Bits aren't Bites! Balkanizing spectrum creates scarcity

David P. Reed
Visiting Scientist, MIT Media Lab
dpreed@reed.com
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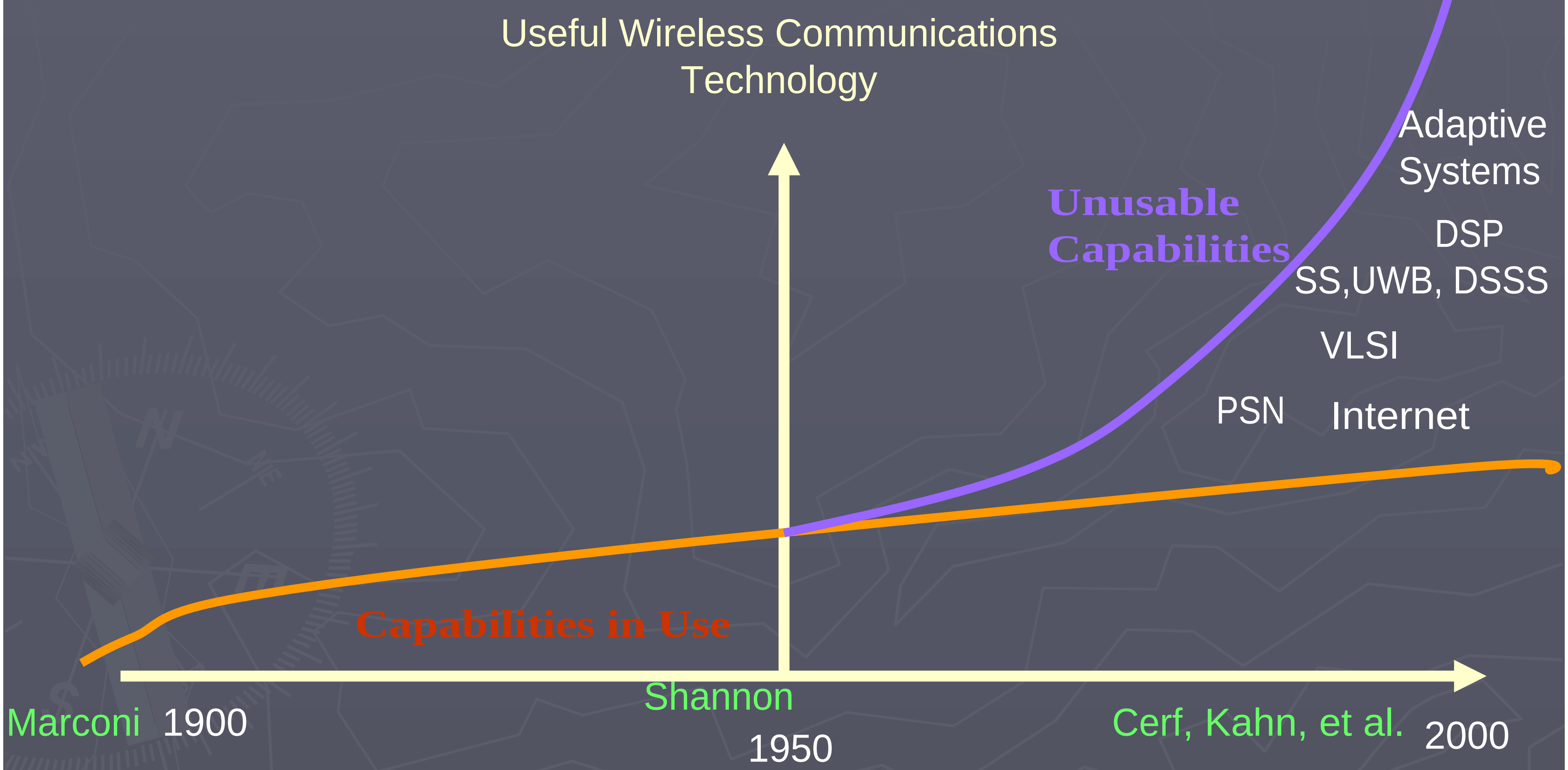
Agenda

- Scalability matters most
- Does spectrum have a capacity?
  - "Spectrum, a non-depleting but limited resource" (Michael Gallagher, DoC)
- Interference and information loss
- Capacity, architecture, and scaling laws
- Economics and architecture

Sustaining vs. Disruptive Technology in a Regulated Industry

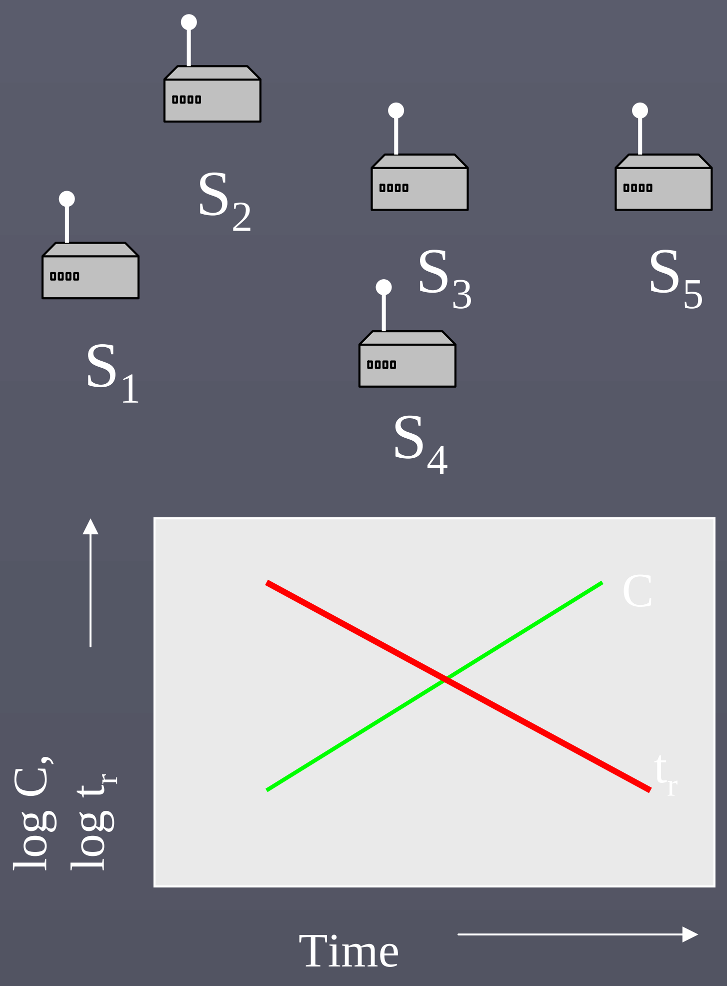


Mainframe communications vs. decentralized communications

- Mainframe to PC evolution
  - Eliminate barriers to innovative uses
  - Enable new technologies
- Mainframe communications to decentralized communications
  - Eliminate barriers to innovative uses (802.11)
  - Enable new capabilities (pervasive C&C)

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



Does spectrum have a capacity?

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

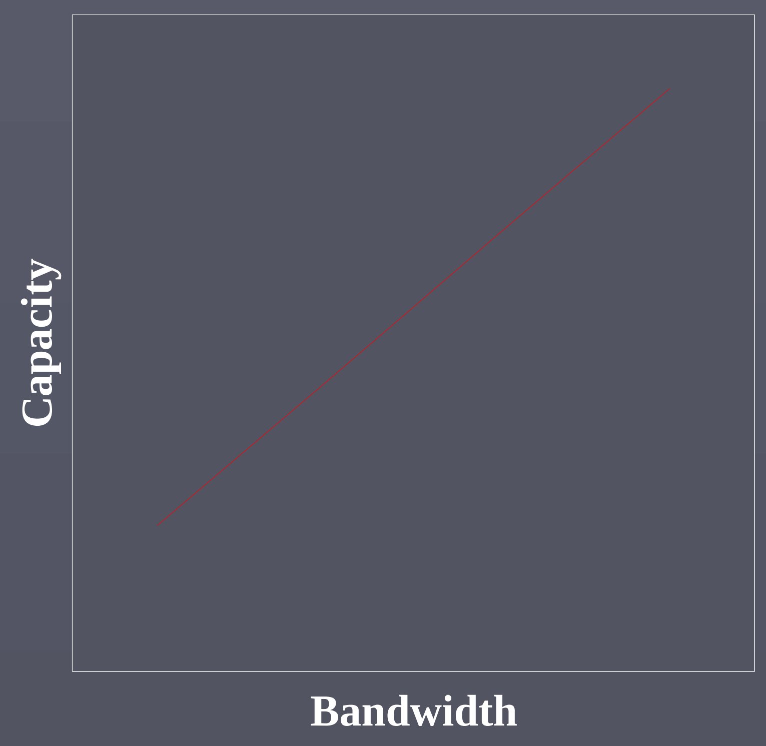
C = capacity, bits/sec.

W = bandwidth, Hz.

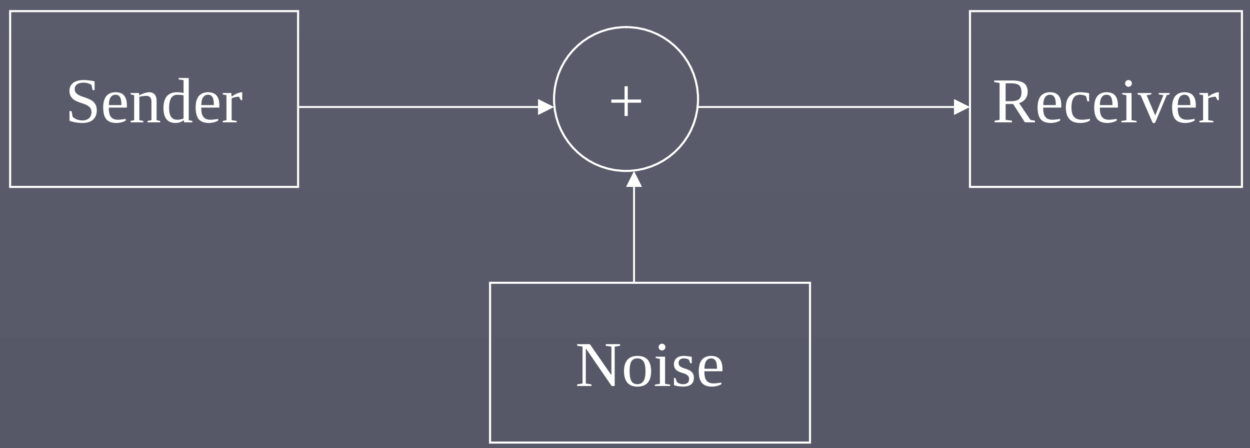
P = power, watts

N_0 = noise power, watts.

Channel capacity is roughly proportional to bandwidth.



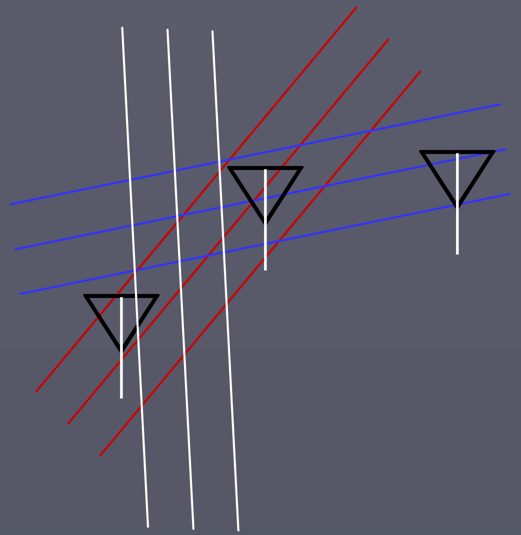
We don't know the *full* answer.



"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]

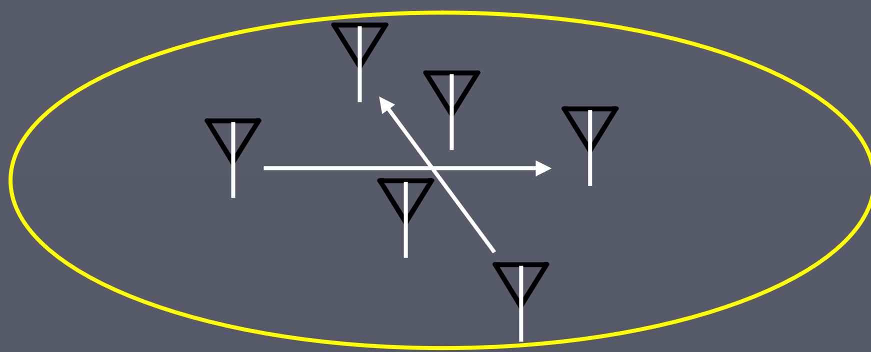
Interference and information loss



- 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

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 total transport capacity, C_T, in bit-meters/second?

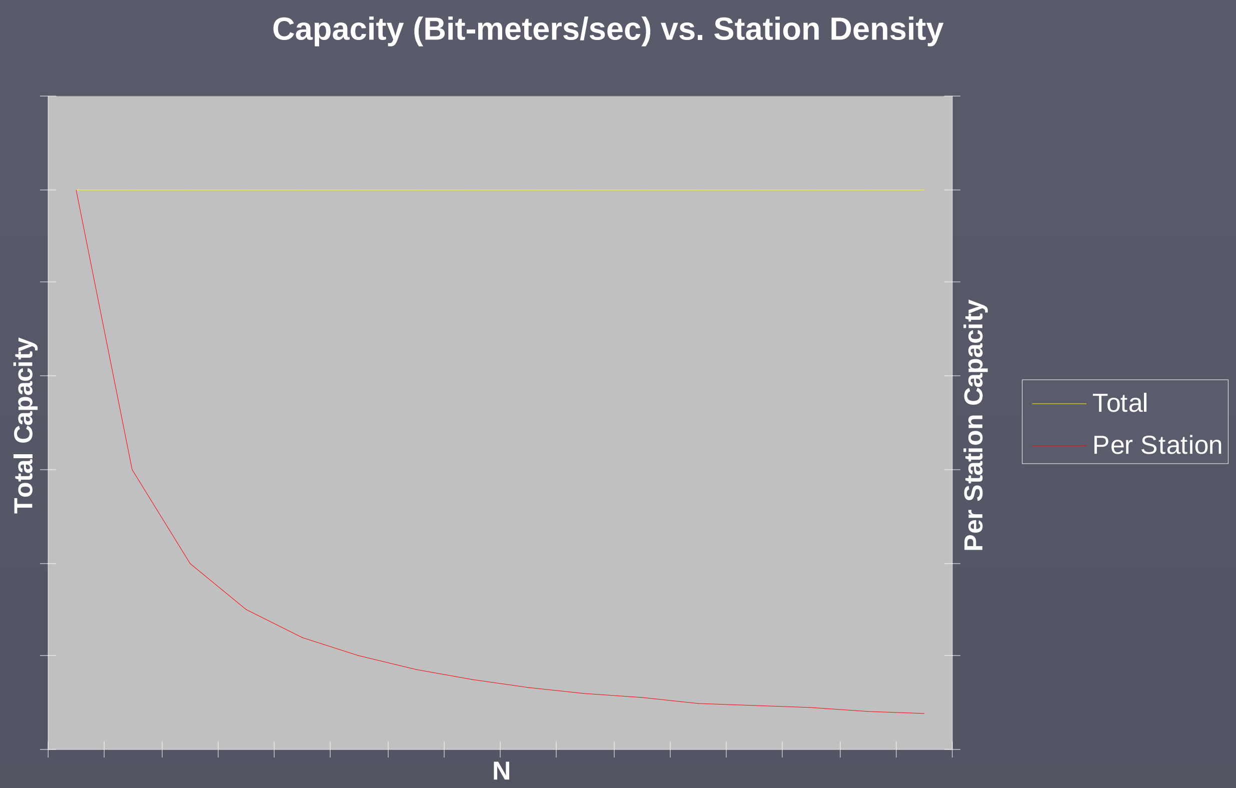


$b_{s,r}$ = bits from s to r

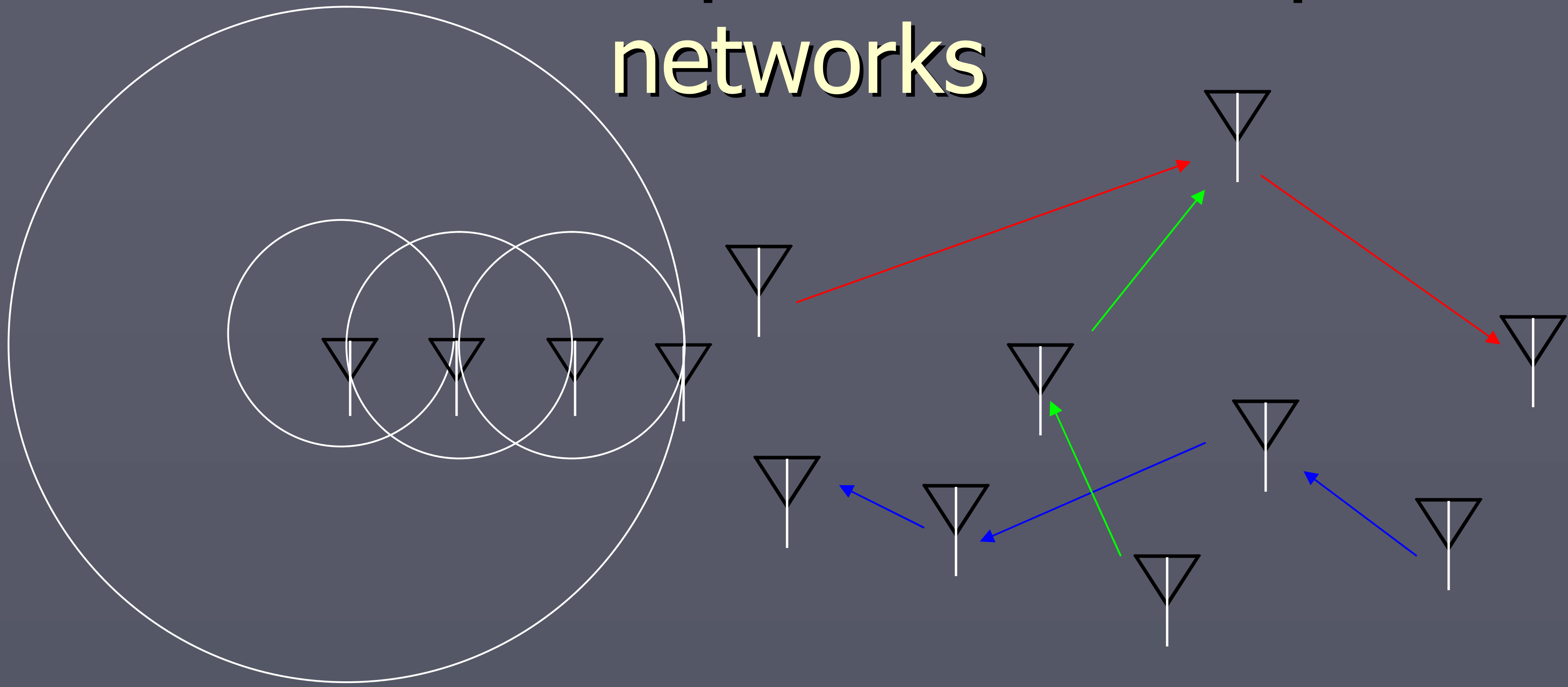
$d_{s,r}$ = distance from s to r

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

Traditional, intuitive "Spectrum capacity" model



Architectural improvement: repeater networks

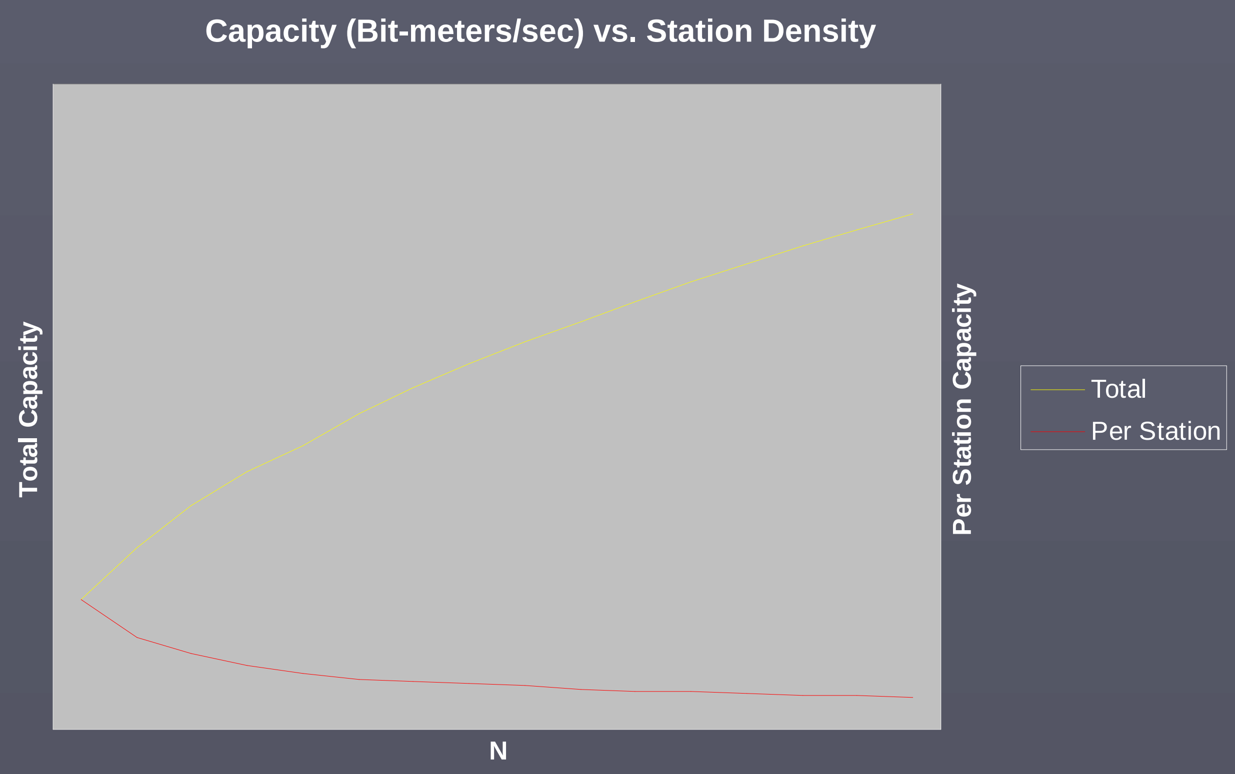


Energy/bit reduced by 1/hops.

Many paths can operate concurrently.

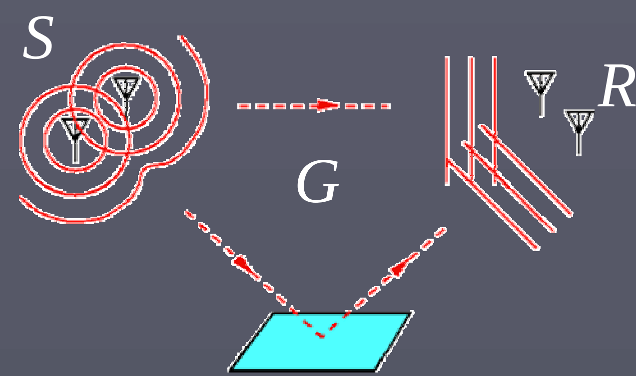
What is repeater network's capacity?

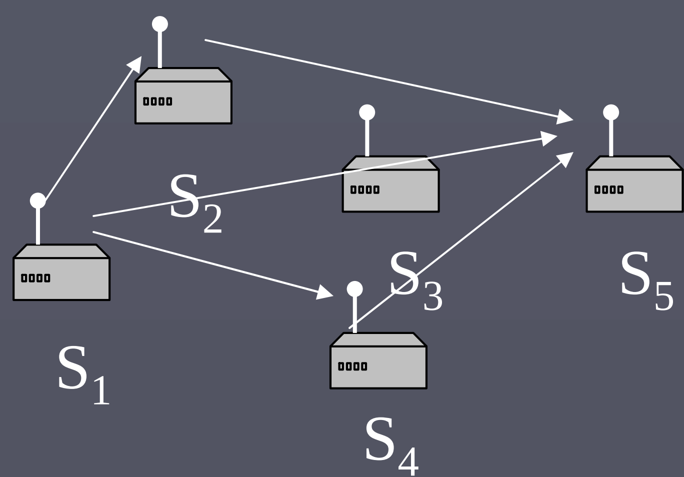
Repeater Network Capacity



Architectural improvement: Spatially organized waveforms

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

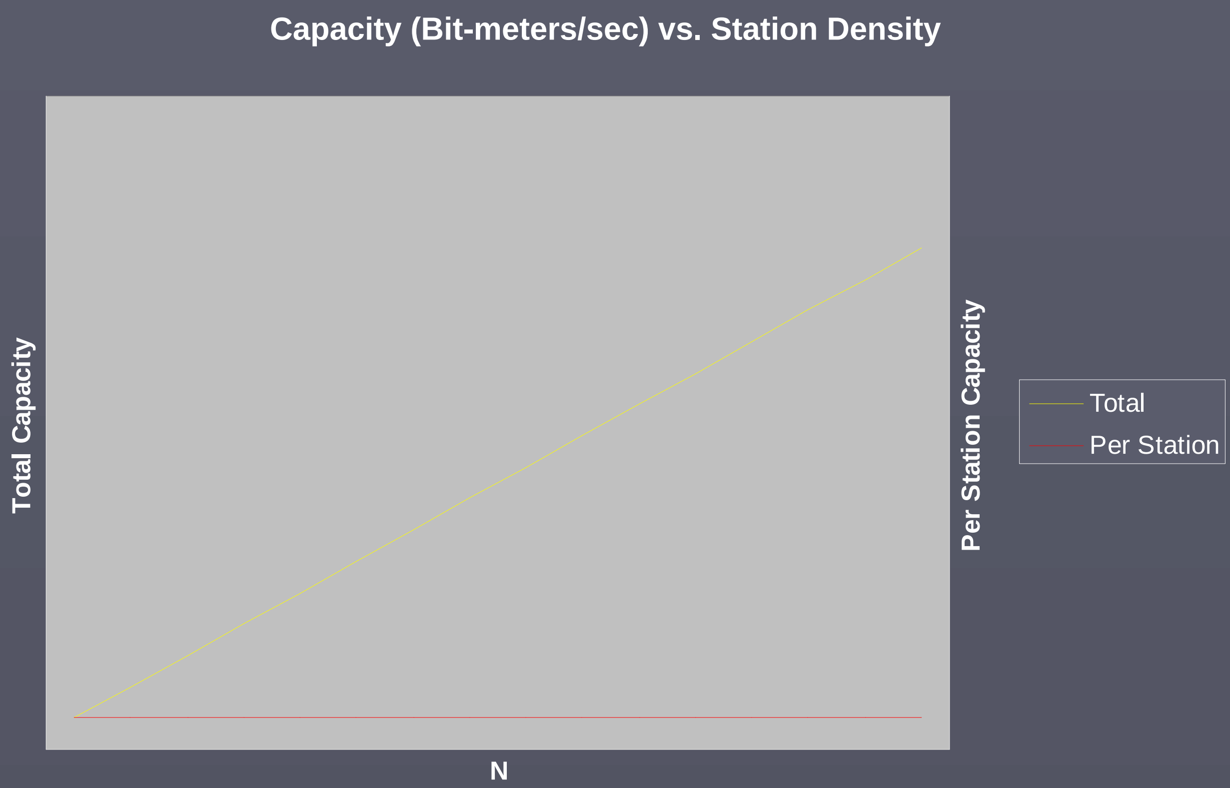




Other counterintuitive results from multiuser information theory, network architectures, and physics

- Multipath increases capacity
- Repeating increases capacity
- Mobility increases capacity
- Repeating reduces energy (safety)
- Distributed computation increases battery life
- Channel sharing decreases latency and jitter

Network Capacity under Cooperation Likely to Scale w/Demand



Many economic utilities scale beneficially in network structures

Besides total system capacity,

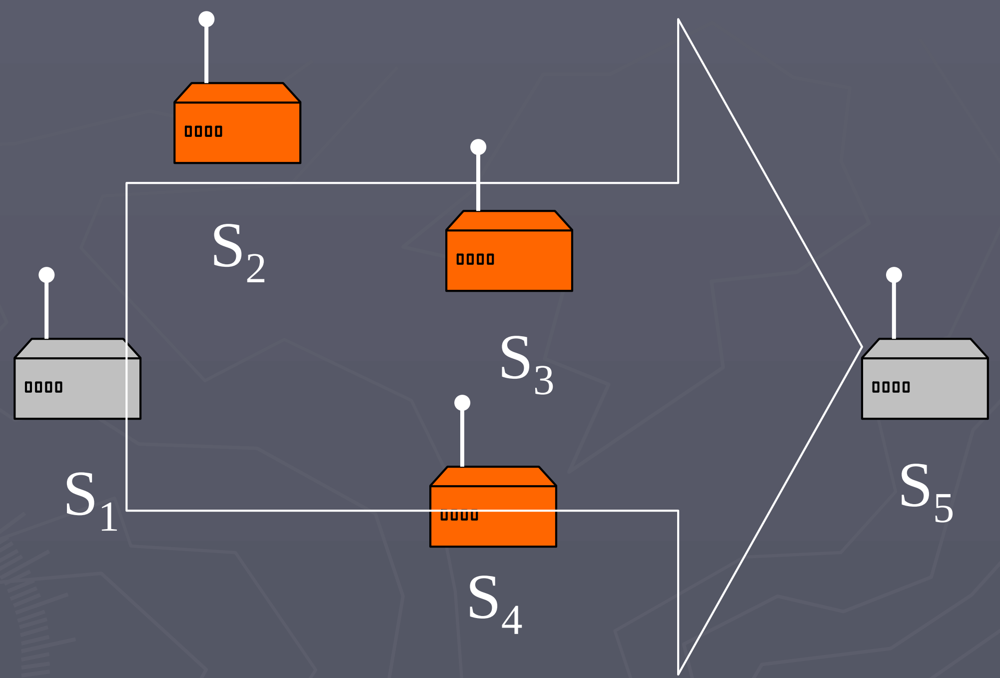
Value in terms of "optionality" (Real Options) grows:

- Flexibility in allocating capacity to fluctuating demands (e.g. burst capacity proportional to total systems bandwidth and dispersion)
- Flexibility in "random addressability" (e.g. Metcalfe's Law)
- Flexibility in group forming (e.g. Reed's Law)
- Dynamic robustness against attacks
- Dynamic dispersion of signal for physical privacy

“Cooperation gain” vs. “Tragedy of the Commons”

- Markets in property rights are “solve” the “tragedy of the commons” by allocating a valuable, scarce commodity to its most valuable uses
- But property rights and tragedy of commons assume the valuable commodity is conserved
- Yet capacity and other economic utility of spectrum can increase with cooperation, and if proportional to N, each new user is self supporting or better.

Cooperation vs. balkanization

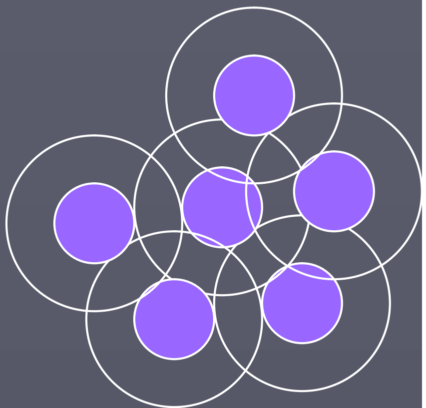


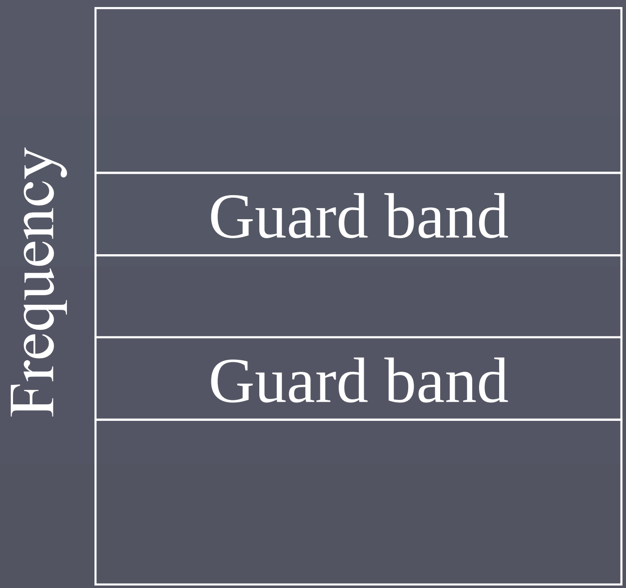
Cooperation: Potential C_T proportional to N?
Balkanization: C_T constant or worse.

Problems with static partitioning –"transaction cost economics"

- "Guard bands" costly – partitioning in space, frequency, or time wastes capacity
- Partitioning impacts flexibility:
  - Burst allocation capped
  - Random addressability & group-forming value severely reduced
- Robustness reduced, security reduced.

Space and Frequency Division





So what do we do?

- Centrally designed/regulated must become self-regulating
- Internetworking (no balkanization – create interoperability
- End-to-end argument (hourglass model)
- Society of Cognitive Radios
- Open architecture
- Plan for evolution and obsolescence (no guarantees to investors)

The end-to-end argument

- Implement functions at the end points or edges, if at all possible
- Add function in the network only if it's the only possible way to do it.

- (corollary: "Stupid Network")

But why? Uncertainty about what's possible and what's useful maximizes option value.

The hourglass model

- Create maximum flexibility
- Preserve independence of use from implementation
- Retain scalability