Active Wireless Sensing and Applications in RFID-enabled Systems

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Motivation and Overview

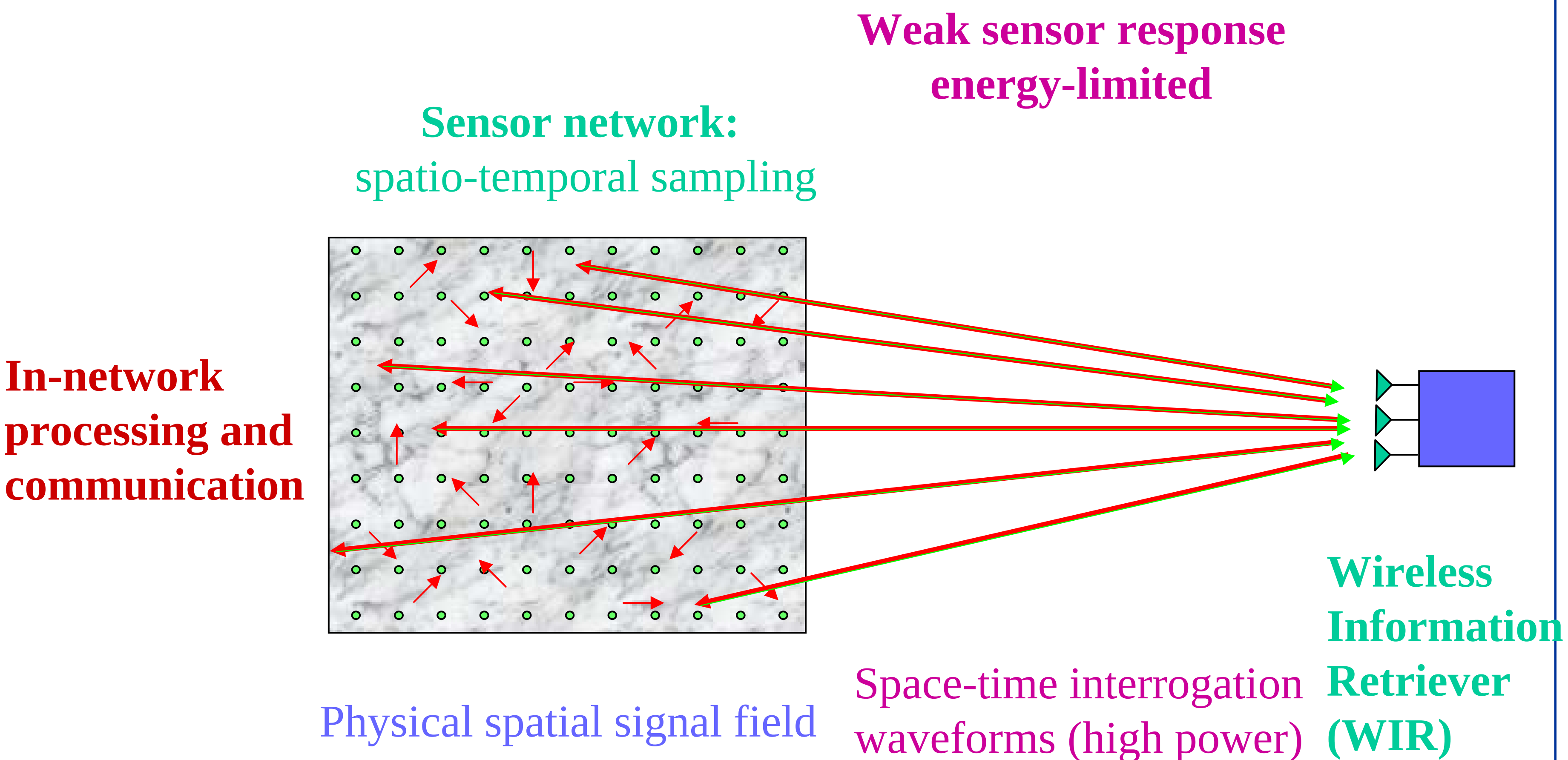
- In-network processing:
  - Excess delay and energy consumption (e.g. routing)

- Active Wireless Sensing (AWS) for information retrieval from an ensemble of sensors:
  - Rapid, energy-efficient, high rate
  - “dumb” sensors
  - “smart” information retriever: interrogates sensor ensemble with RF waveforms
  - Agile RF front-ends: “multi-resolution” information retrieval

- Leveraging multiple technologies: netted sensors, space-time wireless communications, radar

- Potential commercial application: RFID-enabled sensing systems (e.g., bio-chemical sensing)

Active Wireless Sensing



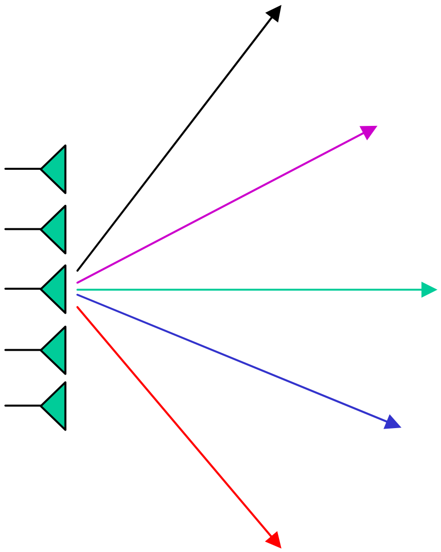
Basic Communication Protocol

- Carrier synchronization: The WIR transmits a carrier tone to synchronize the frequency of local sensor oscillators
- Interrogation: The WIR transmits a spread-spectrum (PN code) spatio-temporal waveform s(t)
- PN Code Acquisition by sensors
- Sensor transmissions: sensors modulate the PN code to transmit their (compressed) measurements to WIR:
  - Non-coherent transmission
  - Coherent transmissions

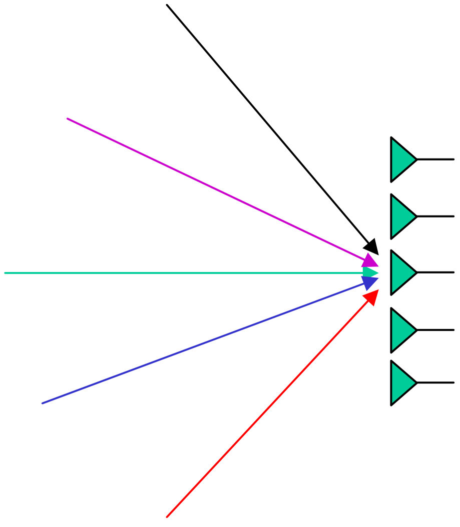
AWS: Challenges and Solutions

- Separating weak sensor signals from the aggregate response
  - Space-time communication over multipath channels
  - Radar imaging (Madhow UCSB)
- Distributed synchronization requirements
  - Active “programming” by the WIR
- Energy-efficiency:
  - Array/directivity gains at the WIR
  - Distributed source-channel matching: “coherent” sensor transmissions matched to field smoothness

Antenna Arrays: Spatial Selectivity



Transmitter (TX) Array



Receiver (RX) Array

Spatially selective transmission

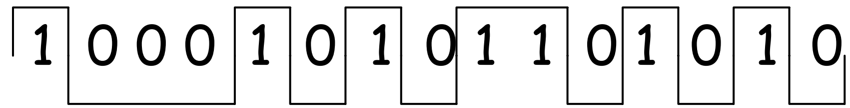
Spatially selective reception

Number of distinct beams = number of antenna elements

Multipath Sensor Response

Suppose M-element uniform linear array (ULA) at the WIR

Transmitted PN code: $q(t)$
Duration = T
Bandwidth = W



PG = N=TW $\quad$ $T_C = 1/W$

Received signal: $$\mathbf{r}(t) = \begin{bmatrix} r_1(t) \\ \vdots \\ r_M(t) \end{bmatrix} = \sum_{i=1}^{K} \beta_i e^{-j\phi_i} \mathbf{a}(\theta_i) q(t - \tau_i) + \mathbf{w}(t)$$

$$\mathbf{a}(\theta) = \begin{bmatrix} 1 \\ e^{-j2\pi\theta} \\ \vdots \\ e^{-j2\pi\theta M} \end{bmatrix}$$

Array steering/response vector

$$\theta = \frac{d}{\lambda}\sin(\phi)$$

β_i = sensor data

ϕ_i = phase offset (random)

τ_i = roundtrip delay

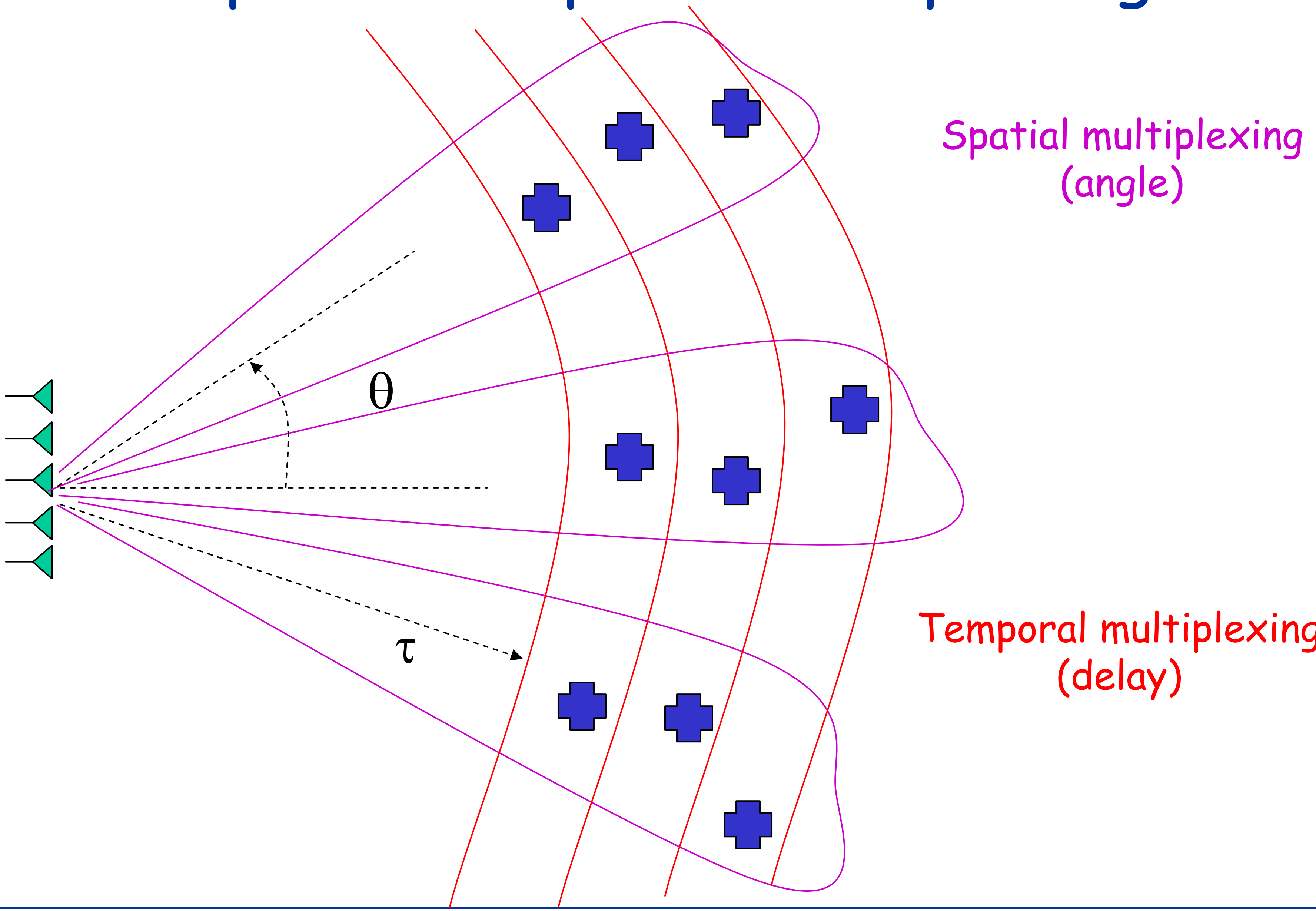
K = number of sensor in the interrogated ensemble

Multipath Resolution in Angle-Delay

- Spatial resolution: resolve the received signals from M fixed uniformly-spaced directions via receive beamforming

- Delay resolution: resolve the signals in each direction (beam) by correlating with delayed versions of the PN code

Spatio-Temporal Multiplexing



Information Retrieval via Angle-Delay Beamforming

MN=MTW space-time signal space dimensions

K interrogated sensors

Angle-delay matched filtering:

$$z_{m,\ell} = \int_0^{T+2\tau_{max}} \mathbf{a}^H(\tilde{\theta}_m)\mathbf{r}(t)q(t-\ell/W)dt$$

$$= \beta_{i(m,\ell)} e^{-j\phi_{i(m,\ell)}} \gamma(\theta_{i(m,\ell)}, \tau_{i(m,\ell)}) + w_{m,\ell}$$

$$\tilde{\theta}_m = m/M \ , \ \ m = 0, \cdots, M$$

$$\ell = 0, \cdots, L \ , \ \ L = \lceil \tau_{max} W \rceil$$

Angle resolution: $\Delta\theta \approx \frac{1}{M}$

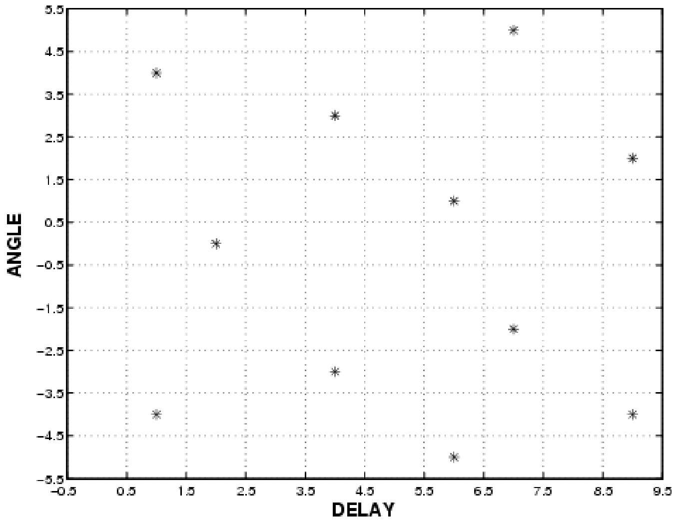
Delay resolution: $\Delta\tau \approx \frac{1}{W}$

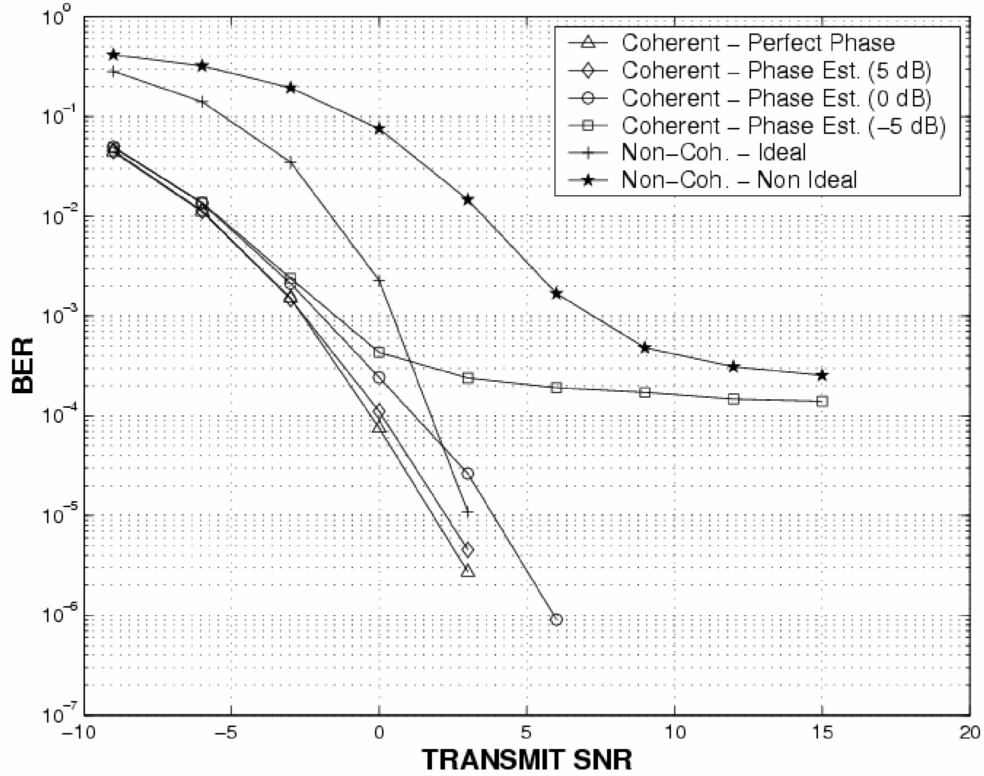
A single sensor in each bin for sufficiently large W; K < ML

Two Extreme Examples

- M=11 antennas, N=PG=127, L=11
- K sensors populating ML=121 angle-delay resolution bins
- Case I (high-rate): Independent sensing of 11 distributed events with K=11 independent measurements
- Case II (low-rate): Redundant sensing of a single localized event with K=12 correlated measurements
- Non-coherent (on-off) and coherent (BPSK) binary signaling from each sensor
- Case I: 11 bits/transmission. Case II: 1 bit/transmission

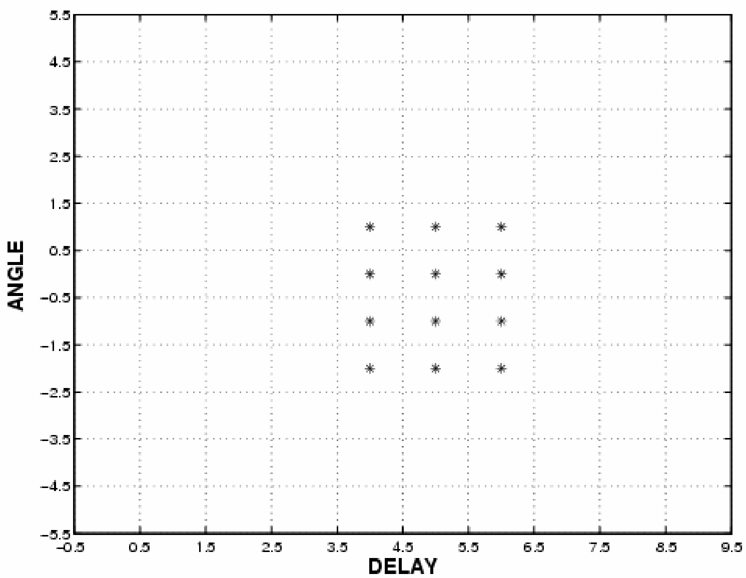
Independent Sensing of Distributed Events

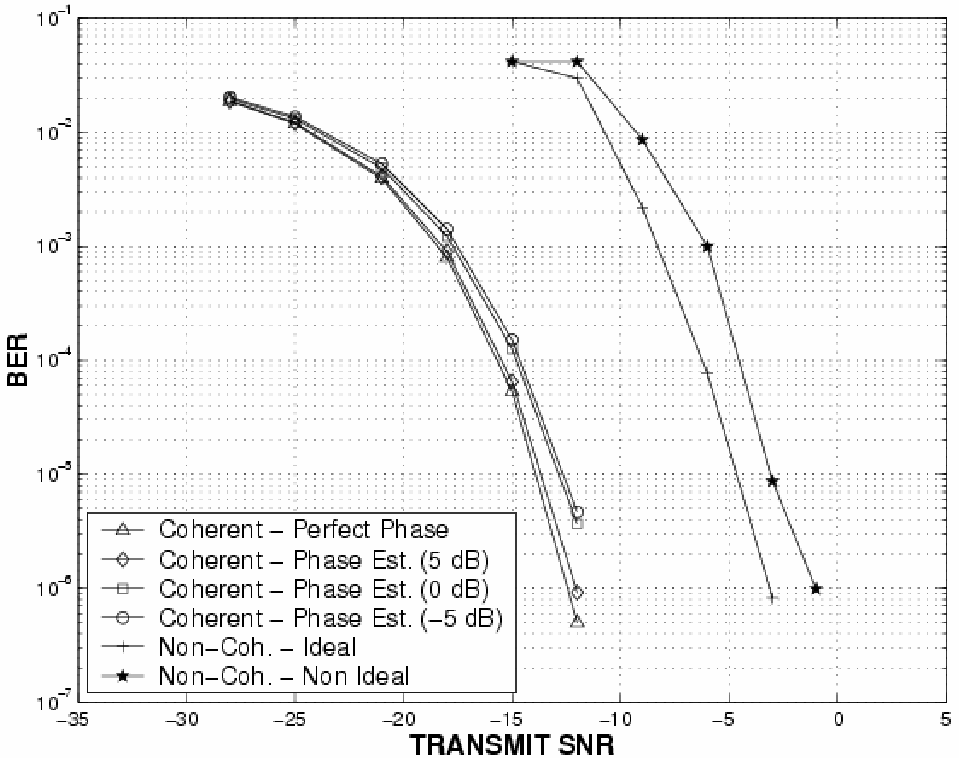




11 bits per transmission interval

Redundant Sensing of Localized Event

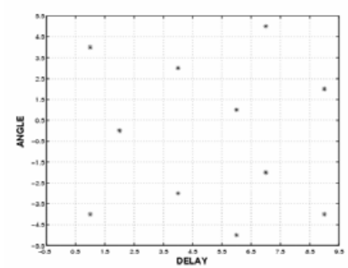


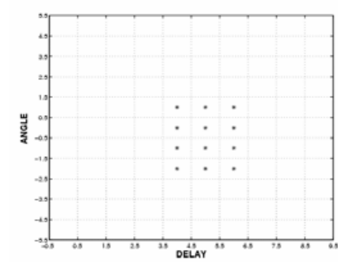


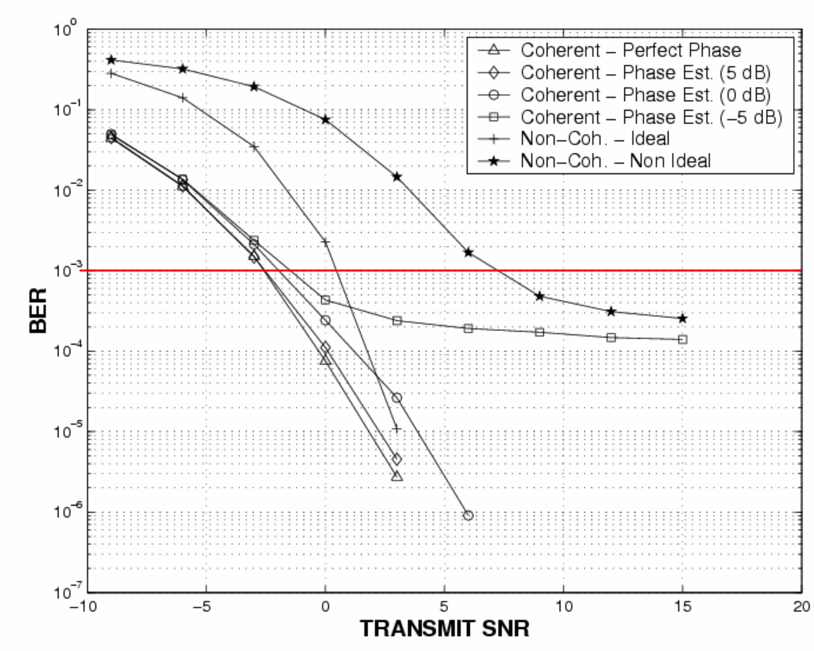
Redundant sampling to reduce energy consumption

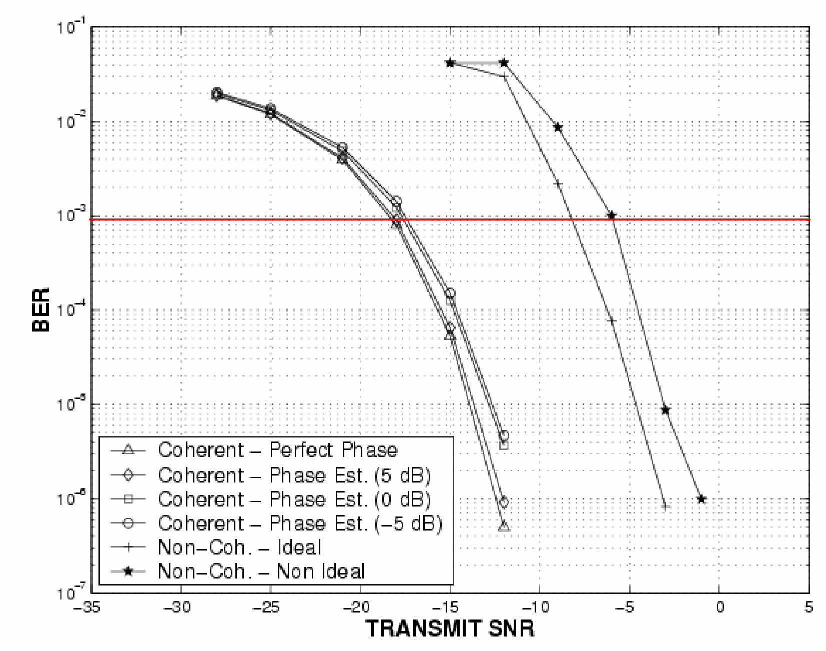
1 bit per transmission interval

Rate-Energy-Fidelity Tradeoff







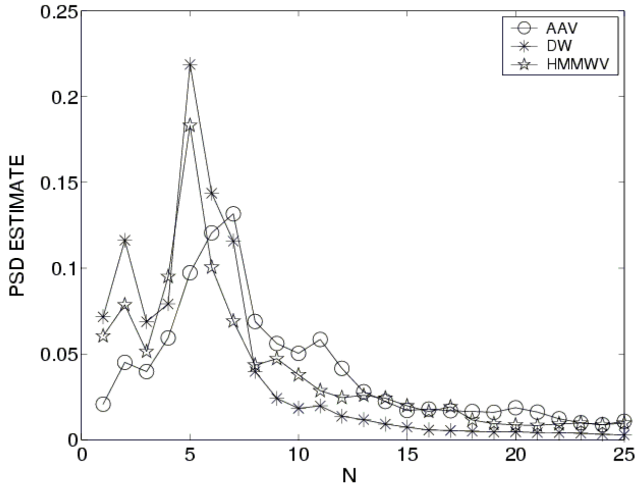


BER=0.001

Non-coh: $\frac{E_b}{N_0} = 0.46$ $\qquad$ $\frac{E_b}{N_0} = 0.25$

coherent: $\frac{E_b}{N_0} = 0.05$ $\qquad$ $\frac{E_b}{N_0} = 0.02$

Vehicle Classification Using Acoustic Sensors



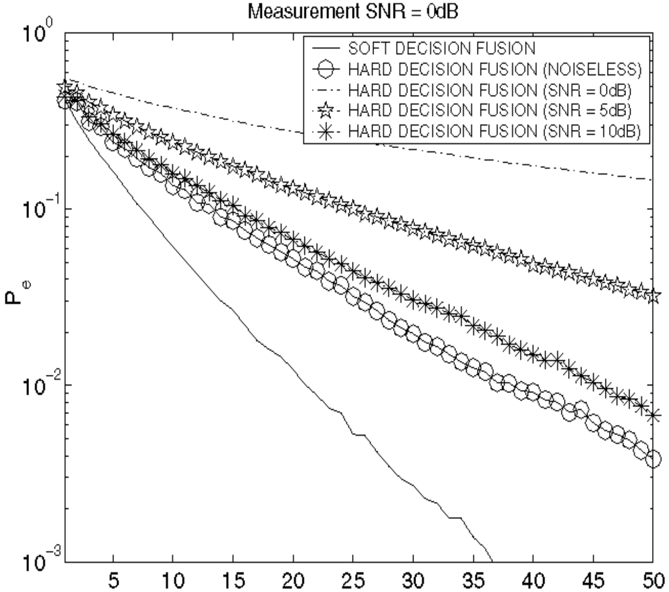
AAV – tracked (Amphibious Assault Vehicle)

HMMWV – wheeled (Humvee)

DW – wheeled (Dragon Wagon)

SITEX02 Data. DARPA SensIT Program.

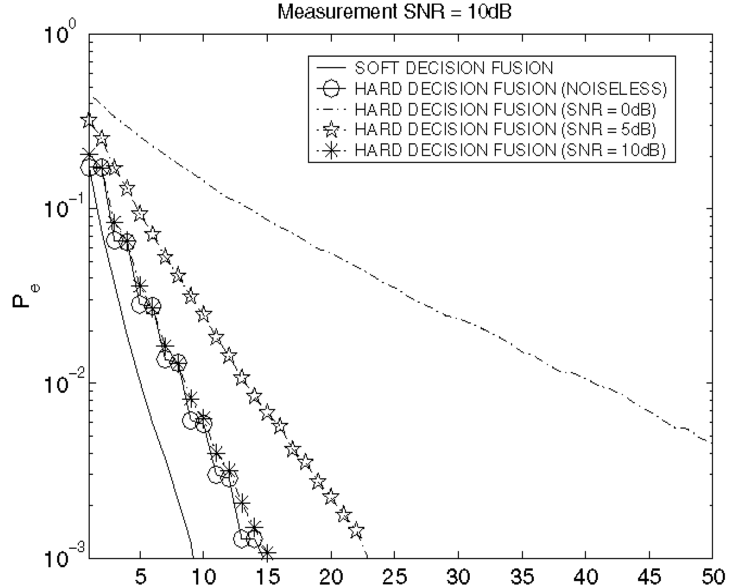
Decision Fusion Advantage



k

Meas. SNR = 0dB

L=3 vechicles



k

Meas. SNR = 10dB

$$P_e(k) \approx \frac{1}{\sqrt{k}} e^{-Dk}$$

D – error exponent: decreases from soft to hard decision fusion

D governed by the worst K-L distance between pairs of hypotheses

D'Costa, Ramachandran, Sayeed 2004

Dumb sensors: Type-based detection; Liu & Sayeed 2004

Application Scenarios for RFID

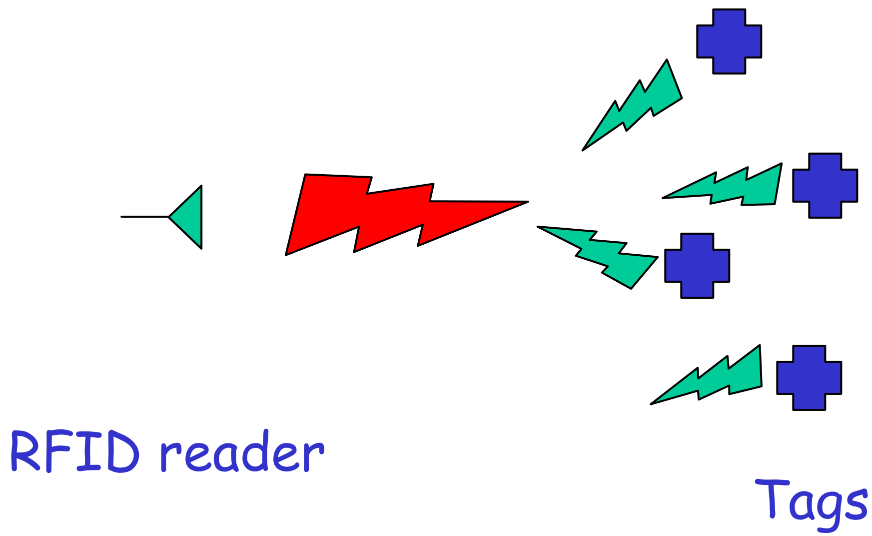
- Antenna arrays on Readers

- AA Reader + SNet

Potential applications:

- Inventory localization and tracking
- Flexible TAG reading:
  - Faster information retrieval
  - Longer reading range
  - No portals or docking stations
  - Load-first read-later

Current Reader Technology



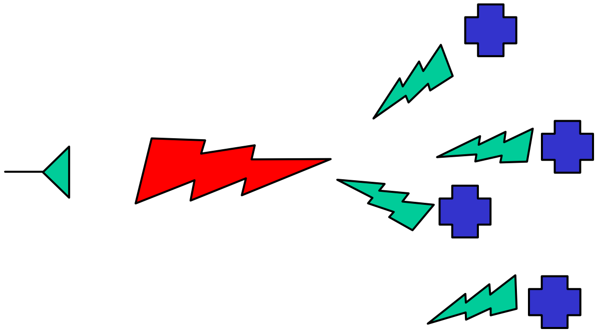
Problem: all tags in the range respond and thus interfere

Solution: the reader sends out a sequence of pulses to prune out the desired tag ID.

Example: 4 bit tag IDs. 16 possible IDs. Say desired ID = 1011

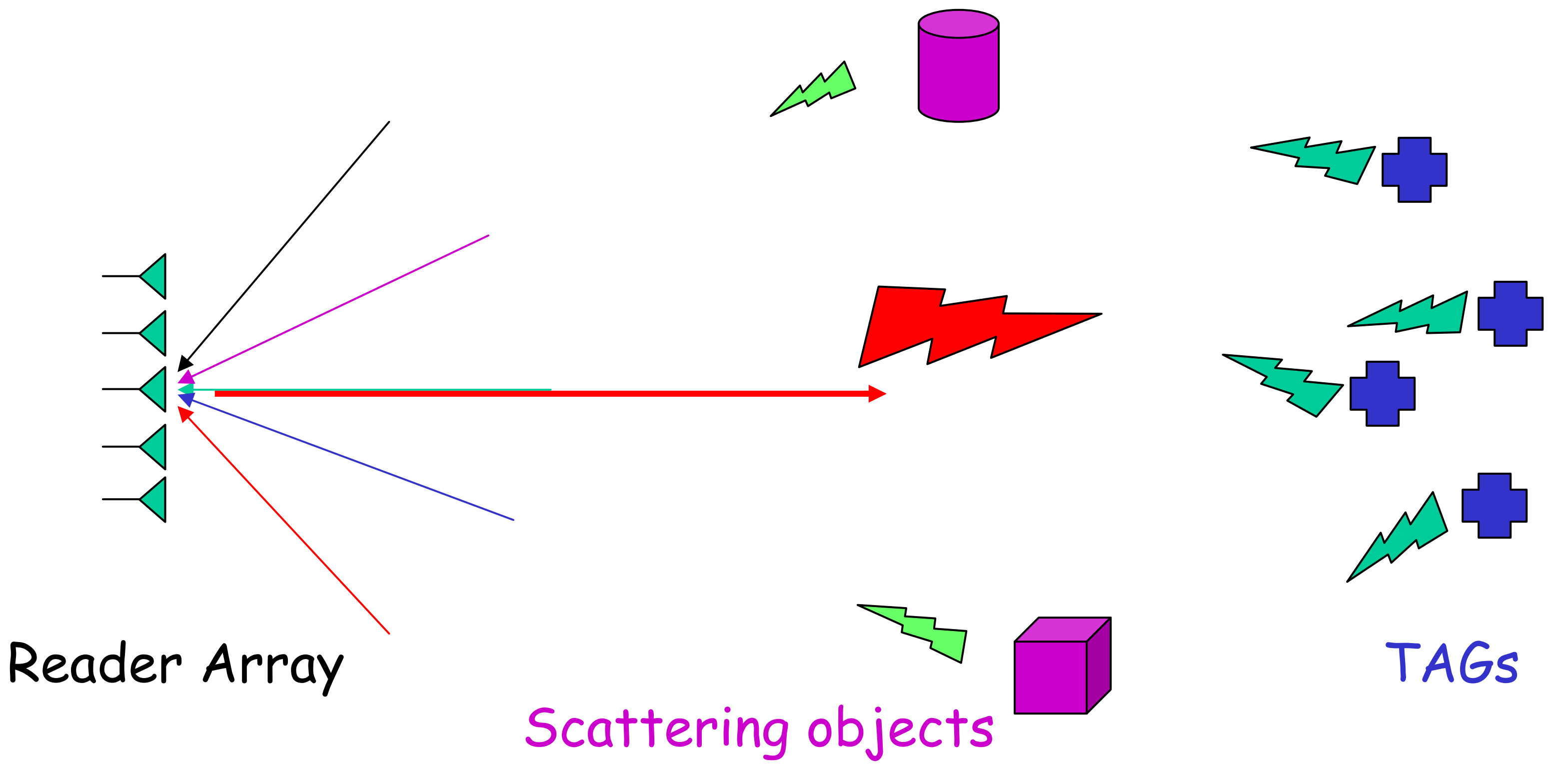
Q1. All tags with 1st bit "1" respond →16 to 8 tags: 1xxx
Q2. All tags with 2nd bit "0" respond → 8 to 4 tags: 10xx
Q3. All tags with 3rd bit "1" respond → 4 to 2 tags: 101x
Q4. All tags with 4th bit "1" respond → 2 to desired tag: 1011

Key Problems facing Current Technology



- Long acquisition times: Collisions from multiple tag responses
- Short-range (line-of-sight) reading (portals)
- Unreliable readings (weak signal at the reader due to passive operation, tag orientation)
- Multipath signal reflections due to nearby objects
- Interference from other RF sources and RFID readers
- Accuracy of tag localization

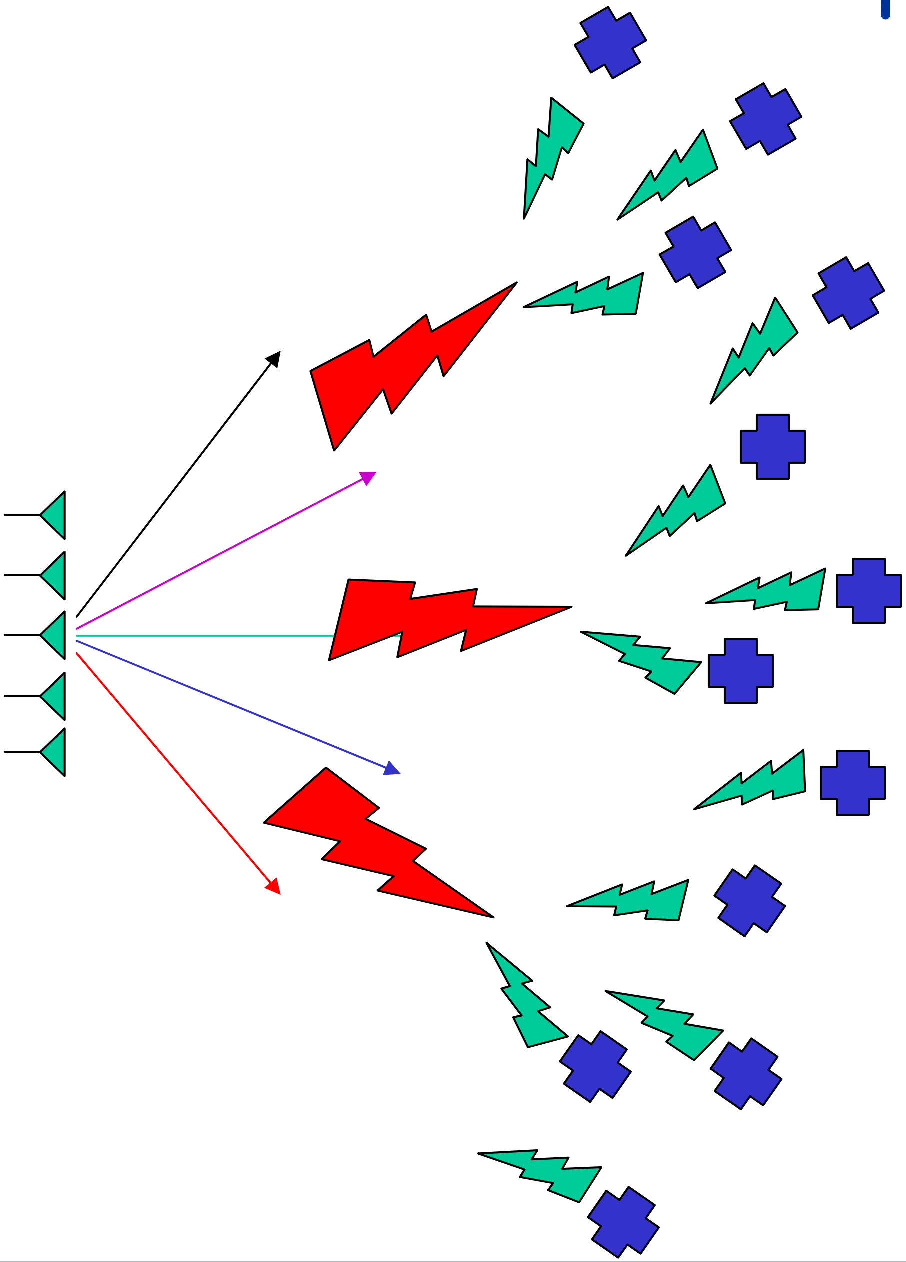
Beamforming



TX mode: Focus all power in one direction
RX mode: Collect scattered signals from all directions

Increased range, reliability, accuracy
Tag localization
Relatively longer acquisition times

Multiplexing



TX mode: multiple parallel queries in different directions

RX mode: separately process signals from different directions

Faster acquisition times

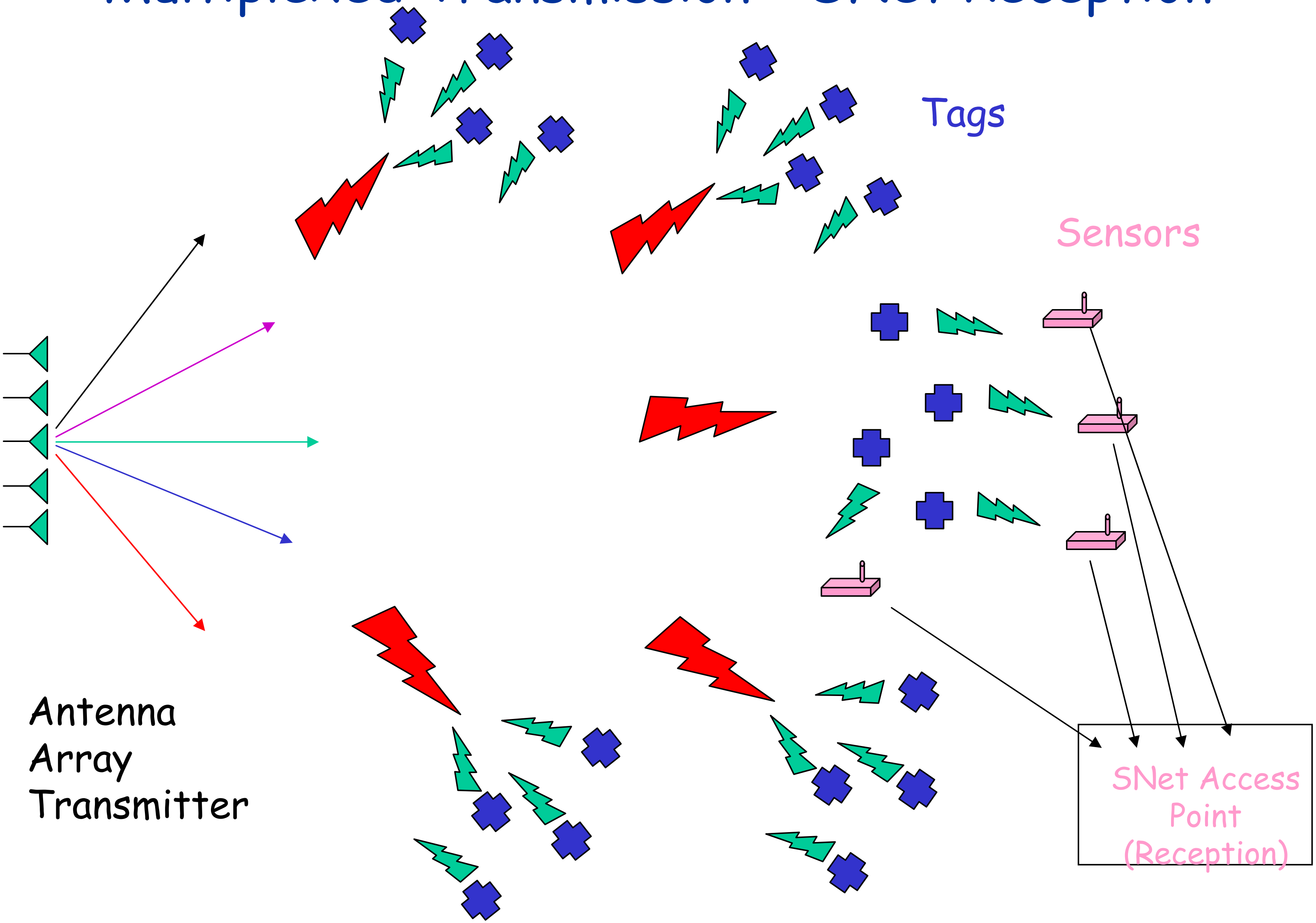
Tag localization

Short-range reliability

Multiplexed Transmission + SNet Reception

- Multiplexing: multiple, parallel tag queries from the reader in different directions
- Problem: lesser power in different directions makes reception of the resulting Tag signal difficult at the reader
- Potential solution: Weak signal reception via a dense SNet of cheap sensors

Multiplexed Transmission + SNet Reception



A Longer Term Scenario

Transmission:

A large antenna array on the ceiling

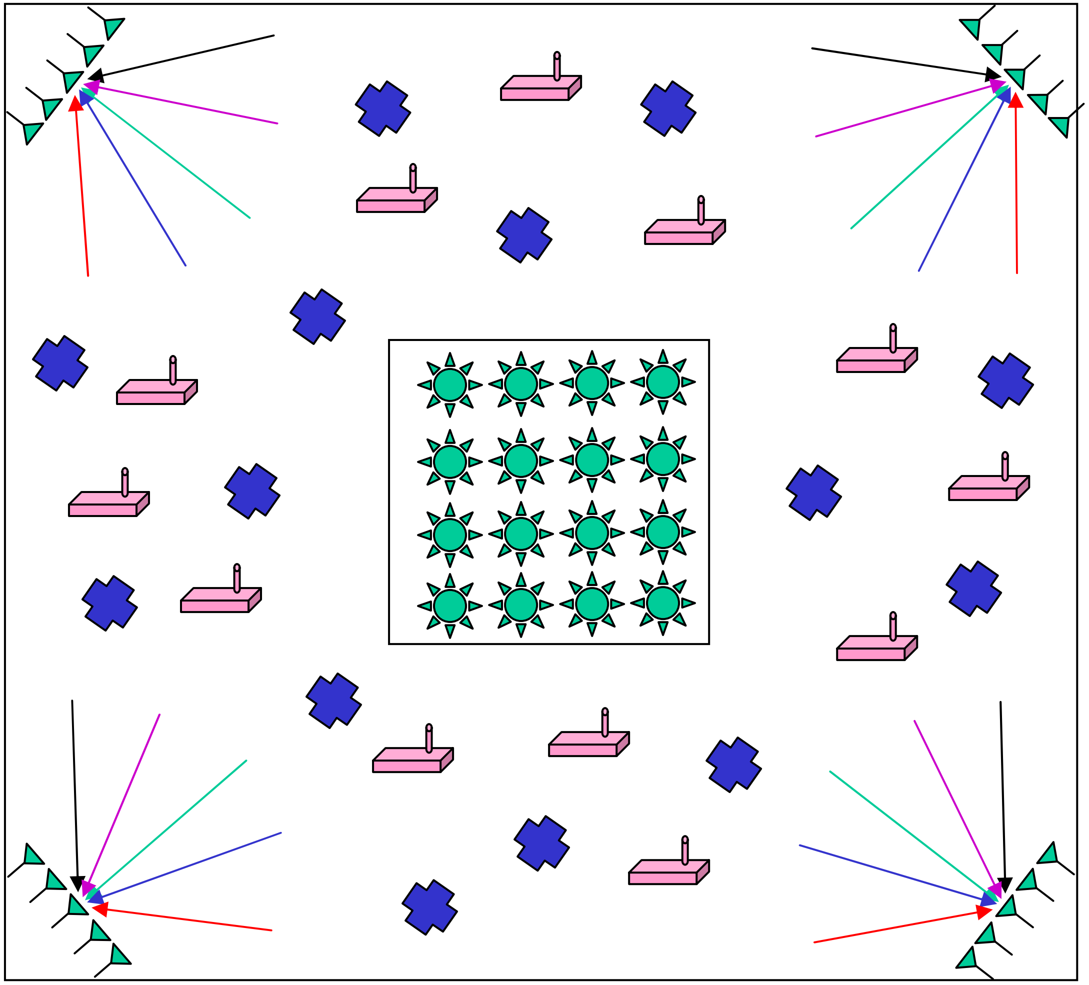
A subset of array elements activated at any time

Reception:

Multiple access points with antenna arrays

+

SNet



Potential applications:

Warehouse inventory maps
tag tracking in a warehouse

Sensor Networks with RFID Tags

- Cheap tags + cheap sensors
- Bio-chemical sensors
- Coherent sensing/reflection with multiple closely spaced tags

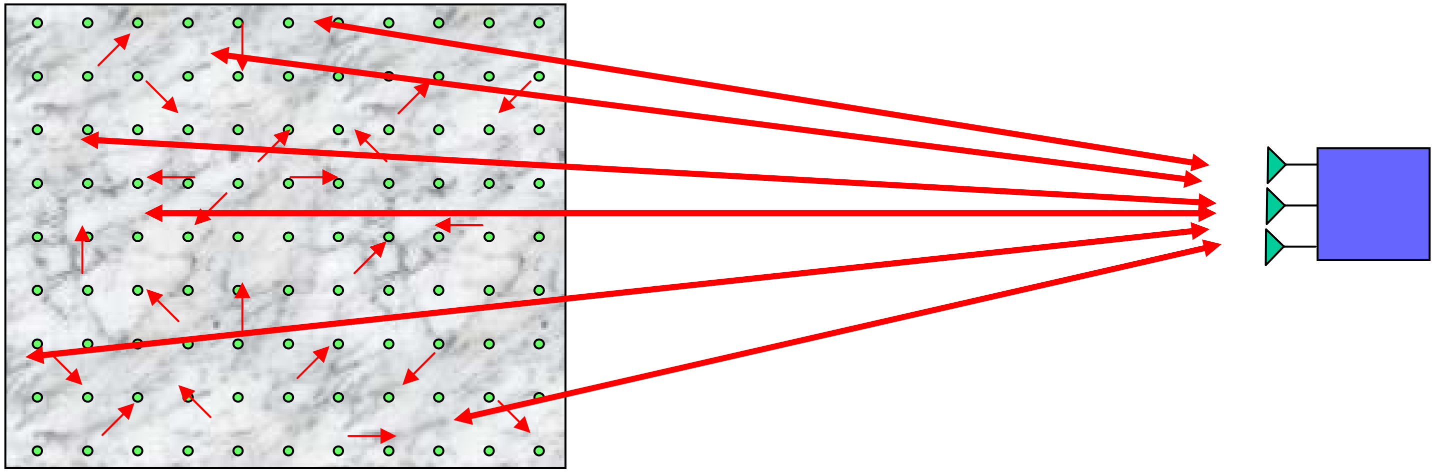
Sophisticated RFID Readers

- Multiple tag identification is mathematically analogous to a multi-user communication problem
  - A basestation (reader) communicating with multiple users (tags)
- Advanced coding and modulation techniques could be exploited for rapid and reliable tag identification
  - Challenge: the resource-poor (passive) tags
  - SNets: an attractive alternative to active tags?
- Robustness to other sources of RF interference could be attained with not-too-sophisticated signal processing in reception algorithms
- Software radio + agile multi-band antennas, could facilitate inter-operability between different tags, readers and frequencies of operation

Conclusions

- Hierarchical information retrieval: Using powerful WIR's to retrieve information from UGS's
- Rapid information retrieval in delay-critical tasks
- Information retrieval via "high-dimensional" space-time waveforms:
  - Querying an ensemble of sensors simultaneously
  - Secure protocols (coded waveforms)?
- Multi-resolution learning of the signal field:
  - Agile RF-front ends: variable space-time resolution
  - Learning "features" in a cluttered environment

Two Sources of Error



Noisy sensing
(measurement noise)

noisy communication
(noisy, possibly fading communication links)

Optimizing energy-fidelity tradeoff:
interplay between sensing, processing, and communications
Matched source-channel communication

Gastpar & Vetterli 03; Bajwa, Sayeed, Nowak 05

Whole Bigger Than the Sum

- Energy-Density Tradeoff:
  - For a given energy consumption, fidelity increases with sensor density
- Illustrate in:
  - Distributed detection
  - Distributed field estimation

Bajwa, Sayeed, Nowak 2005; Liu & Sayeed 2004

Three Key Effects

Local scale: matched to local spatial field coherence (smoothness, correlation)

1. Coherent sensing and estimation: measurement noise reduction

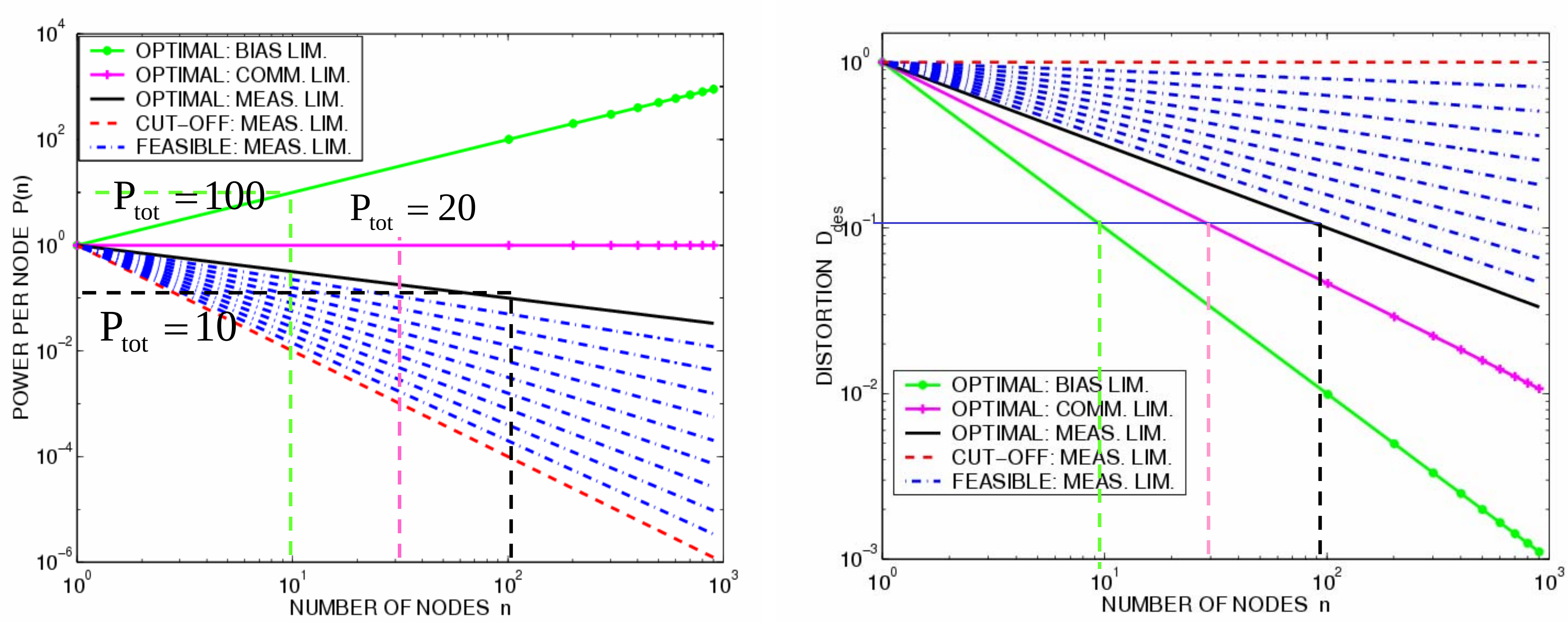
2. Coherent communication: communication noise reduction
(power amplification)

Global scale: independent measurements

3. Statistical spatial averaging: improved decision accuracy
(spatial diversity)

Law of large numbers accentuates these effects
(high sensor density; large sensor ensemble)

Power-Distortion Tradeoff: Impact of Sensor Density



Measurement-limited: $\sigma_w^2 > 0\,, \quad P_{opt} \equiv D_{dis} \equiv n^{-\frac{2\alpha}{2\alpha+d}}\,, \quad m_{opt} \equiv n^{\frac{d}{2\alpha+d}}$

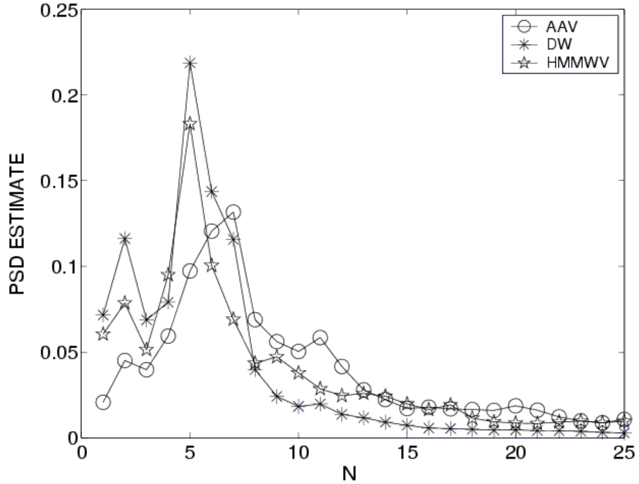
Communication-limited: $\sigma_w^2 = 0\,, \quad P \equiv 1\,, \quad D_{dis} \equiv n^{-\frac{2\alpha}{\alpha+d}}\,, \quad m_{opt} \equiv n^{\frac{d}{\alpha+d}}$

Bias-limited: $\sigma_w^2 = 0\,, \quad P \equiv n^{\frac{2\alpha}{d}}\,, \quad D_{dis} \equiv n^{-\frac{2\alpha}{d}}\,, \quad m_{opt} \equiv n$

Detection and Classification

- S sources (S-ary hypothesis testing)
- Point sources
  - Temporally stationary and bandlimited
  - Spatial field – wave propagation

Vehicle Classification Using Acoustic Sensors



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SITEX02 Data. DARPA SensIT Program.

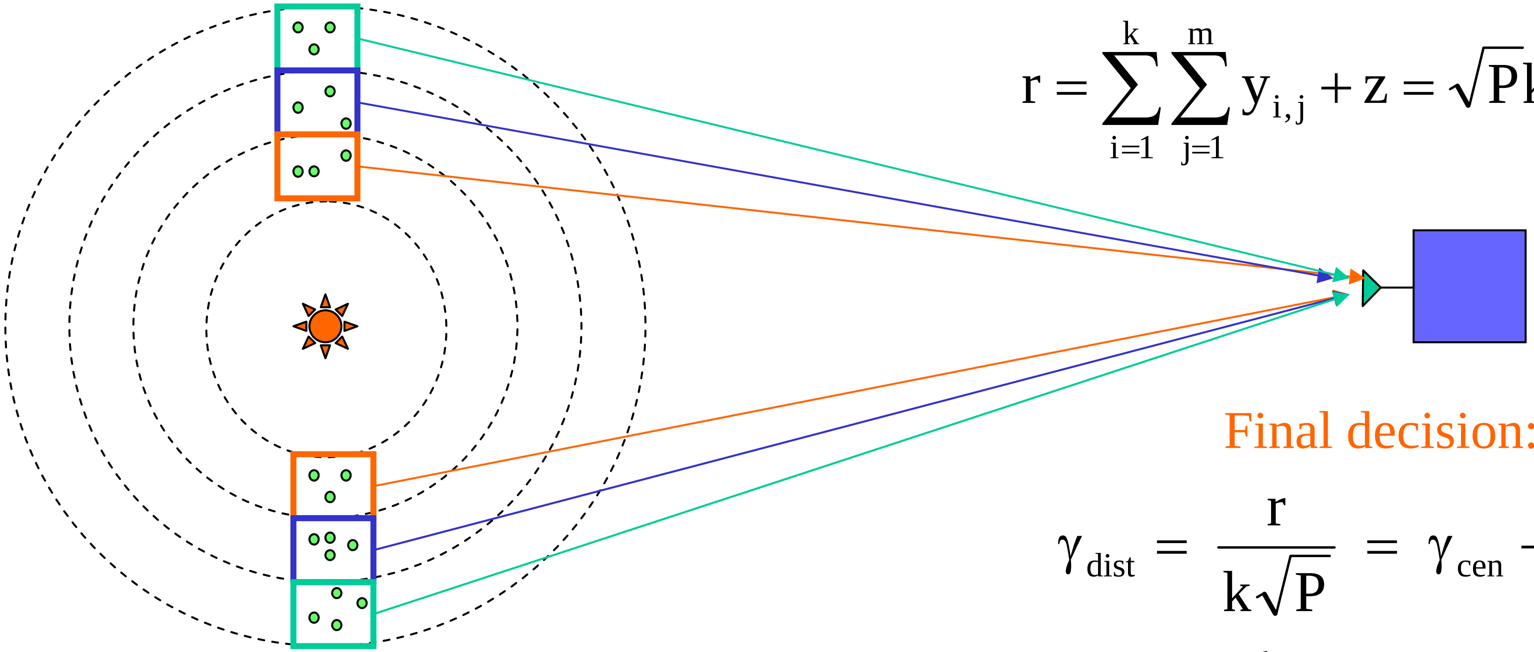
Distributed Classification: Matched Source-Channel Communication

Coherent data averaging in each SCR:

$$\tilde{\mathbf{x}}_j = \frac{1}{k}\sum_{i=1}^{k}\mathbf{x}_{i,j}$$

Fusion of LLRs over the MAC:

$$r = \sum_{i=1}^{k}\sum_{j=1}^{m} y_{i,j} + z = \sqrt{P}k\,\gamma_{cen} + z$$



Final decision:

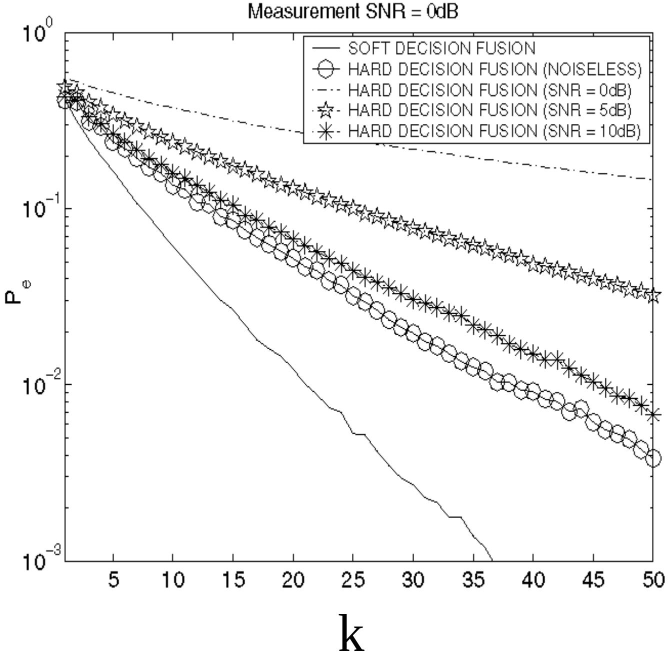
$$\gamma_{dist} = \frac{r}{k\sqrt{P}} = \gamma_{cen} + \frac{z}{k\sqrt{P}}$$

$$\hat{\ell}_{dist} = \begin{cases} 2 \ , & \gamma_{dist} > 0 \\ 1 \ , & \gamma_{dist} \le 0 \end{cases}$$

Coherent local LLR (uncoded) transmission

$$y_{i,j} = \sqrt{P}\ \gamma_{cen,j} \quad , \quad i = 1, \cdots k, \ j = 1, \cdots, m$$

Decision Fusion Advantage



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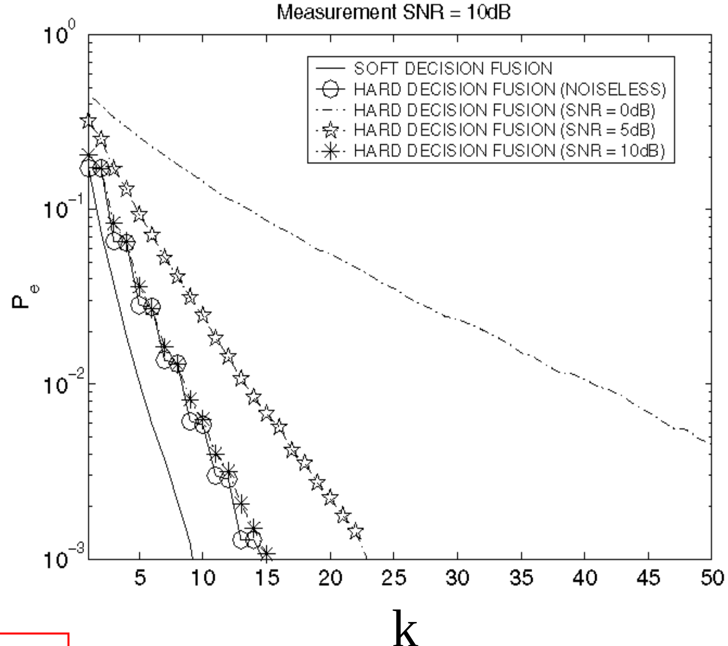

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$$P_e(k) \approx \frac{1}{\sqrt{k}} e^{-Dk}$$

D – error exponent: decreases from soft to hard decision fusion

D governed by the worst K-L distance between pairs of hypotheses

D improves with measurement and comms SNR

D'Costa, Ramachandran, Sayeed 2004

Impact of Sensor Density: More Sensors = Less Power

n=km nodes $$P_{e,dist}(m) \approx e^{-\left(D_{cen} - \frac{m}{2Pn^2}\right)m}$$

m = independent degrees of freedom; k = sensing redundancy/DoF