Bits aren't bites: Constructing a "Communications Ether" that can grow and adapt

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Agenda

- How can we best meet the demand for wireless communications capacity?
- Does "spectrum" have a capacity?
- "Interference" and information loss
- What's new?
- Making capacity scale
- **Viral network** architectures

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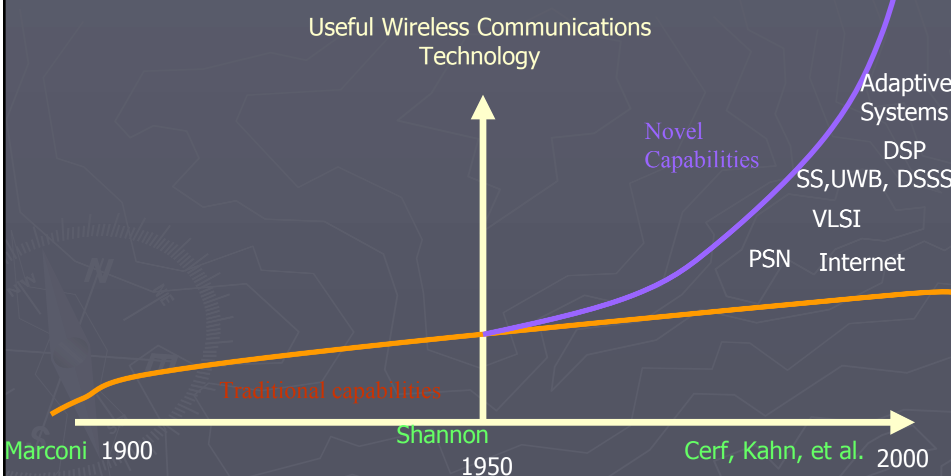
Sustaining vs. Disruptive Technology in a Regulated Industry



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Mainframe communications vs. viral communications

- Mainframe to PC evolution
  - Lower economic barriers to innovative uses
  - Enable new computing technologies (sound and video)
- “Mainframe communications” to viral communications
  - Lower barriers to innovative uses (802.11)
  - Enable new capabilities (sociable devices)

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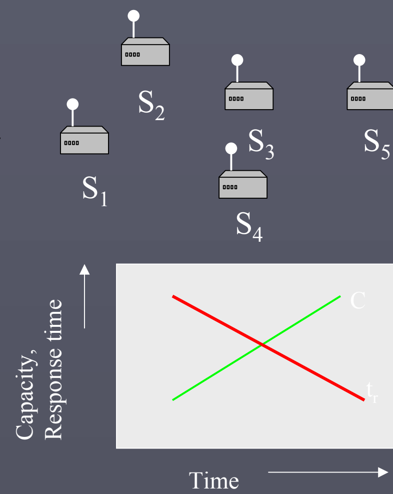
The big problem: scalability is starting to matter

- Pervasive computing must be wireless
- Demand for connectivity that changes constantly at all time scales
- Capacity and response time expectations evolve exponentially



A Viral Network Architecture

Viral network definition:

- each new user preserves or increases capacity and other economic value to existing users, and
- benefit to new user increases with scale of existing network

Examples:

- Fax machines
- Internet
- "Society of Cognitive Radios"

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Does "Spectrum" have a capacity?

The *radio tradition* evolved from 1900-1950:

Resonance provided a means to use multiple radio systems at one time

As new radio based services were invented, they were given new frequencies

Some frequencies worked to send messages farther than others.

Power let you send the same signal farther.

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Shannon's answer: bits and "channels"

$$C = W \log(1 + \frac{P}{N_0 W})\text{, due to Claude Shannon}$$

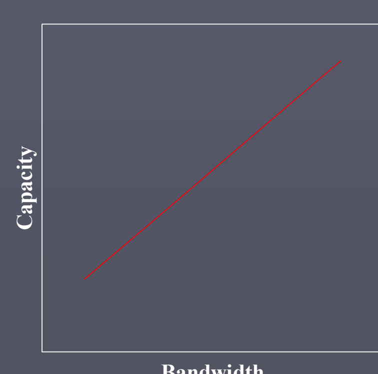
C = capacity, bits/sec.

W = bandwidth, Hz.

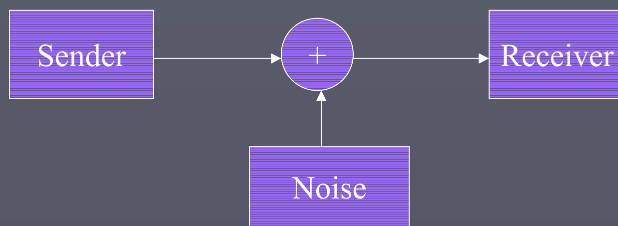
P = power, watts

N_0 = noise power, watts/Hz.

Channel capacity is roughly proportional to bandwidth, and logarithm of power.



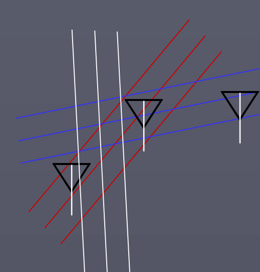
We don't know the *full* answer.

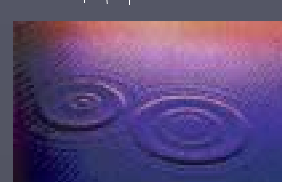


"Standard" channel capacity is for one sender, one receiver – says nothing about the most important case: many senders, many receivers.

"The capacity of multi-terminal systems is a subject studied in multi-user information theory, an area of information theory known for its difficulty, open problems, and sometimes counter-intuitive results." [Gastpar & Vetterli, 2002]

Interference and information loss





•Regulatory interference = damage

•Radio "interference" = *superposition*

•No information is *actually* lost

•Receivers may be confused

•Information loss is a systems design and architectural issue, not a physical inevitability

Where does "interference" occur, and who causes it?

When a new radio is added to the system, does it displace capacity? (Does it require new resources not already in use?)

When a new radio is added to the system, does it impose costs on others, even though there is no displacement of capacity?

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When a new radio is introduced into the system, does it displace capacity?

The waves emitted by a new transmitter at a new point in EM space are mathematically *orthogonal* to every other such wave.

Does the set of receivers in the space provide an adequate basis to recover the original signals?

Spatial sampling theorem: in most cases, yes.

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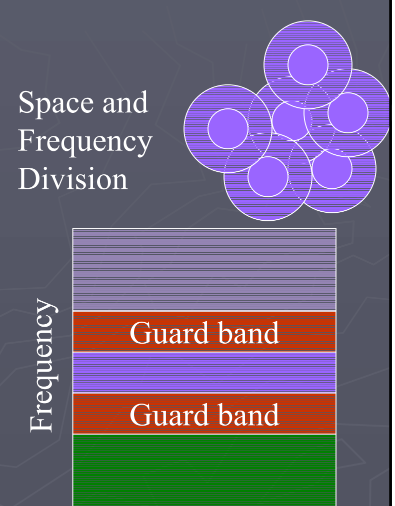
When a new radio is added to the system, does it impose net costs on others, even though there is no displacement of capacity?

- Achievable information capacity
  - Increase transmitters per receiver
    - Increases available rate region with N.
  - Increase receivers per transmitter
    - Increases available rate region with N.
  - Equal transmitters and receivers???
- Achievable latency
- "Computational costs"
  - Per-node cost of encoding/decoding
- "Evolutionary costs"
  - Cost of sharing with legacy designs
  - Growth rate

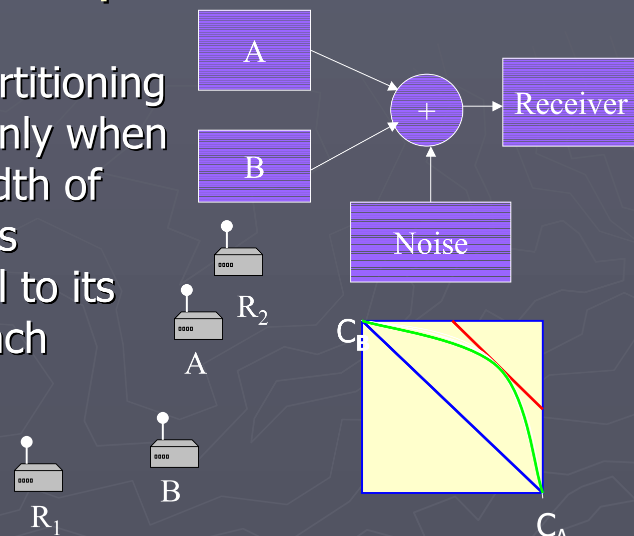
Partitioning wasteful

- Demand is dynamic
  - Bursts capped
  - Random addressability & group-forming value severely reduced
- Partitioning in space, frequency, or time wasteful



Slepian-Wolf

Frequency partitioning is optimal only when the bandwidth of each band is proportional to its power at each receiver



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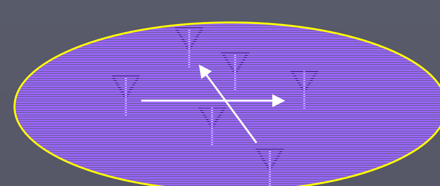
Transport Capacity: One important measure of radio network capacity

Network of N stations (transmit & receive)

Scattered in a fixed space

Each station chooses randomly to send messages to other stations

What is achievable total *transport capacity, C_T*, in bit-meters/second?

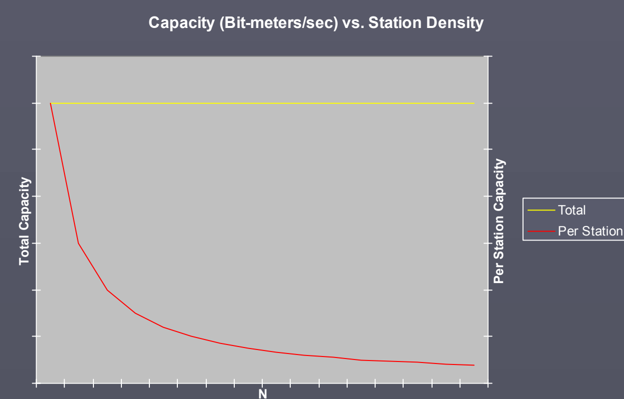


$b_{s,r}$ = bits from s to r

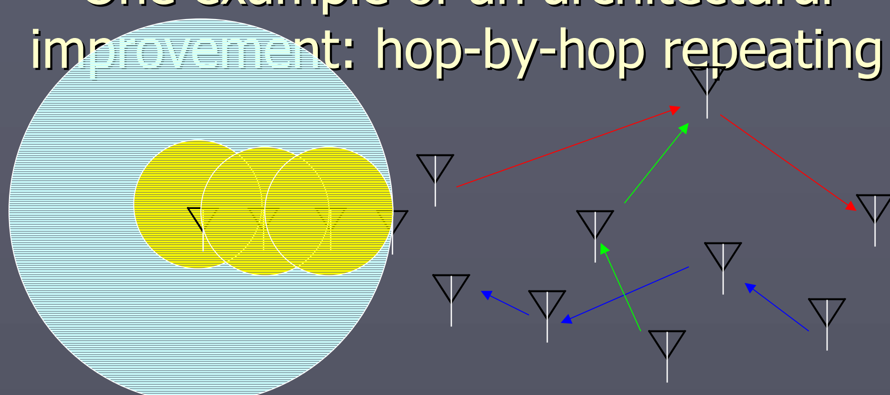
$d_{s,r}$ = distance from s to r

$$C_T = \frac{\sum_{s,r \in N} b_{s,r} \bullet d_{s,r}}{t}$$

"Spectrum capacity" model under static partitioning



One example of an architectural improvement: hop-by-hop repeating

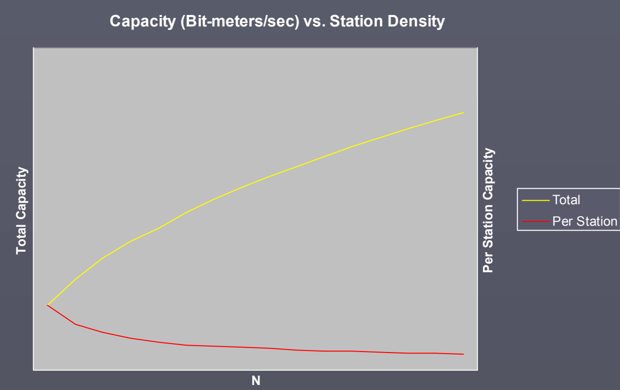


Energy/bit reduced by 1/hops.

Many paths can operate concurrently.

What is repeater network's capacity as radios are added?

Repeater Network Capacity

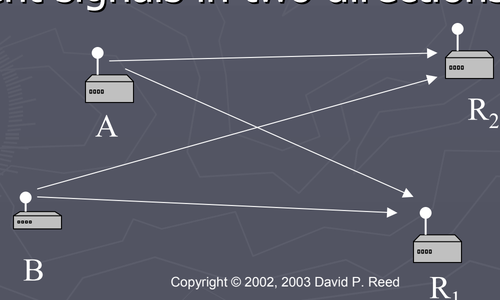


Spatial organization

Directional antennas provide fixed allocation

Smart antennas provide dynamic allocation

A single smart antenna can receive two different signals in two directions at once



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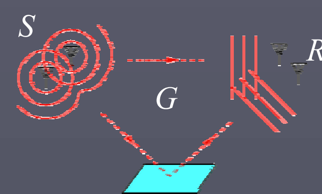
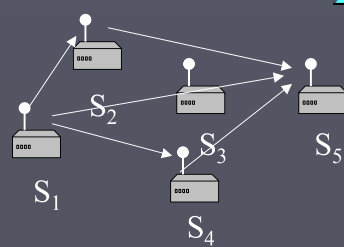
Another spatial organization approach: Spatially organized waveforms

- BLAST - diffusive medium & signal processing
  ("exploiting multipath")
- Cellular telephone systems
- MIMO systems
- Cooperative signal regeneration





Another spatial organization approach: When propagation gets worse, system capacity can go up

- Indoor environments
- Trees
- Hills
- Urban landscapes

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Does adding new radios impose other costs?

Three ways forward:

Obsolescence – better systems replace old ones

Upward compatible evolution – newer systems compensate for old ones

Upgrade existing systems – existing systems adapt to new ones

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Software Defined and Cognitive Radios

DSP Generates and Recognizes Waveforms

Adaptive Control Algorithms

MEMS/Nanotech "Software Antennas"

System adaptation and evolution costs drop to near-zero

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UWB and "VWB"

- Impulse radio uses coded sequences of extremely short high energy pulses to achieve high-rate communications
- Pulses have energy in very wide bandwidths, very low average energy
- Can coexist invisibly with many radio services
- Non-impulse-based "Very Wide" band is more costly, and certainly more legacy-compatible.

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Costs in security, robustness?

- End-to-end encryption can assure private and authenticated communications as needed
- Dynamic and adaptive reconfiguration enhances security against attack, robustness against failure
- Spatial spreading of signals (lower energy, more spatial diversity) helps dramatically

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A Society of Cognitive Radios

Viral network definition:

- each new user preserves or increases capacity and other economic value to existing users, and
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Cognitive radios that can cooperate to extract the maximum capacity from the medium, while behaving politely to radio systems with more limited capabilities

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The Viral Communications Principles Version 0.2

- Each radio brings its own orthogonal space
- Each radio brings its own computational capacity
- Cooperation allows the combined capacity of all radios to be dynamically allocated, and thus benefits all in available capacity to individuals – "Cooperation gain"
- Disperse communications load widely

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Some research problems in "society of cognitive radios"

Discovery problem – how does a new radio discover existing "Society" to join

Internetworking problem – how do two "Viral networks" decide to interconnect, and what framework is used for interconnection?

"Etiquette" problem – how does a society of cognitive radios know when and how to be polite to legacy radios

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Discovery problem

Related to the problem of bootstrapping IP connection (DHCP, …), modem training sequences…

Discovery happens in the RF –

options include beacons, …, but how can they be standardized

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Internetworking problem

Distinct from wired Internet
- Potential low cost gateways "everywhere"

Tightly coupled with problem of managing coexistence when partitioned.

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What are the technical opportunities and challenges before us?

- To achieve scalability and evolvability, centrally designed/regulated must become self-regulating
- Internetworking creates flexibility of configuration
- Develop coexistence strategies based on scalability, not fixed capacities.
- A Society of Cognitive Radios that can assist each other when appropriate and feasible
- Open architecture to reduces barriers to interconnection and upward compatible evolution
- Expect rapid, technology and demand driven evolution and obsolescence – we don't know what will be the best technologies, the best architectures, and the dominant applications

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