



# MAKING SENSE OUT OF SENSOR NETWORKS

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Anthony Ephremides  
University of Maryland

SECON  
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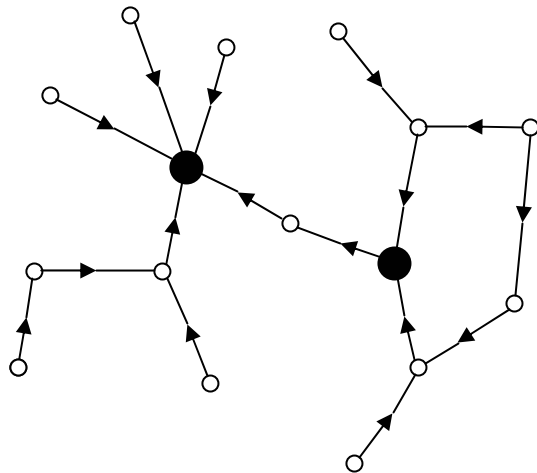


# WHAT IS SPECIAL ABOUT A SENSOR NETWORK?

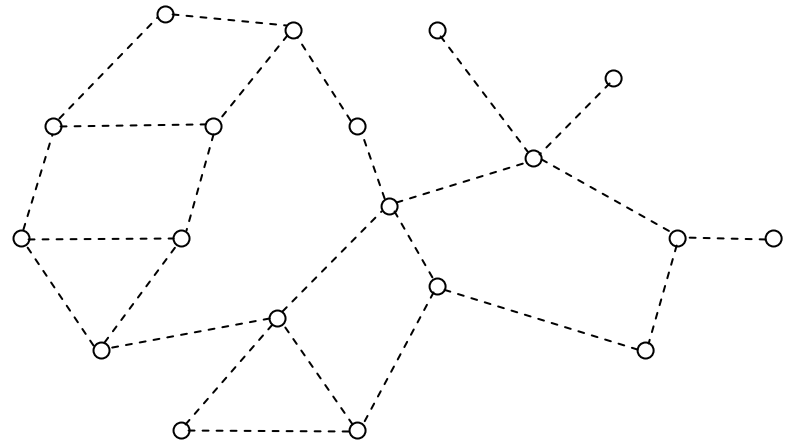
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- Confusion and Hype
- Non-Wireless and Wireless
- Non-Wireless:
  - Signal Processing
  - Data Aggregation/Fusion
  - Distributed/Centralized
- Wireless:
  - All of The Above, plus
  - All The Networking Aspects

# FOCUS ON WIRELESS SENSOR NETWORKS



Sensor



Ad Hoc

WHAT IS DIFFERENT?

On Surface: TOPOLOGY

Below the Surface: SPECIAL(AND OVERRIDING) PERFORMANCE OBJECTIVES



# WHAT IS DIFFERENT?

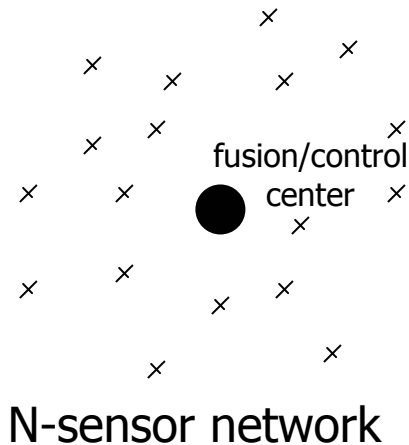
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- A SENSOR NETWORK IS NOT A GENERAL TRAFFIC-CARRYING TRANSPORT MECHANISM (An Ad Hoc Network, by contrast, is)
  - IT IS A DATA GATHERING MECHANISM
  - PERFORMANCE OBJECTIVE:
    - MAXIMIZE PROBABILITY OF CORRECT DETECTION
    - or
    - MAXIMIZE THE OBJECTIVE OF THE DATA GATHERING (Environmental Monitoring, Surveillance, Patient Monitoring, Object Tracking, ...)
- AND
- MAXIMIZE USEFUL LIFETIME

New {

Not new but  
under new light {

# SPECIAL PERFORMANCE MEASURE



Example: DEPLOYMENT OF A NETWORK FOR TARGET DETECTION

- EACH SENSOR  $i=1, \dots, N$ , MAKES  $T_i$  MEASUREMENTS,  $Y_{i1}, Y_{i2}, Y_{i3}, \dots, Y_{iT_i}$

Q: Is it preprogrammed or is it instructed?

Q: What does it measure?

Objective: Use these measurements to decide a binary hypothesis  $H_0, H_1$ .

Usual Detection Formulation

$$\frac{P(\bar{y} / H_1)}{P(\bar{y} / H_0)} \underset{H_0}{\overset{H_1}{>}} T$$

- If priors are known and a cost criterion is known, minimize that criterion (Bayesian)
- If priors are not known but the criterion is known, minimize that criterion for the worst prior (minimax)
- If neither priors nor cost criterion are given, maximize probability of correct detection subject to a false alarm constraint (N-P)



# BUT WHAT IS THE DATA?

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## Option 1:

- All the measurements to the control center
- Requires transmission of all the data to the fusion center
- Excellent detection performance { Still, sub-options of sequential detection }
- Potentially energy wasteful
- Potential for congestion
- Aggravation of usual "Networking" problems

## Option 2:

- Reduced data to the control center
- Need for localized processing
- Extreme case: each mode decides and transmits one bit to the Fusion Center
- Potentially, degraded detection performance
- Shift of energy focus on the processor (Hardware)
- Reduced "Networking" problems



# INTERESTING IMPLICATIONS AND TRADE-OFFS

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- Transmission energy vs Processing energy
  - “LORE” that transmission energy dominates is false
  - A powerful processor and an army tank radio consume comparable amounts of energy
  - Deployed sensors will have low-transmission power and will be required to perform possibly complex processing
  - Hence this is a genuine trade-off (more on this later)
- More traditional “Networking” issues
  - Neighbor discovery
  - Interference control
  - Routing

} Not independent of the energy issue



# NEIGHBOR DISCOVERY

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- So, who is a “NEIGHBOR” ?
- Depends on transmission power (among other communication system parameters)
- And on channel
- And on whether other “NEIGHBORS” transmit to “THEIR NEIGHBORS” (the usual MAC/Physical Layer Quagmire)

Hence

- Even the most fundamental topological issue is coupled to energy and other layers



# INTERFERENCE CONTROL

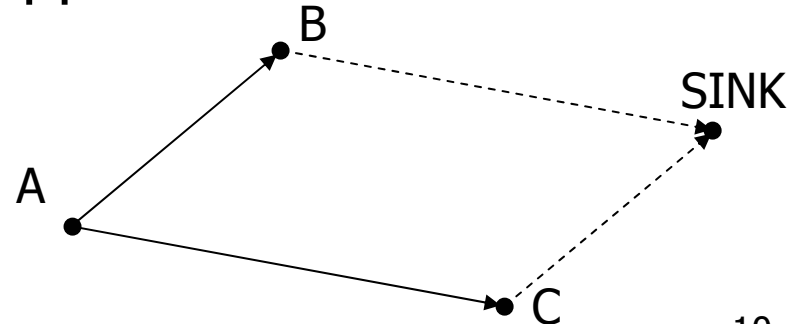
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- What to do in a sensor network?
  - 802.11?
  - TDMA/Schedule?
  - Pure random access?
- What kind of processor does the sensor embedded system have?
- What traffic profile is anticipated?
- What topological knowledge is there?  
(Geographical or Connectivity-based)
- How is the energy trade-off resolved?

} Overhead of all sorts

# ROUTING

- If previous issues are resolved  
(and they couldn't be without consideration of Routing)
  - How should routes be selected ?
- Single sink
- But...need link metric
- In Ad Hoc networks we map delay and throughput to link metric (link "state", hops, queue size,...)
- And energy can also be mapped to link metric
  - Transmission power
  - Residual energy





# ROUTING (cont)

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- But how do we map “Target Detection Probability” to a link metric?
- Similarity to telephone network (or “Voice” network) and blocking probability
- Interesting result: Youngchul, Tong, Ephremides (CISS 2005)
  - If signal field has a Markovian structure in space, then the appropriate link metric that captures detection probability is distance
  - But in a “Reverse” sense (the farther, the better!)
  - Intuitively sensible
- New trade-off (energy → nearest neighbor detection → farthest neighbor)

# BACK TO ENERGY

## (Transmission-Processing Trade-off)

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- Importance of hardware (already in the picture through antennas, amplifier, etc)
- Focus on embedded system processor (related cost issue)
  - Device circuit level (multiple voltages)
  - Microprocessor architecture level (algorithm that is implemented)
  - Compiler level (memory organization)
- e.g. ■ A compression algorithm can be very energy intensive
  - Its implementation (by means of hardware) affects the processing/transmission trade-off



# DEVICE CIRCUIT LEVEL

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- Down to laws of thermodynamics
- Fundamental limit:  $3 \times 10^{-21}$  J/bit (if entropy is not preserved)  
Close to 0 (if entropy is preserved)  
(at the cost of delay)
- MICA2, MICA2DOT:  $\sim 80$  mW at 40 kbs ( $\sim 2 \times 10^{-6}$  J/bit)
- Supply voltage, threshold voltage, thermal voltage, load capacitance, temperature, oxide thickness, clock frequency affect energy consumption.
- Connection to higher layers through clock frequency that also depends on voltages (and on switching activity, or on computation load)
- Mixing of analog and digital techniques
- Hardware adaptivity (e.g. ADC rate)



# ARCHITECTURE LEVEL

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- Memory management
- Data bus size
- Register and local memory data width
- Address translation mechanisms (energy consuming)
  - Design choices at this level can capture application level requirements or, at a minimum, DSP algorithm requirements
- Handling downloadable code
- Variable bit-size samples
- Turning off of memory cells
  - Again cross-layer dependencies



# COMPILER LEVEL

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- Use of scratch-pad memories
  - Migrates the data management function from the hardware to the software
- Energy advantage
- Challenge: use them for downloadable code
- Event-driven protocols/algorithms require unpredictable memory bank use
- Periodic (predictable) protocols/algorithms are effective (ie. Energy efficient) in switching off unneeded hardware
- ❖ New light into the debate concerning event-driven protocols (reactive routing, random access MAC) vs periodic protocols (proactive routing, TDMA, scheduled transmissions)
- ❖ Genuine cross-layer dependence between embedded system compiler and network protocols



## ANOTHER INTERESTING ASPECT: UWB

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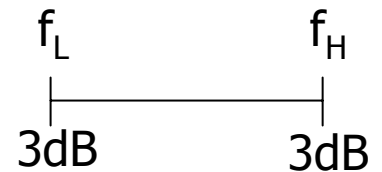
- Confirms how physical layer affects upper layers
- Why is UWB applicable to sensor networks?
  - What is UWB?

Ultra-wide band communication (UWB)

- Transmission in the unlicensed bands

$$B = 2 \frac{f_H - f_L}{f_H + f_L} > \frac{1}{4}$$

- At 2.5GHz,  $f_H - f_L \approx 500$  MHz
- Severe power restrictions by FCC





# UWB (cont.)

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- Carrierless transmission
- Very narrow pulse trains at baseband (alternative to CDMA: time-hopped sequences)

So, relevant to sensor networks because:

- Very low power (energy efficient)
- High bandwidth

And more importantly:

$$R \sim \text{SINR}$$

$$R = \log(1 + \text{SINR}) \approx \text{SINR}$$

if SINR = small

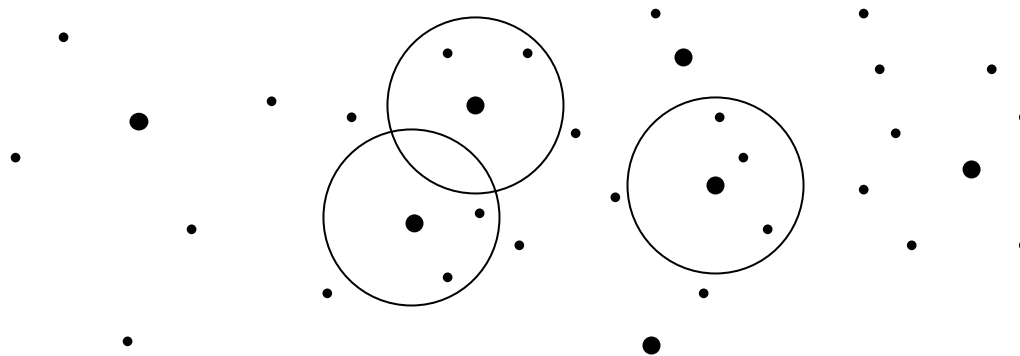


# NETWORK IMPLICATIONS OF UWB

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- Recent work established that if you want to maximize proportional fairness (i.e.  $\sum_i \log R_i$ )
  - where  $R_i$  = rate over link  $i$  -
  - i. Then MAC must satisfy an **exclusion** region
  - ii. No power control is needed  
i.e.  $P=0$  or  $P=P_{\max}$   
(B.Radunovic, J.Y.Le Boudec)

# IMPLICATIONS OF UWB (cont)



- Imposition of schedule restrictions
- But interest in energy efficiency permits relaxation of the second conclusion ( $O-P_{\max}$ )
- Hence each exclusion region depends on chosen power of transmission
- Hence a more tractable cross-layer structure



# BACK TO THE BEGINNING

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- Does all this make any sense?
  - Sensor networks have special mission
  - Sensor networks must be energy efficient
    - Strengthening of the cross-layer dependencies
    - Concrete identification of new trade-offs
    - Hardware comes into the picture
    - Special case of UWB is an example of further specification of the networking issues
- Bottom line: sensor networks are quite different from general Ad Hoc networks