Constructing a "Communications Ether" that can grow and adapt

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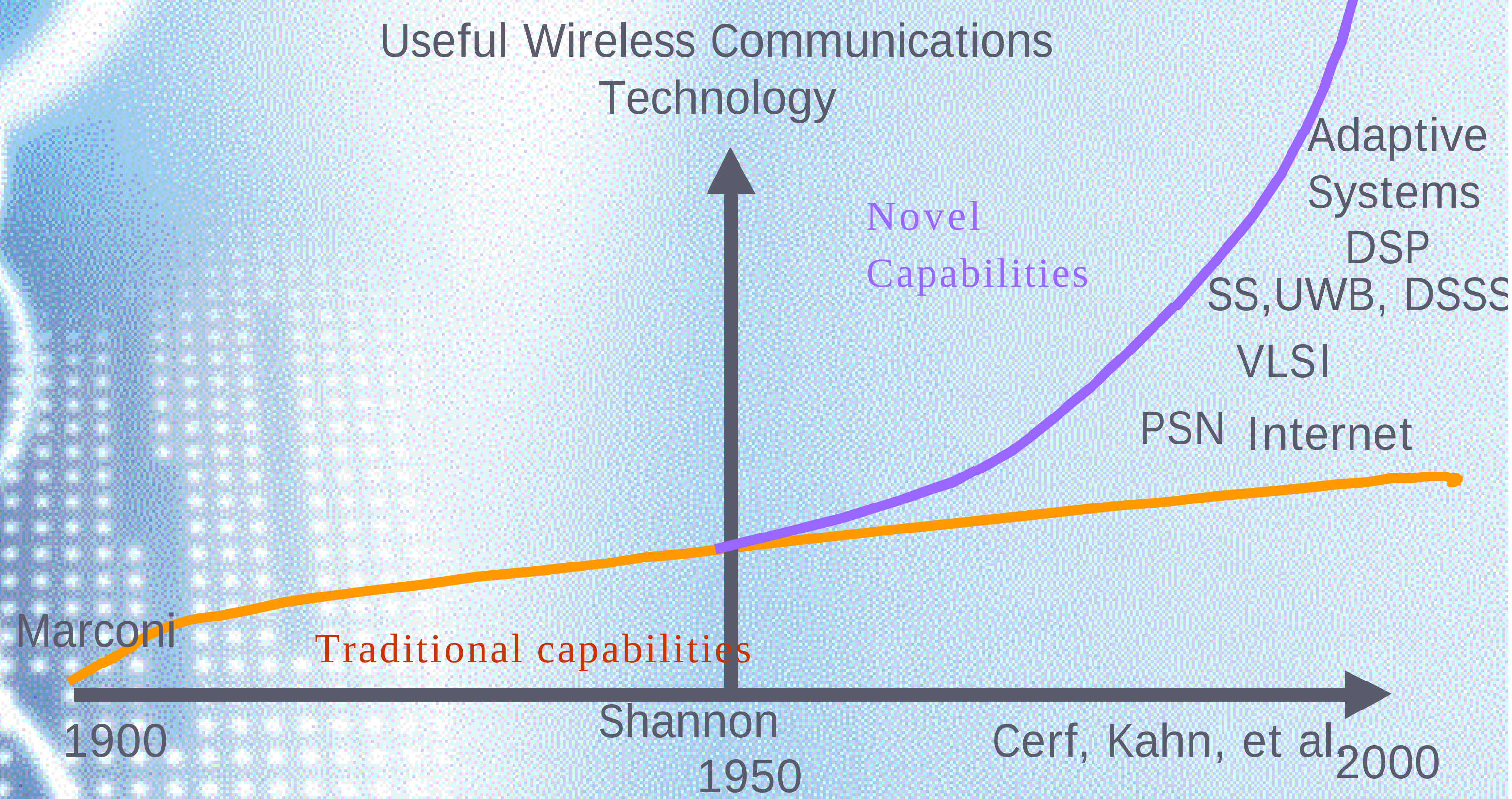
Extreme Communications

Agenda

- How can we best meet the demand for wireless communications capacity?
- Does “spectrum” have a capacity?
- “Interference” and information loss
- Making capacity scale
- **Viral network** architectures

Sustaining vs. Disruptive Technology in a Regulated Industry

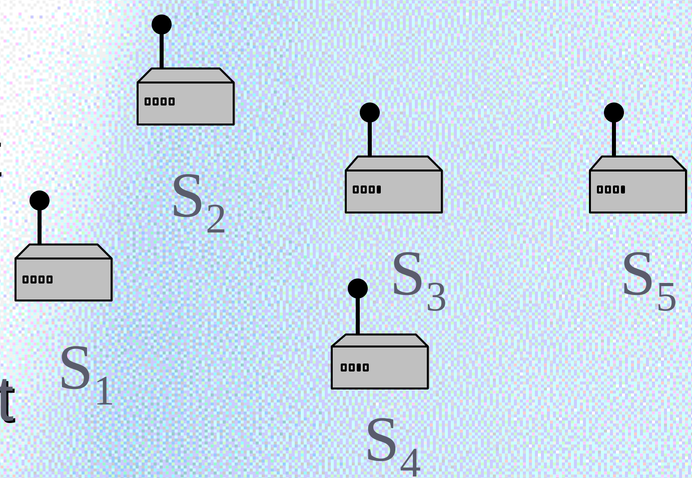


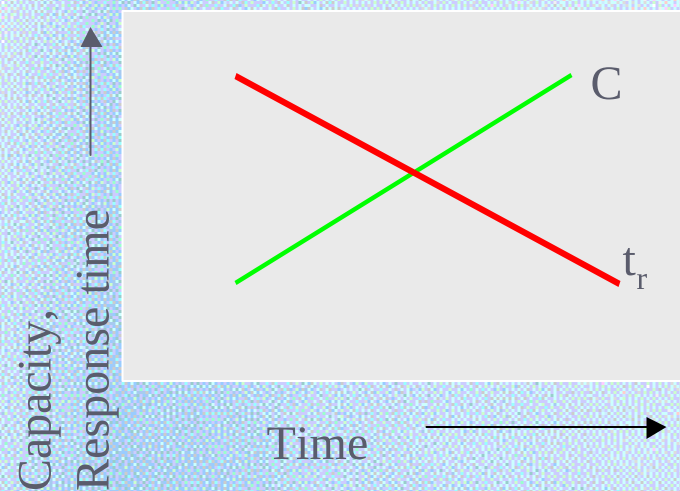
Mainframe communications vs. viral communications

- 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)

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"

Themes of Viral Communications Architectures

- Dense scalability
- Adaptation
- Cooperation
- Multiuser information theory
- RF photon/wave dynamics

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.

Shannon's answer: bits and "channels"

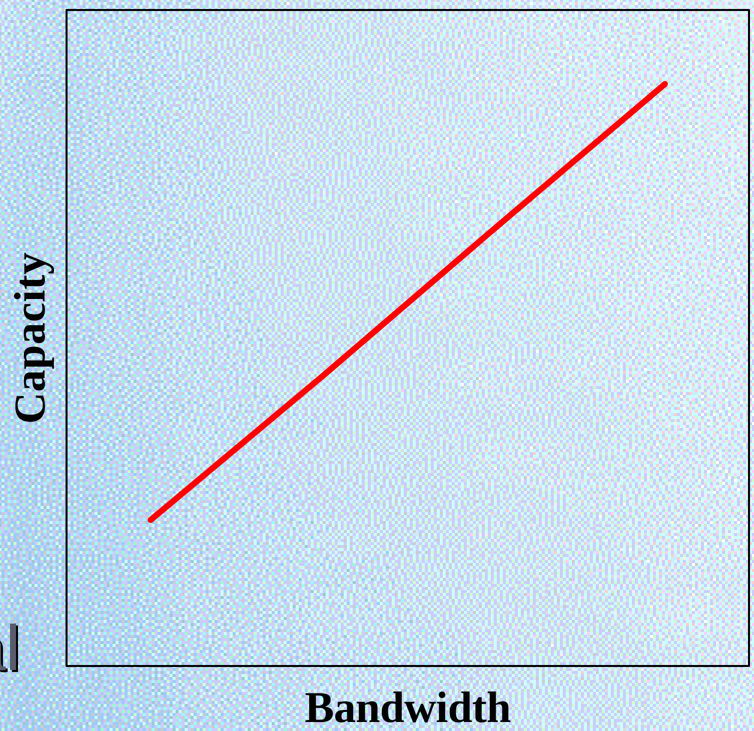
$$C = W\log(1+\frac{P}{N_0 W}),\ \text{due to Claude Shannon}$$

C = capacity, bits/sec.

W = bandwidth, Hz.

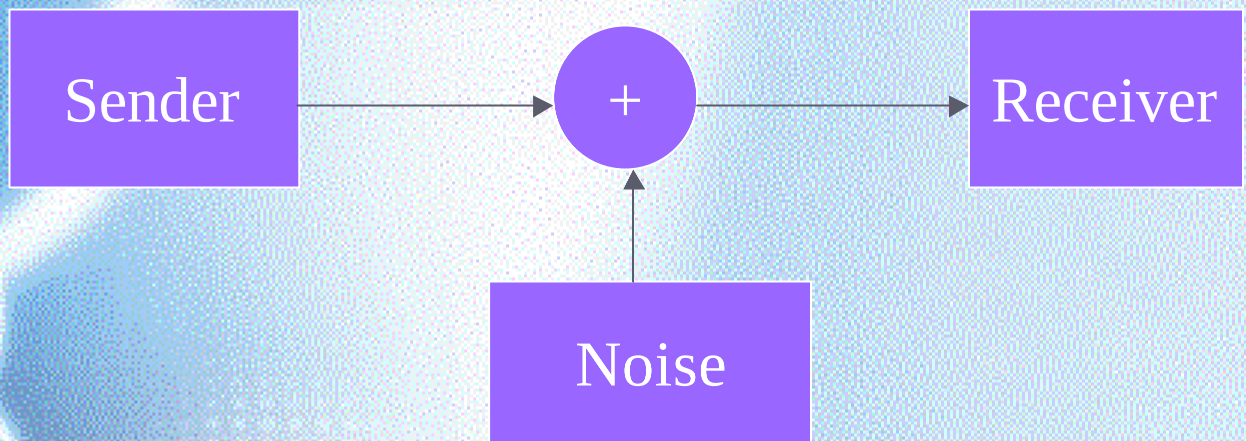
P = power, watts

N_0 = noise power, watts/Hz.



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

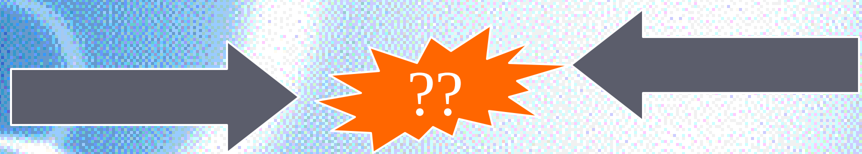
We don't know the *full* answer.



"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



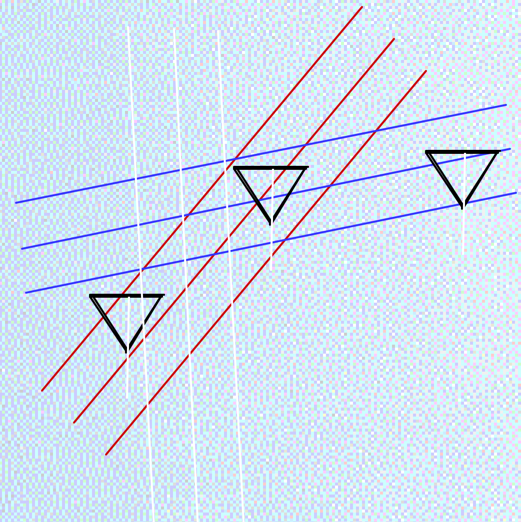
Radio "interference" = *superposition*

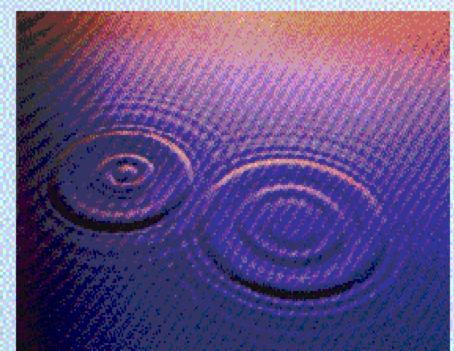
Regulatory interference = damage

No information is *actually* lost

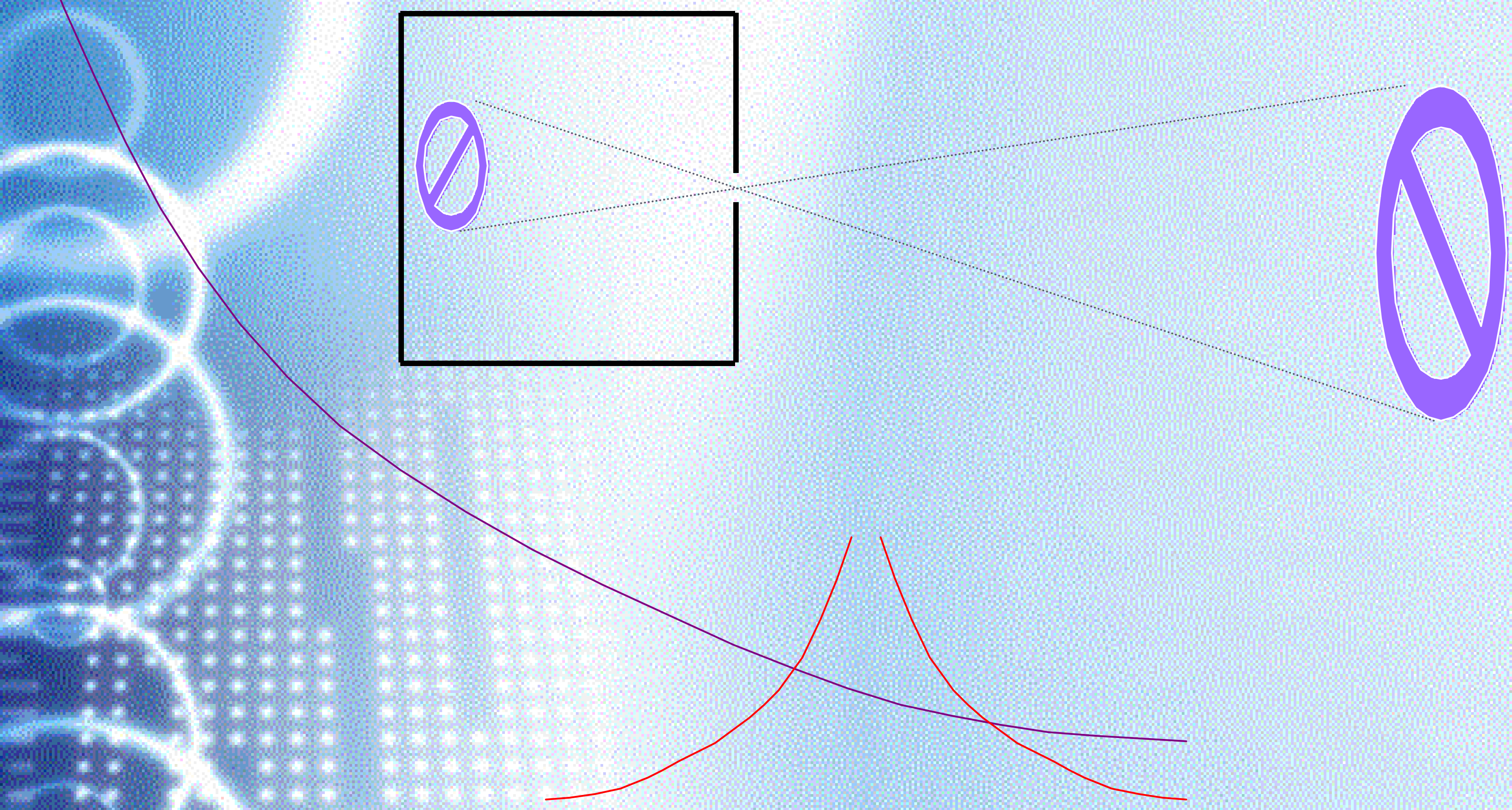
Receivers may be confused

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





"There is no cat-5"
RF is not a virtual wire



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?

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: if there are more samples than sources, yes.

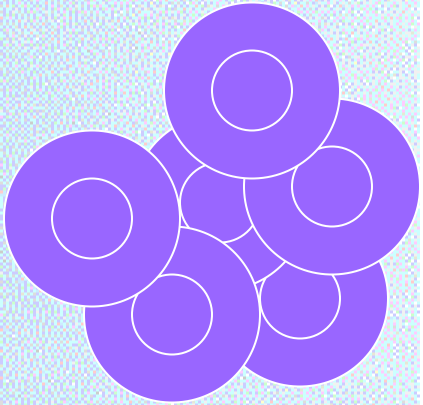
When a new radio is added to the system, does it impose net costs on others, even though there is no displacement of capacity?

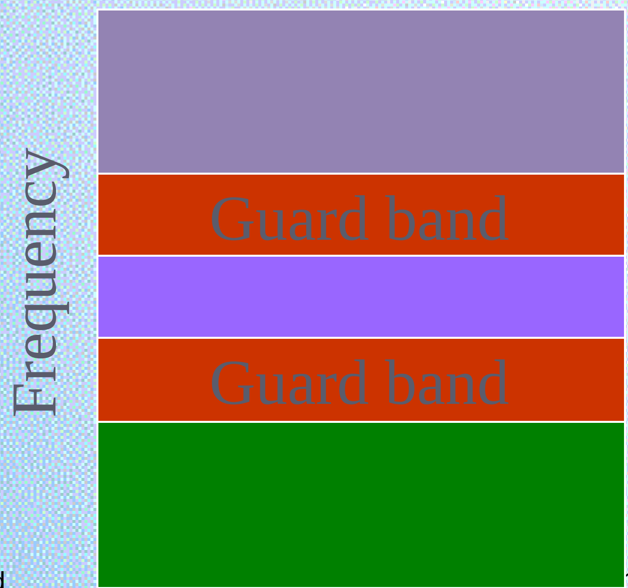
- Achievable latency?
- "Computational costs"
  - Per-node cost of encoding/decoding
- "Evolutionary costs"
  - Cost of sharing with legacy designs
  - Growth rate

Static partitioning wasteful

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

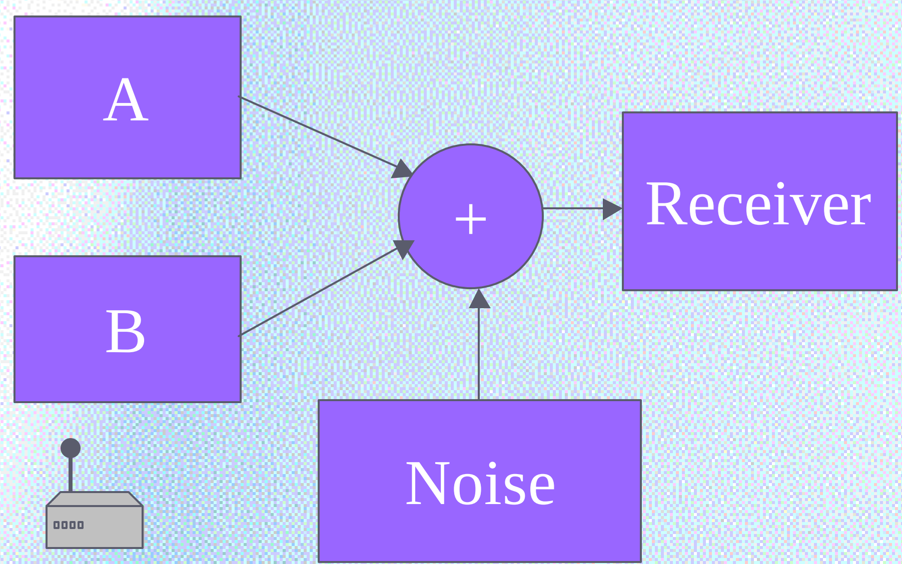
Space and Frequency Division

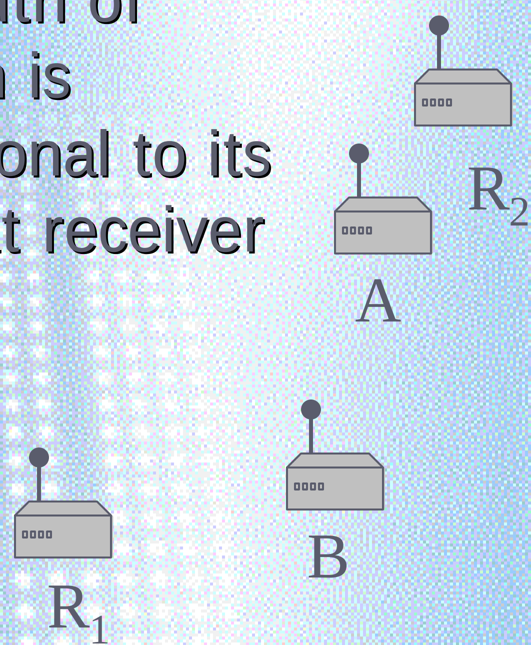


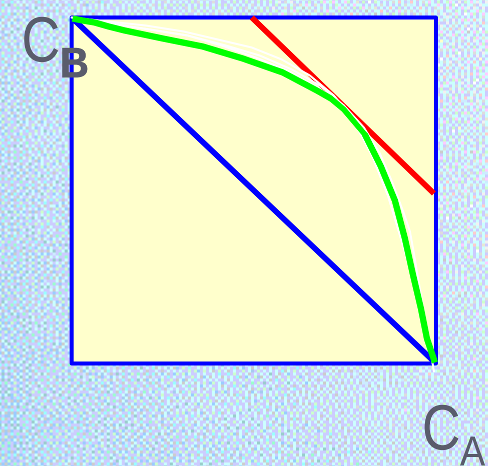


Example: Frequency partitioning

- Frequency partitioning is optimal only when the bandwidth of partition is proportional to its power at receiver

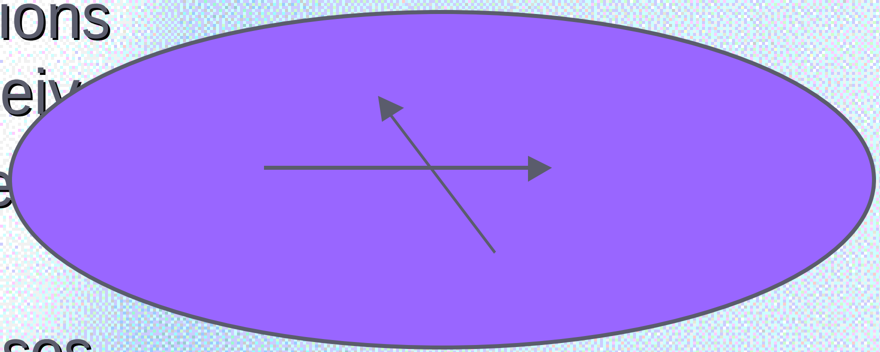






Transport Capacity: One important measure of radio network utility

- Network of N stations (transmit & receiv
- Scattered in a fixe space
- Each station chooses randomly to send messages to other stations
- What is achievable total *transport capacity*, C_T, in bit-meters/second?



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

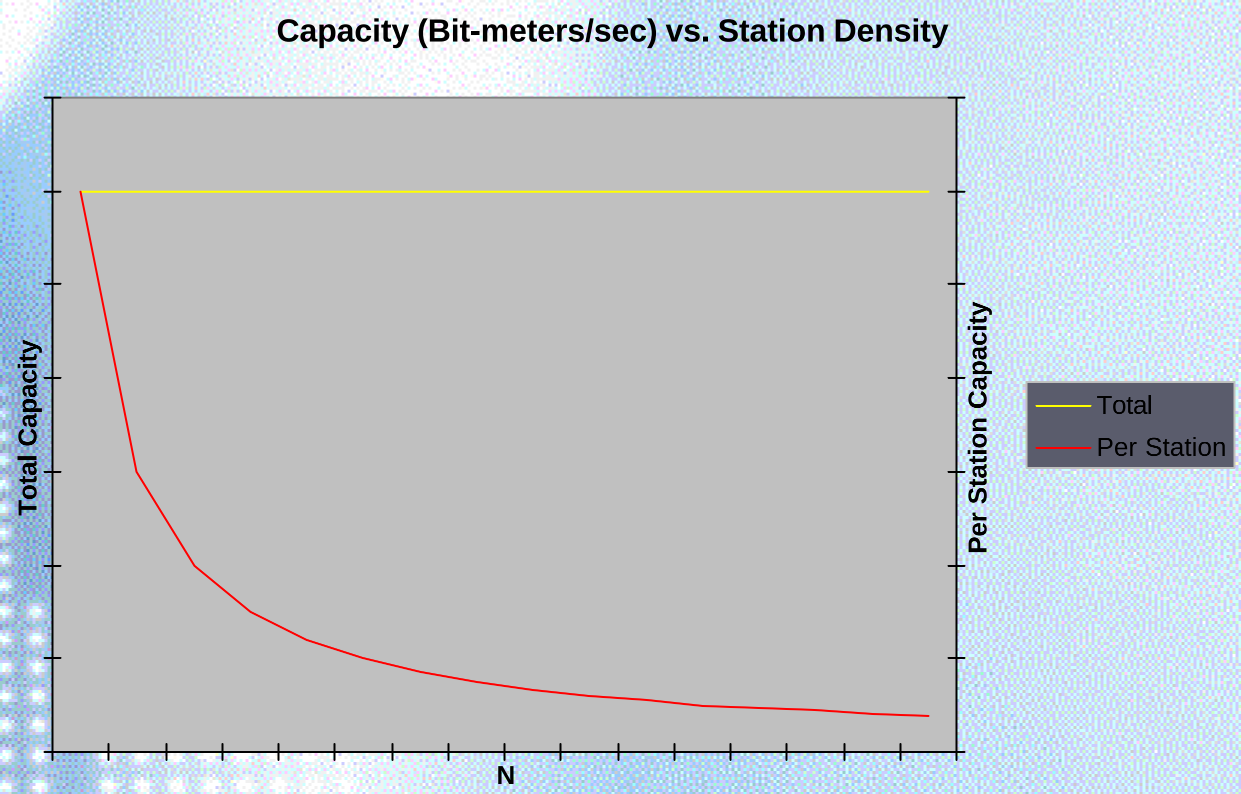
$$d_{s,r} = \text{distance from } s \text{ to } r$$

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

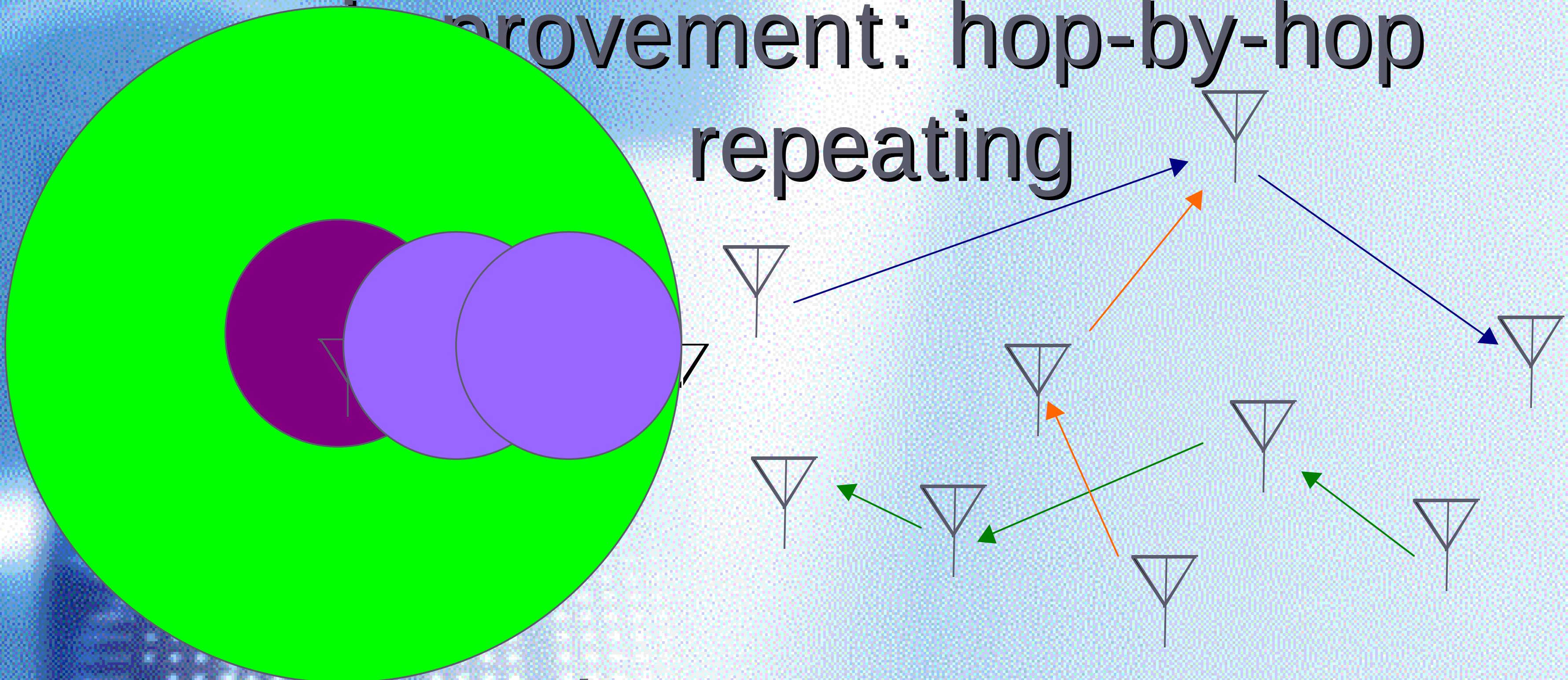
Additional measures

- Flexibility of load handling (given a priori probability distribution of traffic arrival, what is the probability of successful delivery)
- Probability of meeting latency constraints
- Energy required in xmit & receive
- Adaptability to propagation environment
- Cost for adversary to disrupt selected subset of communications.

“Spectrum capacity” model under static partitioning



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

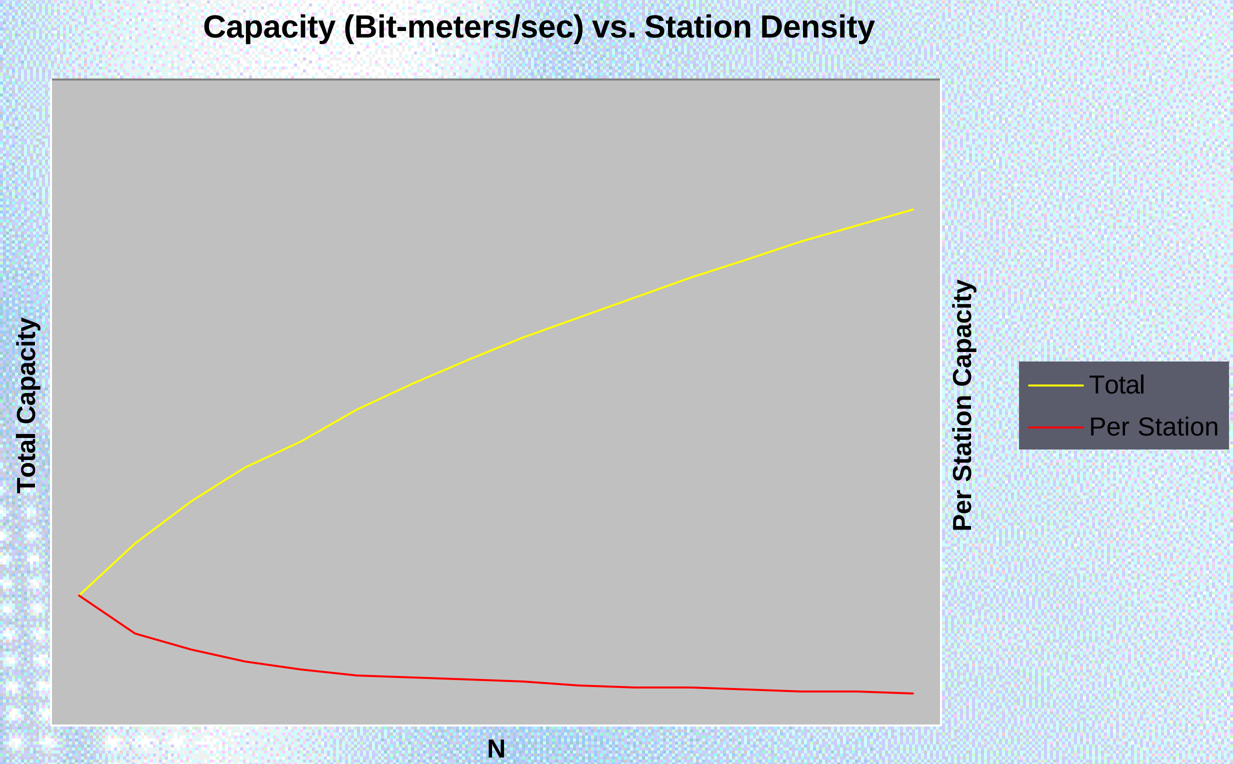


Energy/bit reduced by 1/hops.

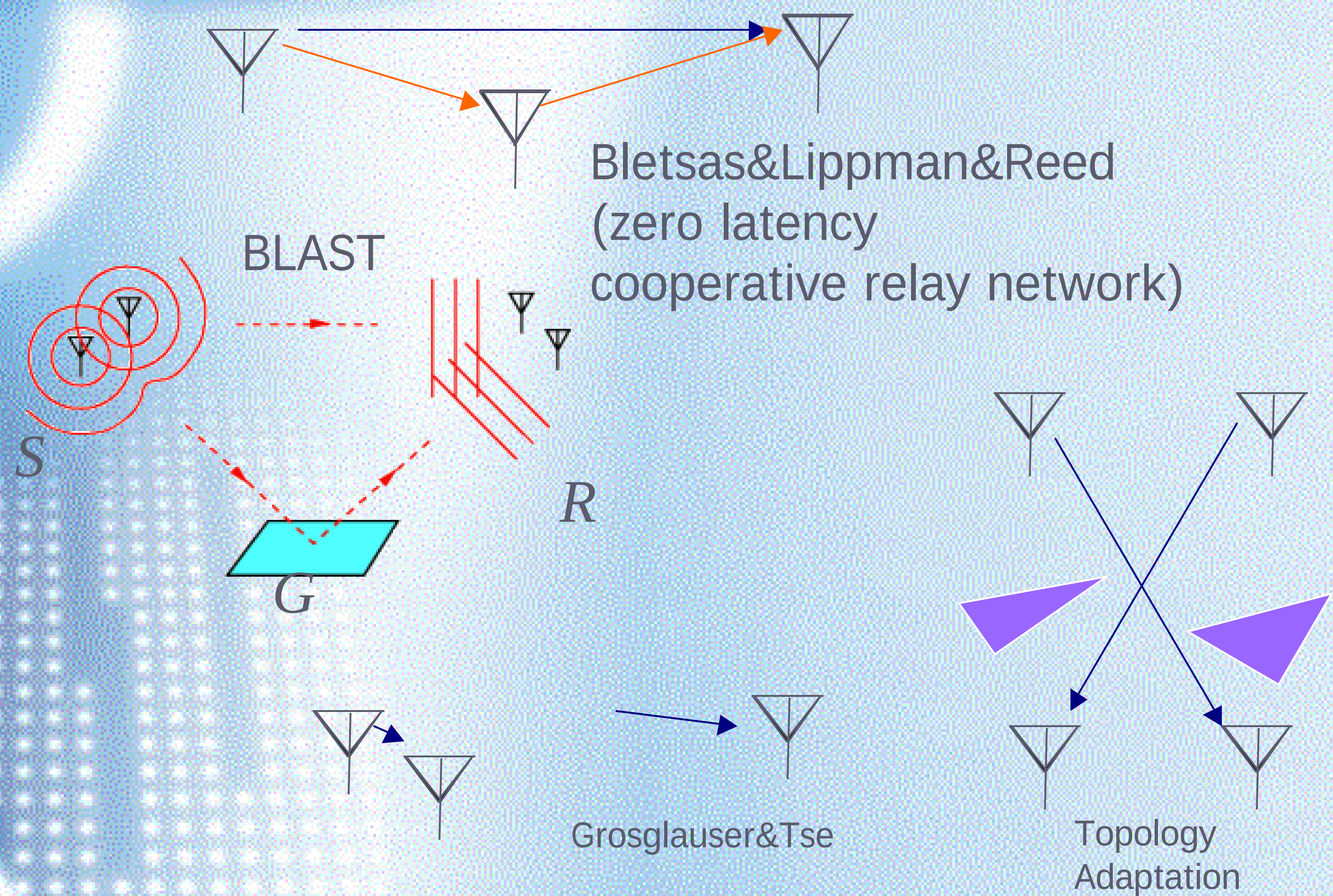
Many paths can operate concurrently.

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

Repeater Network Capacity



Channel physics, memory, DSP



Need 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

Software Defined and Cognitive Radios

- DSP Generates and Recognizes Waveforms
- Adaptive Control Algorithms
- "Software Antennas" (configurable structures)

- System adaptation and evolution costs drop to near-zero

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

A Society of Cognitive Radios

- 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
- Cognitive radios that can cooperate to optimize value under actual demand, while behaving politely to radio systems with more limited capabilities

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
- Cooperate with legacy systems

Structuring a "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?
- Resource Allocation problem – given dynamic demand, allocating capacity on the fly while minimizing energy costs
- "Etiquette" problem – how does a society of cognitive radios know when and how to be polite to *legacy* radio systems

Discovery problem

- Discovering as many options as possible for interoperation
- Introduction-based or encounter-based

Internetworking problem

- Distinct from wired Internet
  - Potential low cost gateways "everywhere"
- Tightly coupled with problem of managing coexistence when partitioned.

Resource allocation problem

- Analogous to “congestion control” in wired networks, but different
- Manage dynamic “channelization” and distributed buffer load

Etiquette Problem

Location, lookup, or signal pattern recognition based

What are the technical opportunities and challenges before us?

- To achieve scalability and evolvability, centrally designed/regulated wired must become self-regulating, wireless and viral
- Radio *internetworking* creates flexibility of configuration
- Develop radio system coexistence strategies based on scalability and interoperation, not fixed allocation.
- A Society of Cognitive Radios that can assist each other when appropriate and feasible
- Architect for 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