WHAT IS IN WIRELESS SENSOR NETWORKS FOR COMMUNICATION THEORISTS?

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Puerto Rico, May 22, 2006

ANSWER:

ENERGY AND INFERENCE !

See: V. Poor

Plenary Talk at CTW 2006, March 24

"Energy and Inference in Wireless Sensor Networks"

OUTLINE

1. PREVIEW IN TERMS OF AN EXAMPLE

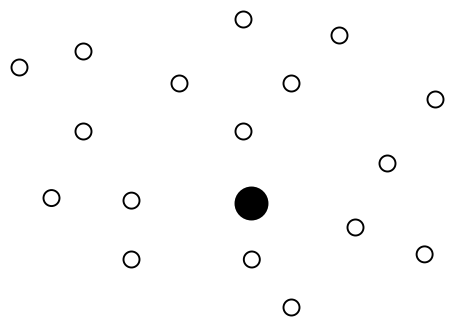
2. EXPLORATION OF THE ENERGY ASPECT
   - Towards the ultimate coupling (application layer to hardware)

3. EXPLORATION OF THE INFERENCE ASPECT
   - in terms of routing

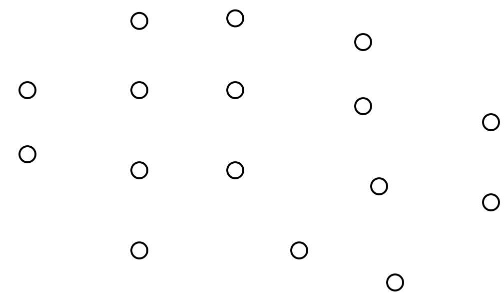
4. ADDITIONAL ASPECTS
   - in terms of cross-layer coupling

PREVIEW

Wireless Sensor Network vs. Ad Hoc Multihop Wireless Network



Collection of measurements



transport of general information

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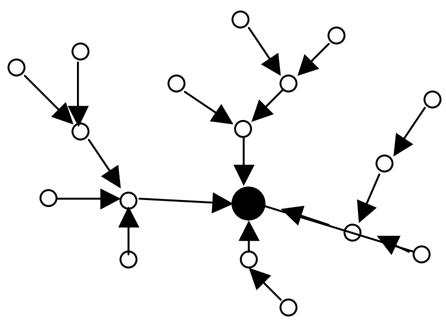

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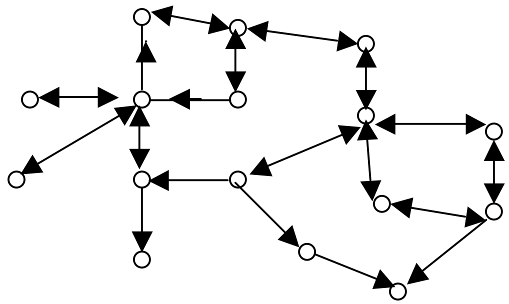

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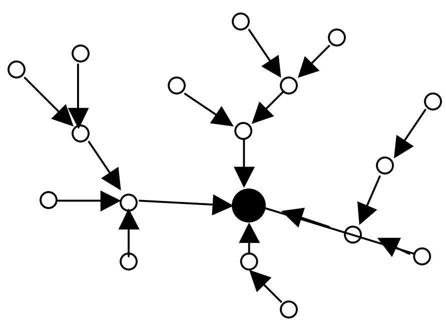

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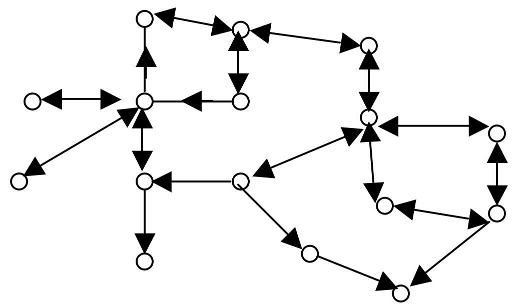


transport of general information

Hence

- Energy (usually as a finite constraint)
- ASOC (Application Specific Overriding Concern)
  e.g. Target Detection

- Rate Regions
- Stability
- Delay
- Energy (usually as a cost)

EXAMPLE

- Sensor nodes are deployed randomly
- Every sensor node makes measurements

•Objective: transfer the “essence” of the measurements to the fusion center

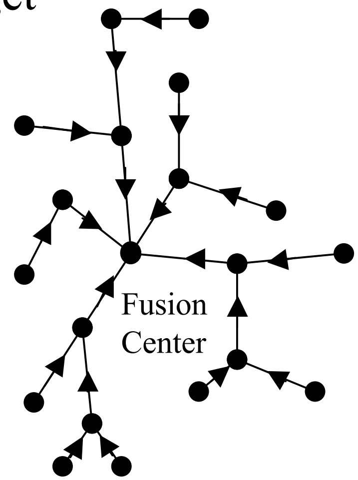
•Longevity requirement (Energy Efficiency)

•ASOC: Mission Performance (decide between

i.e:

Maximize P [correct detection] subject to

* Target



What is new here ?

- Inference through a network (not the same as “distributed inference” and “data fusion”)
- Energy Efficiency: energy is consumed for

i) transmission E_t

ii) processing E_p

iii) sensing E_s

ENERGY EXPLORATION

1. Relative Magnitudes of

   - Lore: dominates
   - False on two counts: i) Computation intensive processing and close proximity (e.g. Implanted Bio sensors)
     ii) Design choices can change the balance (e.g. underwater sensors)

   - Truth: Highly dependent on the application and design

2. In previous example: Data Fusion choices
   - Centralized
   - Distributed
   - Hybrid (including sequential)

   - Probability vs. Energy Consumption (Highly variable results)

Details:

L.Yu, G.Qu, L.Yuan, A.Ephremides: "Energy Driven Detection with Guaranteed Accuracy", IPSN April, 2006

FURTHER REFLECTIONS

- : closely connected to “duty cycle” - relatively very low power

  - but may dominate

- : highly dependent on communication system (including HARDWARE), BER target, and channel.

  ↓

  HPA, Antenna, and…more

- : energy/“operation”: - soft definition

  - strongly dependent on HARDWARE and processing algorithm

  ↓

  Embedded processor, and…above

(worth exploring further……..)

……**REFLECTIONS** (cont.)

Q: Can we "QUANTIFY" the energy cost of the distributed computation of a function ?
(in this case, a suitable test statistic)

includes, therefore, energy
for communication

- LAWS OF PHYSICS: if entropy is not preserved

~ ZERO if entropy is preserved
(at the cost of infinite delay)
based on Thermodynamics and Landau's Law

- BY CONTRAST: MICAs (in transmission mode) consume 80-60 mW at 40-250 kbps

! (Yawing) Gap of !

……REFLECTIONS (cont.)

Back off and consider real microprocessors

- – Device Circuit Level
- – Architecture
- – Compiler

At the Device Level: Energy Dissipation Occurs in Two Ways

(i) Dynamic

(ii) Leakage ~ sub threshold leakage + gate leakage

Note:

(a) Miniaturization reduces dynamic dissipation and increases leakage dissipation

(b) provide hooks to "upper" layers

……**<u>REFLECTIONS</u> (cont.)**

- (Partial) return to analog techniques
    - ASICs for ASOCs
    - NIPS characteristics,   i.e. energy efficiency & speed
- Shift certain functions to hardware (e.g. ADC)
    - with links to upper level functionalities

<u>At the Architecture Level:</u>   abandon general purpose design

- ability to disable unneeded parts of data paths, communication buses and memory
- memory management units for address and page translations to support virtual memory can use application features

hence: again the key is to utilize application specific features and map to application specific needs

……**REFLECTIONS** **(cont.)**

At the Compiler Level

- Replacing cache memories with scratch-pad memories for downloadable code

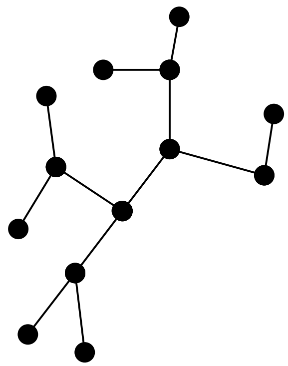
  - software managed
  - energy efficient

  e.g. instructions for measurements
  or processing

- Preference (energy-wise) for scheduled, rather than event-driven, tasks (permits turning off memory banks)
  - Implications on upper layers
    (e.g. proactive (rather than reactive) routing and scheduled (rather than contention-based) MAC)

BOTTOM LINE: higher-layer functions have processing energy implications and vice-versa

<u>BACK TO THE EXAMPLE</u> (on the way to INFERENCE)



- before doing anything with measurements, data network issues need to be resolved

i) "NEIGHBOR" discovery:

(S. Borbash, A. Ephremides: <u>Journal of Ad Hoc Networks</u>)

ii) MAC: SCHEDULED ACCESS (indispensable at a minimum level)

-energy benefits
-need for synchronization
-considerable overhead
-contention-based access: energy inefficient
-better matched to application

iii) ROUTING: How do we "draw" the tree ?

EXPLORING INFERENCE

(in the context of routing)

FACT: deciding on routes to optimize an objective function is a discrete optimization problem that can be solved in general only via high complexity algorithms (often, exhaustive search)

unless…..

the objective function decomposes into link metrics

(in that case, dynamic-programming-based procedures such as Bellman-Ford Algorithm permit efficient and distributed solutions)

EXAMPLES: minimum delay routing in packet switched networks

vs.

minimum blocking probability in circuit-switched networks

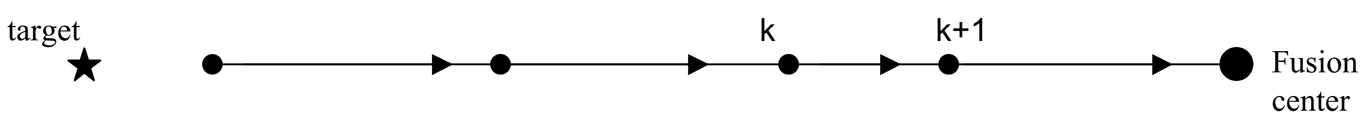
INFERENCE via ROUTING
or ROUTING FOR INFERENCE

COST CRITERIA IN OUR EXAMPLE: energy and probability of correct detection

energy → no problem

probability of correct detection → How to map to a LINK METRIC?

SPECIAL CASE: i) TANDEM OF SENSORS



ii) TARGET SIGNAL IS A GAUSS MARKOV PROCESS IN SPACE

…..**Routing/Inference** (cont.)

(details in Y. Sung, S. Misra, L. Tong, A Ephremides “Cooperative Routing for Distributed Detection in Large Sensor Networks” & earlier versions)

Use of Chernoff Bound:

Schweppe’s Recursive Representation of LR:

Where:

MMSE predictor

&

MMSE of predictor
Independent of past Y’s

.....Routing/Inference (cont.)

Which leads to

and hence

power of innovation process

~ link metric ~

…Routing/Inference (cont.)

provides maximum new information about the underlying process

&

recall

i.e. Cost function is monotonic in the sum of the

Hence is a good choice for a link metric

Turns out

provided that correlation of measurements is not too high

Properties:

……ROUTING/INFERENCE (cont.)

Routing Interpretation: For maximum new information in the aggregation process, a node should use as "next step" in the route, its farthest neighbor

because

- Analysis Interpretation: Maximum new information in the aggregation process over a tandem is proportional to the distance between the neighbors

→ LOGICAL GAP ←

……ROUTING/INFERENCE (cont.)

- USING B-F WITH DISTANCE METRIC YIELDED POOR ROUTES

  (and sometimes NO routes)

- FIXES: i) Augment link metric by adding energy-dependant term

  ii) Enforce topographical direction

- DESIRED FIX: Revisit the analysis in a 2-dim setting

ADDITIONAL INSIGHTS

- THEME SO FAR EMPHASIZED CROSS LAYERING
- SO, DEPART FROM THE EXAMPLE AND CONSIDER ANOTHER CROSS-LAYER DIMENSION IN CERTAIN SENSOR NETWORKS (and not only)
- B.RADUNOVIC (& J. Y. LeBOUDEC):

e.g. in any wideband regime

(large processing gain CDMA or UWB for micro sensors)

THEN SOME SUPRISING RESULTS FOLLOW

<u>IF</u> THE OBJECTIVE IS PROPORTIONAL FAIRNESS

…..read on

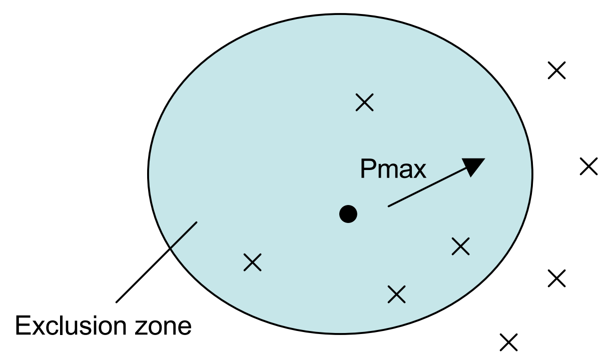
…..ADDITIONAL INSIGHTS

IN THAT CASE, IF A NODE IS ENABLED TO TRANSMIT, THEN

i) it should transmit at max power

ii) there is an exclusion zone around it in which no other node is allowed to transmit

MAC → architectural result based on physical layer considerations



i.e. no power control and/or pure scheduled access

CLOSING THOUGHTS

- wireless sensor networks offer a new network paradigm where ENERGY and an ASOC dominate

  e.g. inference objective

- this leads to concrete and (often) new couplings across layers

  (e.g. from the hardware to the application layer)

- new opportunities/challenges arise for communication theorists as a result

MORE AND /OR DIFFERENT ISSUES TO FOLLOW

- Session tomorrow
- Plenary on Wednesday