



THE WIRELESS REVOLUTION AT CROSSROADS: "WHERE TO NEXT ?"

WPMC, September 10, 2008
Saariselkä, Finland

Anthony Ephremides
University of Maryland

1



WHAT HAS HAPPENED?

- Guglielmo Marconi's discovery
- Almost a century of low-rate, point-to-point communication
- Almost a century of radio and television broadcasting
- Crucial Military System Enhancement (e.g. Spread-Spectrum) and then

----- THE "REVOLUTION" -----

2



WHAT MAKES A REVOLUTION?

- Where do good ideas come from? Do they fall from the sky?
 - **NO!** *They come out of the barrel of a gun !*
 - Mao Zedong –
(Cultural Revolution)
- We learned how to deal with INTERFERENCE
 - * the “__MA”s (FDMA, TDMA, CDMA)
- CELLULAR SYSTEMS (for voice)
- AN “AVALANCHE” FOLLOWED
 - Data
 - Wireless Network Concept (ITF Network and Packet Radio)
 - Ubiquitous Applications

3



WHERE ARE WE NOW?

- TETHERLESS FREEDOM CRAZE
- EXPECTATIONS RISE FASTER THAN TECHNOLOGY
- TECHNOLOGY IS “JUMPING THE GUN”
 - Running ahead of theory (yet, really staying behind)
 - WI-FI, WIMAX, MESH NETWORKS, SENSOR NETWORKS
 - “Struggling” standards (802.11, 802.15, etc)
- SPECTRUM LIMITATIONS
- INTERFERENCE RISING
- AMBITIONS RISING
- MARKETING RISING

----- **WHAT TO DO?** -----

4



MUST RE-ACCESS

- DO WE UNDERSTAND THE ULTIMATE LIMITATIONS OF WIRELESS NETWORKS? (NO)
- CAN WE REALIZE (OR APPROACH) THESE LIMITS? (NO)
- WHY?
- CAN WE SHAPE A VISION?
(YES)
- CAN WE AGREE ON A BLUEPRINT FOR THE NEXT STEP(s)?
(PERHAPS)

5

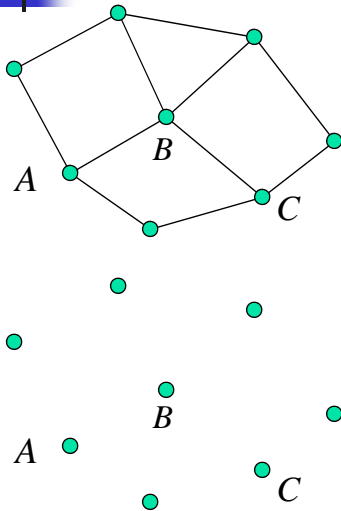


WHY?

- THE "ORIGINAL SIN" OF NETWORKING:
LAYERING
- LED TO GROUNDLESS EXTENSIONS OF NETWORK ARCHITECTURES TO WIRELESS SYSTEMS
- NEGLECTED THE PERVASIVE EFFECT OF THE PHYSICAL LAYER ON ALL OTHER LAYERS
- USAGE OF "GRAPH" MODELS AND NOTION OF "NEIGHBORS"

6

WHY? (Cont.)



- IS THIS A WIRELESS NETWORK?
- WHAT DOES THE "LINK" AB MEAN?
- WHY AREN'T A AND C NEIGHBORS?

← THIS IS A WIRELESS NETWORK!

7

WHY? (Cont.)

- WE HAVE BEEN ASKING THE WRONG QUESTIONS, ALL ALONG.
- e.g.
 - "TWEAKING" PROTOCOLS DEVELOPED FOR BENIGN ENVIRONMENTS
 - ASKING ABOUT CAPACITY OF A NETWORK (but there are no links!)
 - CLAIMING SUCCESS PREMATURELY (MIMO technology)

TRUTH: WE DO NOT HAVE A CLUE!

8



CAN WE SHAPE A VISION?

- MIGRATE FROM “CAPACITY” AND “THROUGHPUT” TO ALTERNATIVE DEFINITIONS OF ULTIMATE CAPABILITIES
 - NON-STATIONARITY
 - NON-ERGODICITY
 - VARIABLE TOPOLOGY (that “cursed” mobility)
 - ENERGY (COSTLY AND/OR FINITE)
- GIVE OPERATIONAL MEANING TO THESE CAPABILITIES
 - AS CODING ACHIEVES CAPACITY
- UNDERSTAND THE SHAPE OF DESIGN CHOICES
 - How to DEFINE SUB-OPTIMAL (BUT SOLVABLE) PROBLEMS WITHOUT ILLUSIONS

9



VISION? (Cont.)

- UNDERSTAND HETEROGENEITY
 - DIFFERENT COST FUNCTIONS FOR DIFFERENT USERS (COOPERATIVE, SELFISH, MALICIOUS, ALTRUISTIC)
 - SECURITY IN THE UBIQUITOUS MEDIUM
- SELECTIVELY (AND CAREFULLY) ADOPT LIMITATIONS FROM PHYSICS
 - CANNOT TRANSMIT AND RECEIVE SIMULTANEOUSLY ON THE SAME CHANNEL
 - FUNDAMENTAL NEED FOR SCHEDULING (with implications on rates)

10



VISION? (Cont.)

- "TEAR DOWN THIS WALL"
 - SLOWLY BUT METHODICALLY CHIP AWAY AT THE LAYER BOUNDARIES
(difference between having layers and coupling them)
- EXTEND INTO THE "SUB-TERRANEAN" LAYERS
 - SOFTWARE (OS, MEMORY MANAGEMENT)
 - HARDWARE (EMBEDDED PROCESSORS, ARCHITECTURE, FABRICS)
e.g. energy per bit (for computation) $\rightarrow 0$,
as delay $\rightarrow \infty$ (if entropy is preserved)

-- REVERSIBLE COMPUTATION --

11



VISION? (Cont.)

- INTERPLAY BETWEEN TRANSMISSION AND REPRESENTATION (like SOURCE *vs* CHANNEL CODING)
 - ALLOWING FOR DISTORTION
(Network Coding is "GOOD DISTORTION")
- CONNECT TO APPLICATION (LAYER)
e.g. ■ INFERENCE IN SENSOR NETWORKS
 - HOW TO "ROUTE" FOR OPTIMAL INFERENCE?

12



NEXT STEP(S)?

- CONCENTRATE ON PACKETS PER SLOT AND MAP THAT TO BITS PER SECOND
- CONCENTRATE ON DELAY-AWARE MEASURES
 - e.g. STABLE THROUGHPUT REGION (Back-Pressure)
- EXPLORE NETWORK CODING
- CO-OPERATION AT PACKET LEVEL
- ENERGY
 - Longevity
 - Hardware Connection

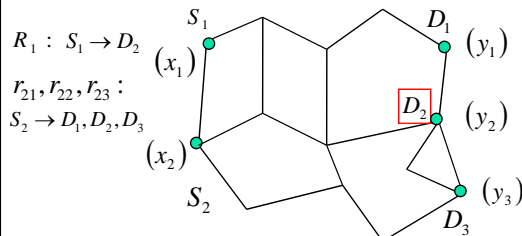
* ----- "TOY" PROBLEMS ----- *

13



PACKETS vs BITS

- AVOID THE "CHOKING" EFFECT OF INFORMATION THEORY



$$p(y_1, y_2, y_3 / x_1, x_2)$$

$$I(x_1, x_2; y_1, y_2, y_3) : R_1 + r_{21} + r_{22} + r_{23}$$

$$I(x_1; y_2 | x_2) : R_1$$

$$I(x_2; y_1) : r_{21}$$

$$I(x_2; y_2 | x_1) : r_{22}$$

$$I(x_2; y_3) : r_{23}$$

- Multi-Access to D_2
- Broadcast from S_2

Subject to flow constraints

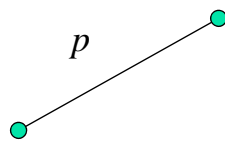
14



PACKETS vs BITS (Cont.)

- BUT DO NOT IGNORE THE **BIT-NATURE** OF THE PACKET CONTENT

e.g. PACKET ERASURE MODEL



p : Prob of packet erasure
(fades; buffer overflows)

CAN'T LET THE NUMBER OF BITS $\rightarrow \infty$
WHILE p STAYS CONSTANT

15



DELAY-AWARE MEASURES

- CAPACITY: bits/s, saturated queues
 - THROUGHPUT: packets/slot, saturated queues
 - "STABLE" THROUGHPUT: packets/slot, bursty arrivals
- } **Need not coincide**

(stability: Positive Recurrence or $P(Q > M) \xrightarrow{M \rightarrow \infty} 0$ or other related criteria)

- * **BACK-PRESSURE: (B-P)**
 - FORWARD PACKETS TO NEIGHBOR WITH MAXIMUM DIFFERENTIAL BACKLOG
 - ACTIVATE THOSE USERS WHOSE COMBINED EFFECT ACHIEVES MAXIMUM REDUCTION TO TOTAL DIFFERENTIAL BACKLOG

16

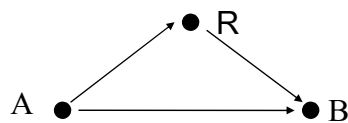
NETWORK CODING

- 1999 BREAKTHROUGH IDEA
- “REVOLUTIONARY”: RANDOMLY MIX THE PACKET CONTENTS!
- RESULT:
 - “CAPACITY” ACHIEVEMENT IN MULTICASTING
 - RATE IMPROVEMENT POSSIBLE IN UNICASTING
 - POSSIBLY COMBINABLE WITH B-P
 - APPLICABLE TO WIRELESS (with care)
 - CONTENT DISTRIBUTION (akin to Fountain Coding)
- PROBLEMS:
 - GROWING OVERHEAD
 - NEED FOR COORDINATION
 - IMPROVEMENT SIZE?

17

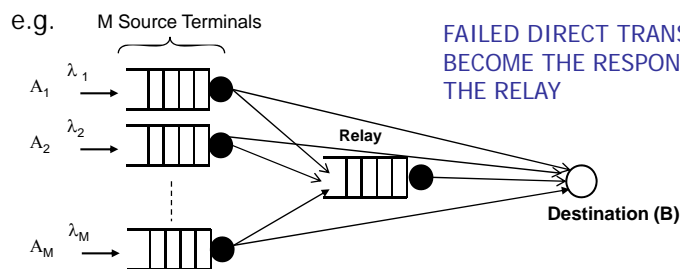
CO-OPERATION

- TRADITIONAL RELAY CHANNEL



INTRICATE INFORMATION-THEORETIC MODELING AND ANALYSIS

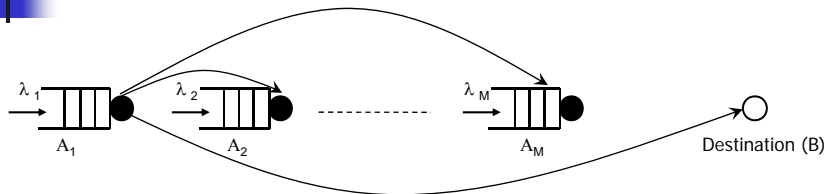
- THINK “SIMPLE” RELAYING OF PACKETS



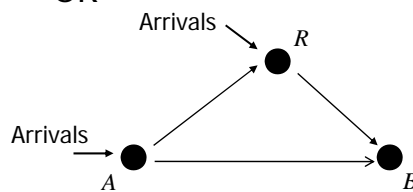
FAILED DIRECT TRANSMISSIONS BECOME THE RESPONSIBILITIES OF THE RELAY

18

CO-OPERATION (Cont.)



- ANY INTERMEDIATE NODE CAN ACT AS RELAY
- OR --



- NOW R HAS ITS OWN TRAFFIC AS WELL
- WHAT UTILITY FUNCTIONS DO A AND R HAVE?

19

ENERGY

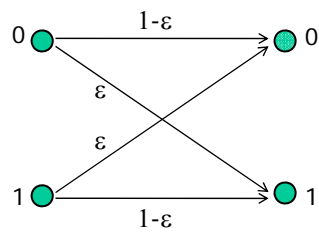
- "FOLKLORE": TRANSMISSION ENERGY DOMINATES
- "REALITY": PROCESSING ENERGY MAY BE JUST AS IMPORTANT
- PROCESSOR LAYOUT AFFECTS ENERGY CONSUMPTION
- TDMA *vs* RANDOM ACCESS
- IN SENSOR NETWORKS:
 - NEIGHBOR DISCOVERY
 - MISSION PERFORMANCE
 - EFFECT ON ENERGY CONSUMPTION

20

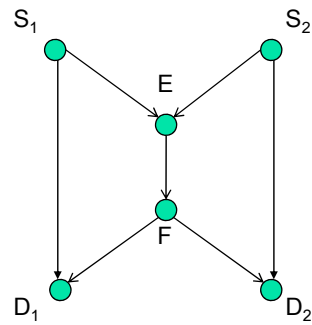
"TOY" PROBLEMS

- THEY ARE "FUN"
- CAN PROVIDE VALUABLE INSIGHTS

■ RECALL THE BSC

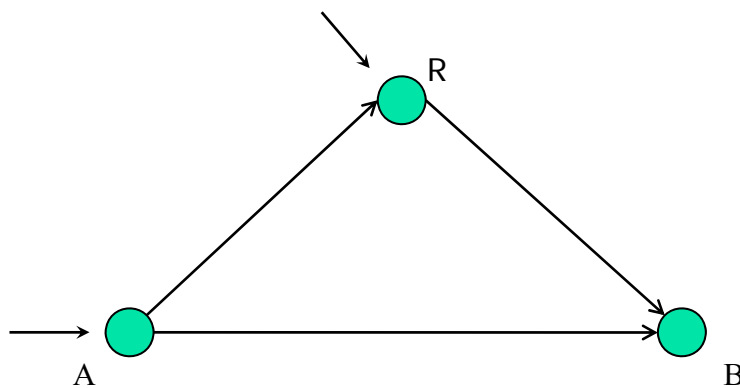


■ THE BUTTERFLY NETWORK



21

"TOY" PROBLEM OF THE DAY



22