ENERGY AWARENESS IN WIRELESS NETWORKING

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ADHOC-NOW

ENERGY EXPENDITURES

1. <u>RF Transmission</u> (and Reception)
   - power amplifier (distance, propagation)
   - antennas (directivity)
   - circuits (VCO etc.)

- Time duration (rate)
- “ON” position

2. <u>Processing</u>
   - buffer management
   - encoding/decoding
   - mod/demod
   - SP
   - detector structure
   - chip layout
   - switching

FIRST (IMMEDIATE) CONSEQUENCE

- Design parameters (and choices) that affect energy consumption, also determine network topology
- "Wireless Link"
- SINR > γ

LHS: received power, **<u>rate</u>**, other users, antenna, etc.

RHS: detector and transmitter structures and **<u>BER</u>**

HENCE: EXISTENCE OF A LINK IS TIED TO ENERGY CONSUMPTION

ADJUSTABLE CONTROL PARAMETERS

- RF power (affects interference)
- rate (active or passive; trades throughput against quality; does **not** affect interference)
- BER (new QoS parameter)

- Resulting Elasticity of Topology

- Immediate Effect on Energy Consumption

NETWORK PERFORMANCE OBJECTIVES

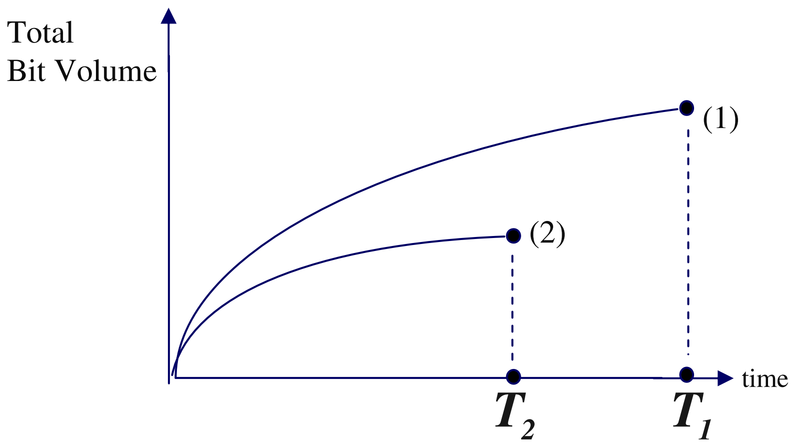
1. What kind of networks?
   - cellular
   - WLANs
   - satellite
   - ad-hoc, multi-hop (relaying)
     - Sensor networks
     - Battlefield networks
     - Potential further infrastructureless networks
2. In all cases:
   - communication performance (throughput, delay, BER, packet loss, blocking, etc.)
   - energy performance (efficiency, “reserves”)

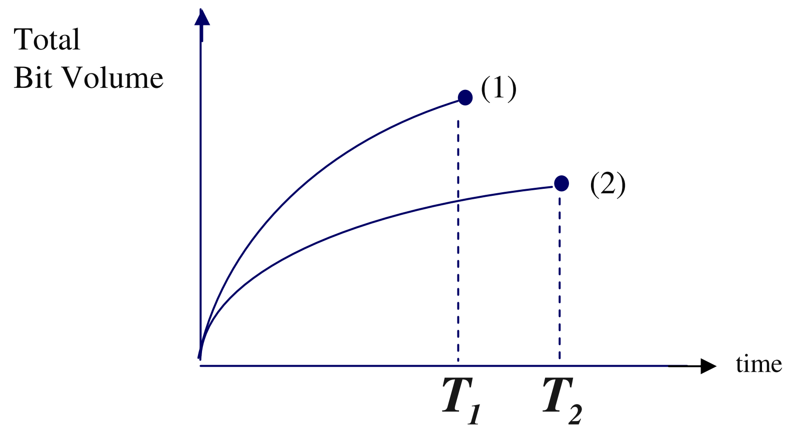
ENERGY "AWARENESS"

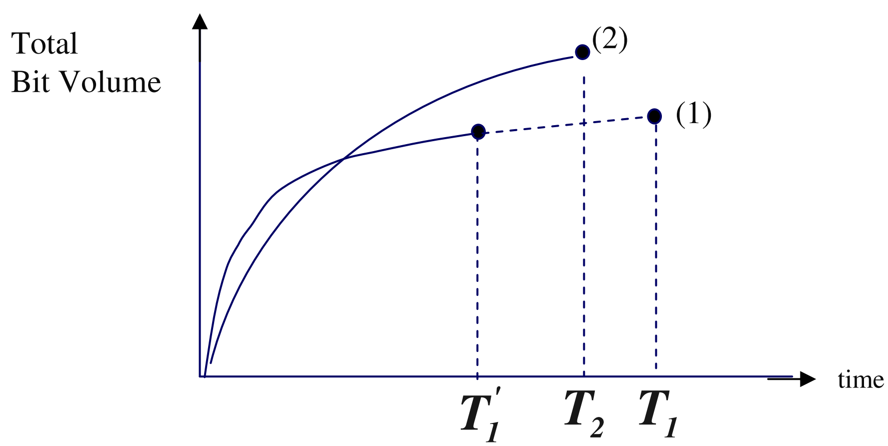
1. Efficiency: max communication performance per "Joule"

2. "Reserves": ?
   - notion of "lifetime"
   - max communication volume over lifetime?

EXAMPLES OF FINITE ENERGY CASE







ENERGY CONTROL

- Coding, Mod, SP, Detector, Antenna, PA, etc., etc.

  (mostly fixed, except SDR)

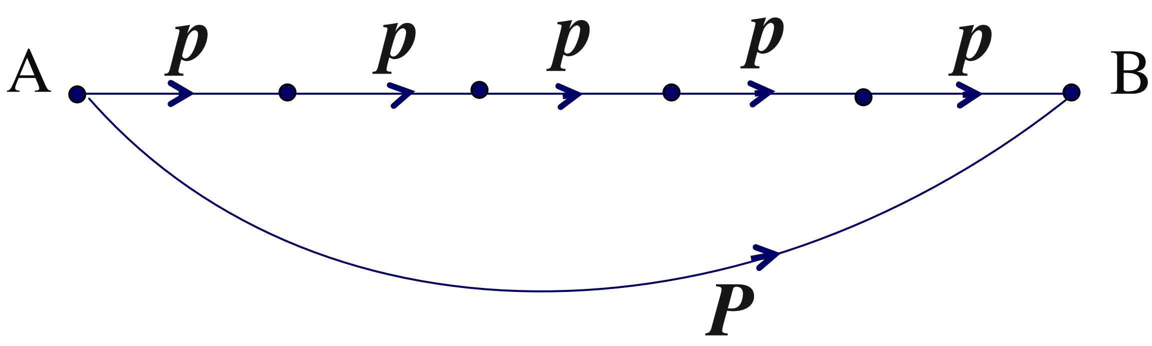
- RF Power, Rate, BER

  ↓ includes "sleeping" schedule

  – hence: Topology of Network
  – hence: Higher Order Protocols

  e.g. <u>routing</u> and <u>multicasting</u>

ROUTING



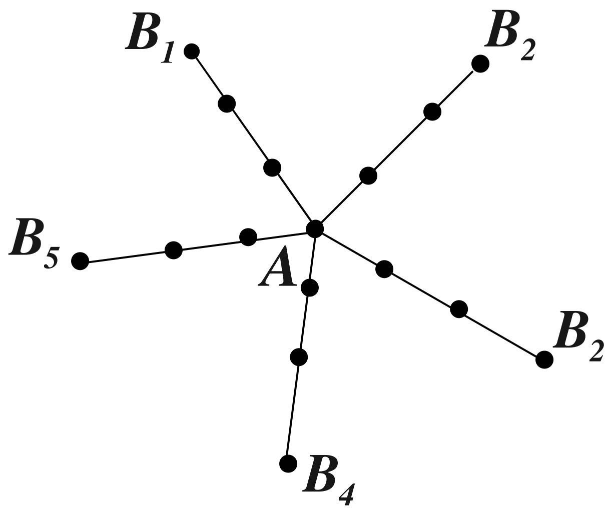
$$P \;\square\; 5p$$

Received power: $\sim \dfrac{1}{r^{\alpha}}$

$$2 < \alpha < 4$$

YET: other factors (interference, control traffic, processing)

MULTICASTING



p = power needed per short hop

P = power needed to reach all

$$P > 3\,p$$

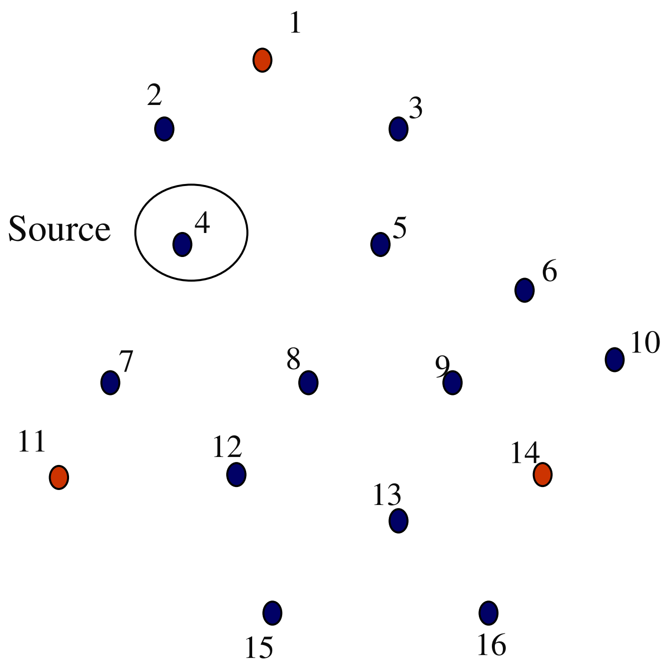
but

$$P \gtrless 5 \times 3\,p$$

Hence: “Yelling” may be preferable to “Whispering”

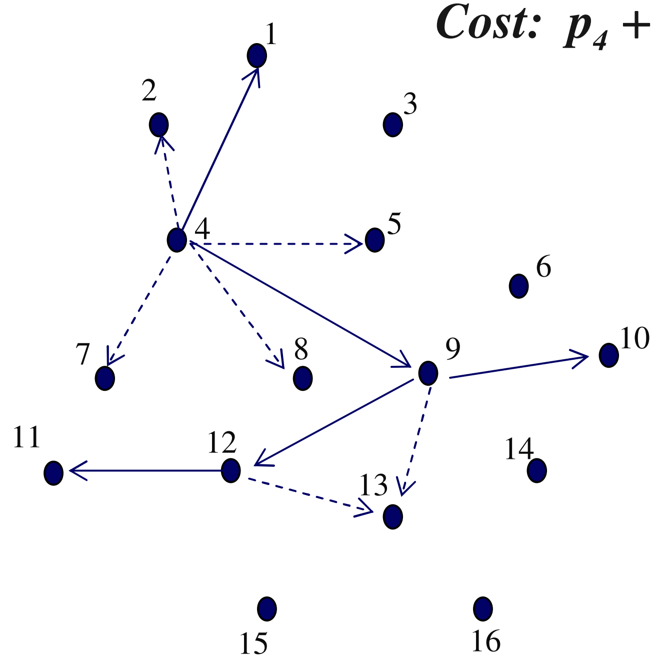
FOCUS ON MULTICASTING

- no mobility
- session traffic (source initiated)
- infinite bandwidth resources (no interference)



Source 4: Destinations 1, 10, 11

Cost: $p_4 + p_9 + p_{12}$



Tree Construction

“NEW” PROBLEM

- FIND MIN COST TREES ON “NODE” GRAPHS (from given source to a set of destinations)
- NEW: Because “LINK” depends on RF power
- DETERMINE AT EACH STEP:
  - Transmission Power
  - Set of “Intended” nodes on Tree
- COST: Total Power of More Sophisticated Metrics

"SAMPLE" METRIC (Yardstick)

$$Y = \frac{1}{K}\sum_{i=1}^{K}\frac{m_i}{n_i}\frac{m_i}{P_i}$$

K : total number of "session" requests over time

n_i: number of destination nodes of i^{th} session

m_i : number of "reached" destination nodes of i^{th} session

P_i : total power of tree of i^{th} session

NOTE: $\frac{m_i}{P_i} = \frac{m_i t_i}{P_i t_i} = \frac{\text{number of delivered bits}}{\text{energy spent to deliver them}}$

t_i : duration of i^{th} session in "bits" (connection to rate)

COMPLEXITY OF TREE CONSTRUCTION

- In "LINK" GRAPHS
  - Broadcasting: MST (polynomial)
  - Multicasting: NP

- IN "NODE" GRAPHS
  - Broadcasting
    AND
  - Multicasting

  } NP

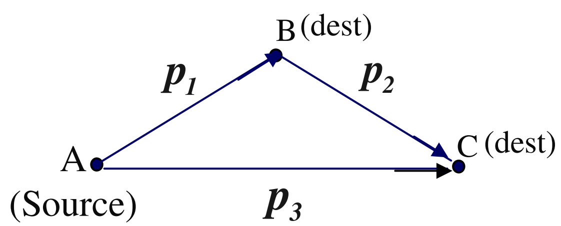
(Multiple recent proofs)

SUBOPTIMAL SOLUTIONS

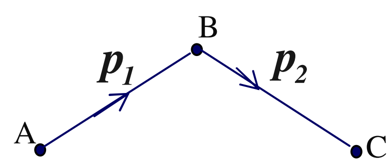
BROADCASTING: BIP

MULTICASTING: MIP with pruning

Common: Concepts of <u>Incremental Power</u>

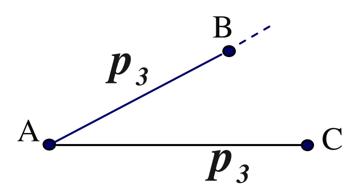


If $p_3 > p_1 + p_2$



Cost: $p_1 + p_2$

If $p_3 < p_1 + p_2$

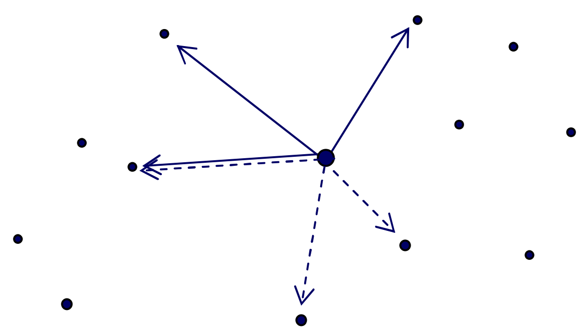


Cost: p_3

ADDITIONAL CONSTRAINTS

- FINITE NUMBER OF TRANSCEIVERS PER NODE (i.e., number of simultaneous sessions that can be supported)
- FINITE BANDWIDTH (i.e., number of frequencies for FDMA)
- DIRECTIVE ANTENNAS

  new feature: beamwidth AND pointing direction



MOBILITY

- RECALL ELASTICITY (crucial for session traffic)
- NEED FOR DISTRIBUTED SOLUTIONS
- HENCE, NEED FOR NEIGHBOR DISCOVERY
- HENCE, NEED FOR PROBING MESSAGES
- HENCE, NEED FOR DISCRETE SET OF POWER LEVELS
- HENCE, NEW PROBLEM

  i.e., construct tree (as before) but with a finite set of discrete power levels.

CASE OF DATA TRAFFIC

- FUNDAMENTALLY DIFFERENT
  - No Tree Construction

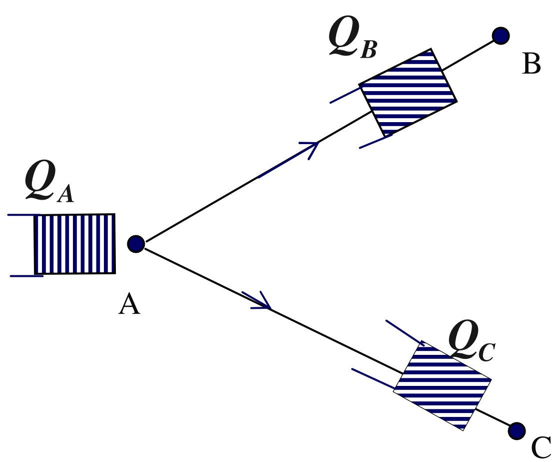
- Hence: Routing with appropriate metrics on the “LINKS”

  Example: CAPTURE

  Communication Performance
  (i.e., delay AND congestion)
  AND
  Energy Performance (i.e., power)

DATA TRAFFIC (Con't.)

NEED TO DEFINE PATHS ("hop" by "hop") FOR EACH PACKET **AND** LINK ACTIVATION



p_B: *power needed to reach B*

p_c: *power needed to reach C*

Q_A, Q_B, Q_c : *queue sizes*

AT EACH "TIME-SLOT": Decide which neighbor(s) to send packet X to (i.e., choose power) **AND** decide which "LINK" to activate

DATA TRAFFIC (Con't.)

COST OF EACH LINK (i,j)

$$D_{ij} = w_p \frac{P_{ij}}{P_{max}} + w_e \frac{E_o - E_j^R}{E_o} + w_d \frac{Q_{ij}}{1 + Q_{ij}}$$

E_o: ***initial energy reserve***
E_j^R : ***current residual energy at j***
Q_{ij} : ***queue size at i for j***

(captures delay and energy)

(Routing Part)

DATA TRAFFIC (Con't.)

COST OF EACH LINK (i, j) in R(i): set of "eligible" neighbors of i

$$W_{ij} = \frac{c_q}{Q_{ij} + Q_{ji} + 1} - \frac{c_d}{1 + \sum_{k \in R(i)} (Q_{ik} + Q_{ki} + \sum_{k \in R(i)} (Q_{kj} + Q_{jk}))} + c_e \frac{P_{ij}}{P_{max}}$$

captures - delay: "longest queue first:
- congestion: "links that block fewest packets first"
- energy: "shortest links first"

R(i): set of "non-conflicting" links at the moment (formed by link)

(Scheduling Part)

ANOTHER NEW "INSIGHT"

THE ANALYSIS OF "ENERGY-AWARE" ROUTING/MULTICASTING REVEALS THE COUPLING AMONG THE "LAYERS"

- Physical Layer Parameters: RF-power, rate, etc.
- MAC Layer Parameters: Scheduling of Transmissions
- Network Layer Parameters: Routing/Multicasting

HENCE

VERTICAL INTEGRATION

– NEED FOR CROSS-LAYER OPTIMIZATION

AND/OR

– NEED FOR CAPTURING CROSS-LAYER INTERACTIONS

"INSIGHT" (Con't.)

ALSO:

- PRESENTATION LAYER PARAMETERS: Compression
    - more compression requires more processing energy
    - more compression reduces the bits to be transmitted, hence saves transmission energy
    - but, it also distorts the signal

WHICH LEADS TO FURTHER COUPLING WITH LINK LAYER

"INSIGHT" (Con't.)

"reliable" bits of an "unreliable" signal

vs.

"unreliable" bits of a "reliable" signal

i.e., detect the "few" bits well

vs.

detect more bits but not as well

(communication theory meets energy-aware networking)

CONCLUSIONS

- ENERGY AWARENESS IN WIRELESS NETWORKS (efficiency AND finiteness)
- "HIGHER"-LAYER PROTOCOLS (Routing, etc.) PLAY CRUCIAL ROLE
- ALL LAYERS INTERACT
- WIRELESS LINK STRENGTHENS THE INTERACTIONS
- VAST SPACE OF CHALLENGING, UNEXPLORED, AND LITTLE-UNDERSTOOD PROBLEMS