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# **THE WIRELESS LINK PERSPECTIVE IN WIRELESS NETWORKING**

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# WIRELESS NETWORKING

- “Maturing” (catalytic effect of MAC)
- Diverse (from cellular to sensors)
- Growing (in \$ and in interest)
- Rich (truly new intellectual and design problems)
- Confusing (if not chaotic)
- Success Stories
- Areas of Challenge

# WHY “CONFUSING”?

- DOES NOT QUITE “FIT” THE WIRELINE NETWORK PARADIGM
  - “Link” is a relative (or “soft”) concept
  - MAC is a key concept
  - Energy is important (all of a sudden)
  - Mobility
  - Relationship to Infrastructure
  - Application Drivers (e.g. sensors, military, etc.)
- COMBINES (INSEPARABLY) MANY DISCIPLINES

# THE “CULPRIT”

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- THE WIRELESS LINK -
  - Breaks down the traditional concept of topology
  - Strengthens the cross-layer coupling
  - Brings in a different culture of thinking

# WHAT IS A LINK?



$$SINR > \gamma$$

***SINR:** RF transmit power, antennas, other users,  
channel, rate*

***$\gamma$ :** detector structure, mod/demod, waveforms, cod/dec,  
BER target*

***Underlined quantities make the notion of a link readily  
controllable***

# CONSEQUENCES

- CLEARLY NO FIXED TOPOLOGY (even without mobility)
- CROSS-LAYER COUPLING
  - power  $\longleftrightarrow$  energy consumption  $\longleftrightarrow$  higher & lower layers
  - other users  $\longleftrightarrow$  MAC
  - rate  $\longleftrightarrow$  throughput  $\longleftrightarrow$  higher & lower layers
  - BER  $\longleftrightarrow$  new QoS measure  $\longleftrightarrow$  application layer
- DIFFERENT CULTURE
  - Rich Theory of Communication
  - Rigorous Analysis, Precise Modeling
  - Complex Details

# CONSEQUENCES (Con't.)

- IGNORING THE PHYSICAL LAYER LIMITS THE MEANINGFULNESS OF NETWORKING ANALYSIS AND DESIGN
- TAKING THE PHYSICAL LAYER INTO ACCOUNT CAN BE DONE SELECTIVELY (but carefully) AND YIELD USEFUL RESULTS

- MULTIPLE ACCESS (from ALOHA to elaborate reservation and scheduling schemes)
  - power control
  - dynamic channel allocation
  - elaborate hand-offs & mobility tracking
  - interfacing to the IP network
  - made cellular telephony & systems the miracle of the '90's
  - enabled WLAN's (802-11, Bluetooth, etc.)
- ROUTING (multitude of algorithms)
  - on demand
  - distributed
  - link state
  - location/direction-based
  - elaborate metrics
  - “all above average”

- EMERGENCE OF FUNDAMENTAL PRINCIPLES
  - “capacity” of ad-hoc networks
  - exploitation of apparent impediments
    - mobility
    - fading (multi-user diversity)
  - understanding energy implications
  - capturing layer interactions

# AREAS OF CHALLENGE

- LACK OF THEORY
  - ultimate limitations: elusive
  - fragmentation of research
  - heavy reliance on heuristics
  - auto “magic” protocols
  - shortage of fundamental research
- APPLICATION DEPENDENCE
  - interfacing to the IP network (3G)
  - sensor networks vs. digital battlefield (40g)
  - home network vs. voice telephony
  - browsing vs. symmetric

# AREAS OF CHALLENGE (Con't.)

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- **SIZE AND SCALABILITY**
  - Complexity (often combinatorial)
  - Performance (often unacceptable)
- **RESOURCES AND ECONOMICS**
  - Precious spectrum instead of cheap fiber
  - Mobility
  - Public spoiled by the internet and cellular voice



# THE ROLE OF THE WIRELESS LINK (examples)



- RATE AS A MEANS OF CONNECTIVITY CONTROL
- TRADE-OFF BETWEEN ENERGY FOR PROCESSING AND FOR TRANSMISSION
- EFFECT OF RF-POWER ON ROUTING AND MULTICASTING AND ON COUPLING WITH MAC
- REVERSAL OF TRADITIONAL THINKING REGARDING CAPTURE
- PRINCIPLE OF OPPORTUNISTIC SIGNLING
- PULSING OF BATTERIES

# CONNECTIVITY CONTROL VIA RATE

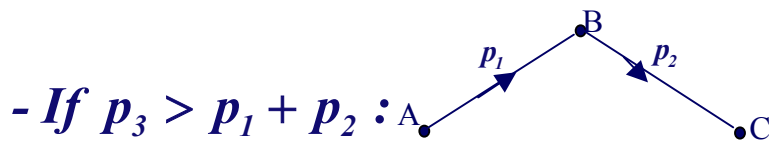
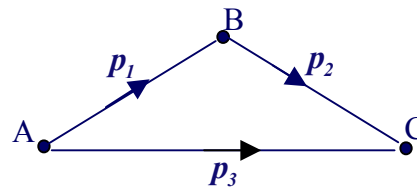
- PREFERABLE TO POWER BECAUSE IT DOES NOT AFFECT INTERFERENCE (non-invasive)
- LOWERING THE RATE PERMITS THE PACKAGING OF MORE ENERGY PER SYMBOL ( $\text{SINR} > \gamma$ )
- SO, A FALTERING LINK CAN BECOME MORE RELIABLE (elasticity)
- A PREVIOUSLY NON EXISTENT LINK CAN BE CREATED
- RATE REDUCTION LOWERS THROUGHPUT OR INCREASES DELAY OR DISTORTS THE SIGNAL
- CAN BE DONE EITHER AT THE TRANSMITTER OR THE RECEIVER

# PROCESSING vs. TRANSMISSION ENERGY

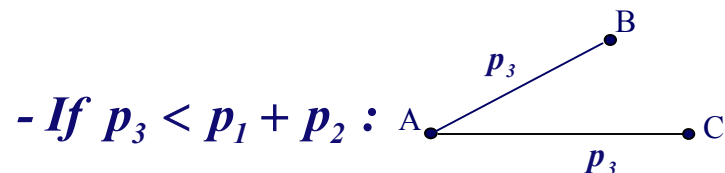
- SAY  $R$   $\text{bits/s}$  SUFFICE TO DESCRIBE A SIGNAL AND  $BER = p$  PERMITS SATISFACTORY RECREATION OF THE SIGNAL
- IF  $R$  IS REDUCED TO  $R/2$  (via additional compression) THE RF TRANSMISSION ENERGY IS ALSO HALVED
- DISTORTION AT THE RECEIVER APPARENTLY INCREASES
- BUT  $p$  CAN BE REDUCED AT THE SAME TIME (the fewer bits are received more reliably)
- OVERALL DISTORTION MAY OR MAY NOT INCREASE
- OVERALL ENERGY CONSUMPTION MAY OR MAY NOT DECREASE
- NOVEL TRADE-OFF (Note: coupling of link layer and presentation layer)

# RF-POWER AND ROUTING/MULTICASTING

- POWER NEEDED TO REACH A NODE AT DISTANCE  $r$   
 $\sim r^\alpha$ ,  $2 < \alpha < 4$
- WHISPERING BETTER THAN YELLING (for unicast)
- TRADE-OFF UNCLEAR FOR MULTICASTING
- WIRELESS MULTICAST ADVANTAGE AND PRINCIPLE OF INCREMENTAL POWER



at cost  $p_1 + p_2$



at cost  $p_3$

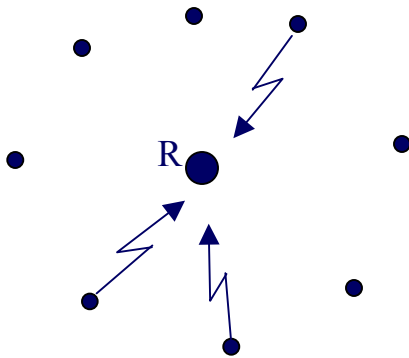
## (Con't.)

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- SEVERAL ALGORITHMS FOR TREE CONSTRUCTION
- SEVERAL ALGORITHMS FOR ACTUAL SOURCE-BASED SESSION MULTICASTING (no mobility and centralized) WITH CONSTRAINED RESOURCES
- NEW METRICS FOR DATA ROUTING THAT CAPTURE COMMUNICATION PERFORMANCE AND ENERGY CONCERNS (note: coupling the bottom three layers).

# CAPTURE

TRADITIONAL THINKING: CAPTURE OCCURS WHEN ONE OF SEVERAL OVERLAPPING SIGNALS IS STRONGER (with MUD, actually, more than one signal can be successfully captured)



THUS

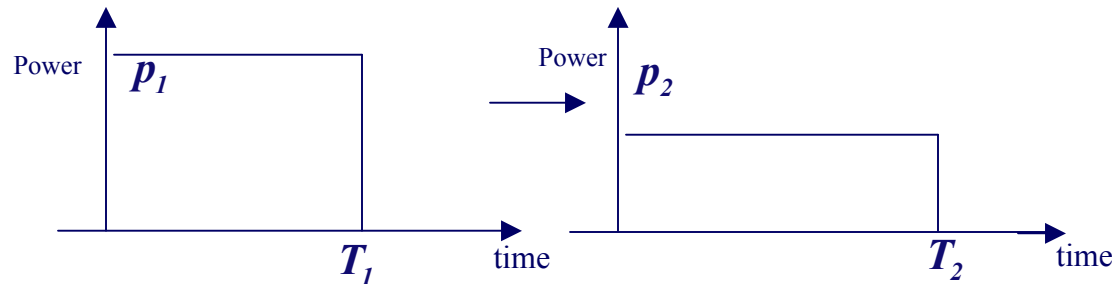
INCREASED THROUGHPUT (in a simple single-cell environment)

TRADITIONAL IDEA: TO ENSURE POWER LEVEL DIFFERENTIATION, ALL USERS SHOULD USE DIFFERENT POWER LEVELS  
(anti-power-control)

# CAPTURE (Con't.)

PHYSICAL LAYER THINKING: CAPTURE MEANS

$$SINR > \gamma \text{ AND}$$



$$\text{If } P_1 > P_2 \text{ then } T_1 < T_2$$

THEREFORE: Multiple power levels permit capture (to increase throughput) but also require some longer packets and hence more frequent “collisions” (that decrease throughput)

**Q: WHICH WAY IS THE TRADE-OFF RESOLVED?**

# CAPTURE (Con't.)

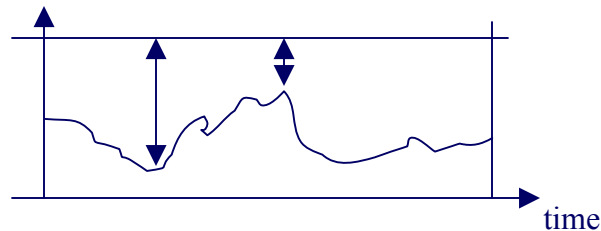
A: TRANSMIT AT MAX (hence equal) POWER

- No capture benefits
- Maximum Time Separation  
(fewer collisions)

NOTE: ARGUMENT FOR ORTHOGONAL  
SIGNALING (in limited setting)

# OPPORTUNISTIC SIGNALING

- ORIGINS: ~'95
- PRINCIPLE: TRANSMIT MAXIMALLY WHEN CHANNEL IS BEST (waterfilling arguments)



- EXTENSION: MULTI-USER DIVERSITY ('00)  
whoever has the best channel at a given time should use it exclusively

NOTE: ARGUMENT FOR ORTHOGONAL SIGNALING  
(another limited setting)

**\*Principle of Exploitation of Adversity\***

- Continuous Draining Reduces Total Energy Supply
- Pulsed Draining Increases Total Energy Supply

NOTE 1: Another Argument for Orthogonal Signaling (TDMA)  
( in yet another limited setting)

NOTE 2: Can pulse in TDMA fashion the cells of a given battery for continuous transmission

# TO WRAP UP

- THE WIRELESS LINK CHANGES THE TRADITIONAL NETWORK PARADIGM IN MULTIPLE WAYS
  - Coupling the Layers
  - “Softening” the Topology
  - Introducing Pillars of Theory
- IT MAY COMPLICATE THE NETWORK DESIGN PROBLEM
- IT MAY ALSO SIMPLIFY IT (Brings New Tools to the Arsenal)
- IT BRINGS “PHYSICAL REALITY” INTO THE “VIRTUAL” NETWORK
- CAN HELP TRANSFORM CHALLENGES TO OPPORTUNITIES

- THE “BIG BANG” OF A UNIFIED UNDERLYING THEORY MAY NEVER OCCUR
- THE FUNDAMENTAL LIMITATIONS MAY BE ILLUMINATED BY LOOKING AT ASYMPTOTIC REGIMES
- WIRELESS WILL BE PART OF OUR FUTURE
- THE FUN HAS JUST BEGUN!