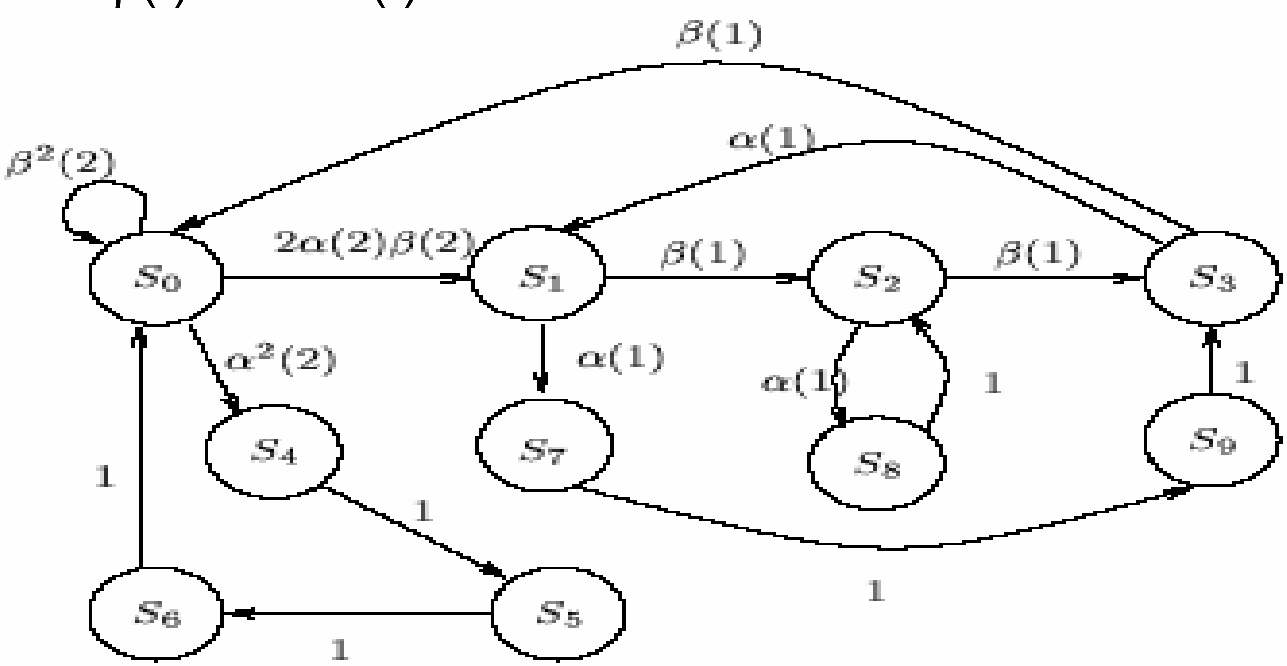
Two Approaches: Optimal detection + optimal scheduling
Joint optimization to maximize throughput

Maharshi, Tong, Swami, 03

Markov Chain for N=2, L=3

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

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

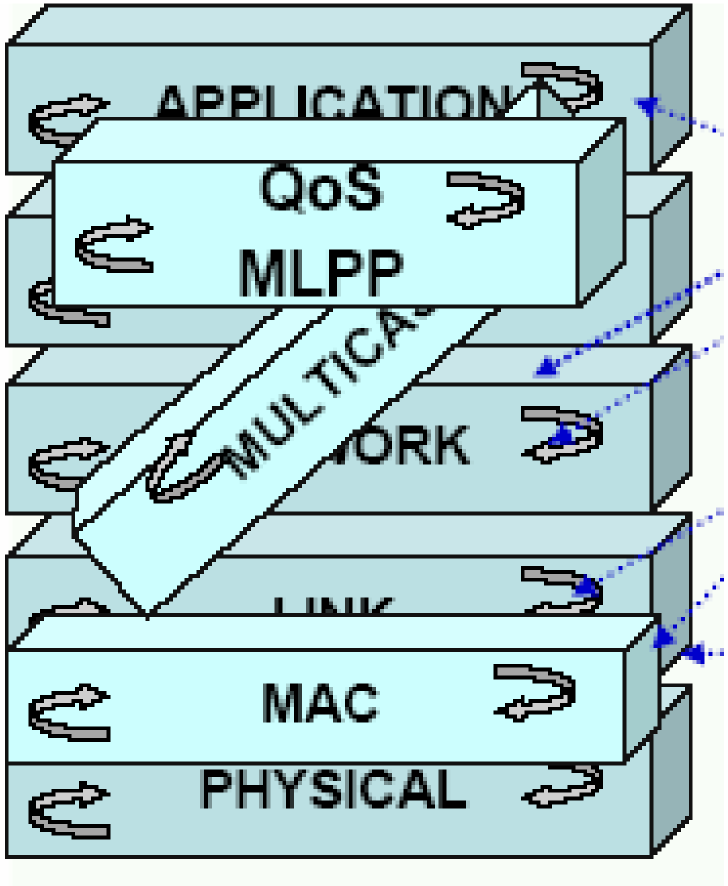


Symbol	State	f_i
S_0	[0 0 0]	2
S_1	[0 0 1]	1
S_2	[0 1 0]	1
S_3	[1 0 0]	1
S_4	[0 0 2]	0
S_5	[0 2 0]	0
S_6	[2 0 0]	0
S_7	[0 1 1]	0
S_8	[1 0 1]	0
S_9	[1 1 0]	0

- ¥ N,L, Markov chain is finite, aperiodic, irreducible → Sty distro π_δ exists
- Throughput = f (threshold); threshold = f(#users, arrival rates, pkt length)

- **CSMA case is more challenging!** **[dyspan, nov 2005]**

Caveats



Too many Knobs & Dials
Too many interactions
Configuration Complexity

- Unintended consequences (Kawadia-Kumar, 2005)
- Security may be compromised
- Application-specific CLD is natural.
- Energy constraint
- Clocks are important
- Only preliminary understanding of cross-layer interactions