How wireless networks scale: the illusion of spectrum scarcity

David P. Reed
[http://www.reed.com/dpr.html]

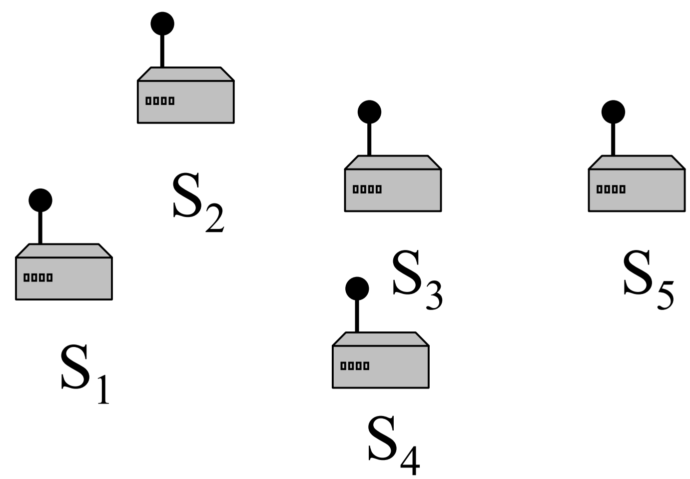
Presented at International Symposium on Advanced Radio Technology
Boulder, CO
March 4, 2002

Agenda

- Scalability matters
- Does spectrum have a capacity?
  - *Spectrum, a non-depleting but limited resource*
- Interference and information
- Capacity, architecture, and scaling laws
- How do networks create value?
- Property vs. physics and architecture

Scalability matters

- Pervasive computing must be wireless
- Mobility leads to demand for connectivity that changes constantly at all time scales
- Density of stations will increase over time



70 years of FCC and regulation

MV Mesaba to Titanic: "Ice report…much heavy pack ice and great number of large icebergs also field ice."

Titanic: "Keep out, I'm working Cape Race ! "

- FCC created when tank circuits were hard to build
- 20 years *before* Shannon created Information Theory, before RADAR, digital electronics, and distributed computing
- We have had 50 years to begin applying these to radio networking
- But radio policy based in 1932 technology, practice

Does spectrum have a capacity?

$$C = W \log(1 + \frac{P}{N_0 W})$$

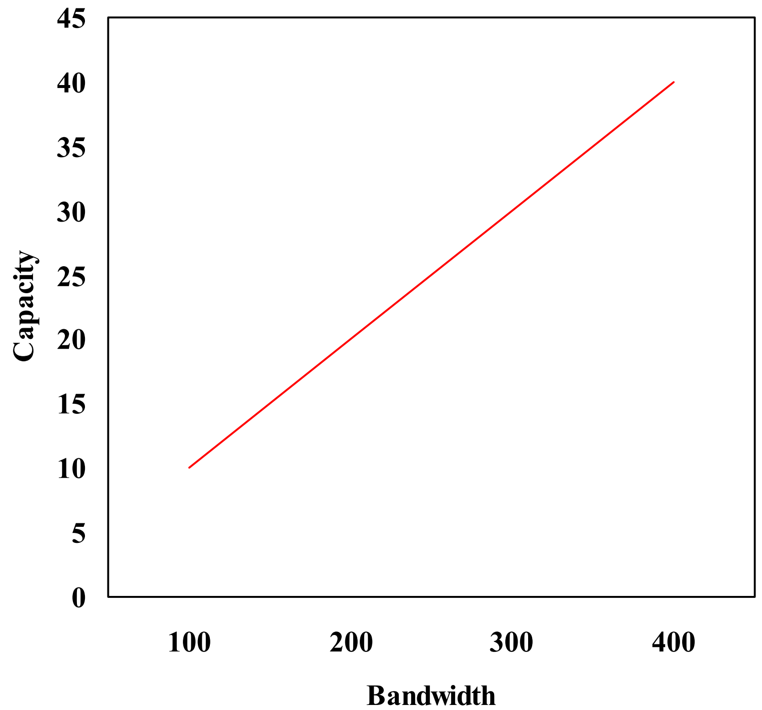
C = capacity, bits/sec.

W = bandwidth, Hz.

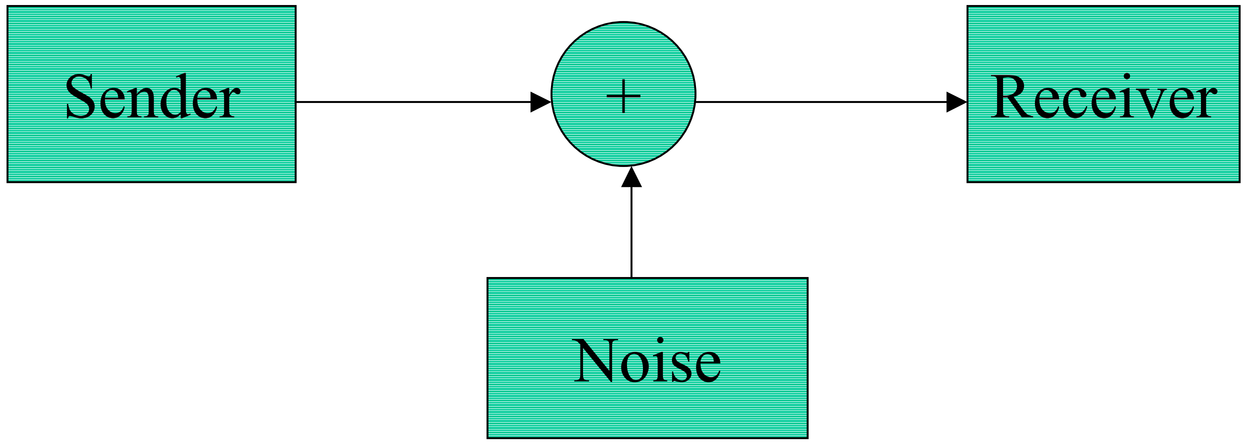
P = power, watts

N_0 = noise power, watts.

Channel capacity is roughly proportional to bandwidth.



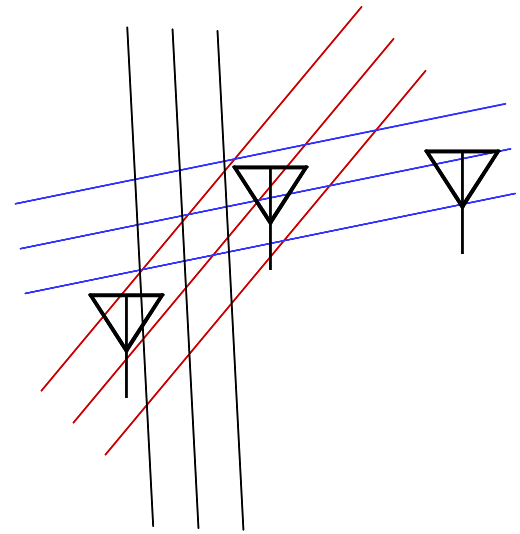
We don't know the answer.



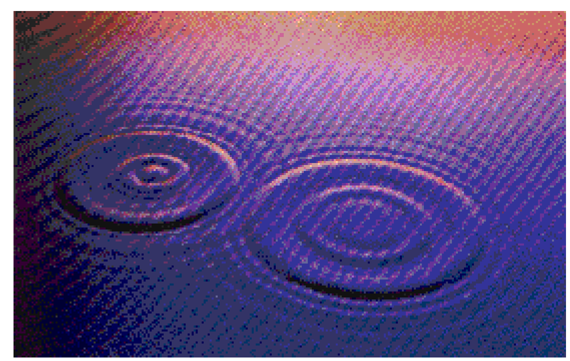
"Standard" channel capacity is for one sender, one receiver – says nothing about multiple senders.

"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

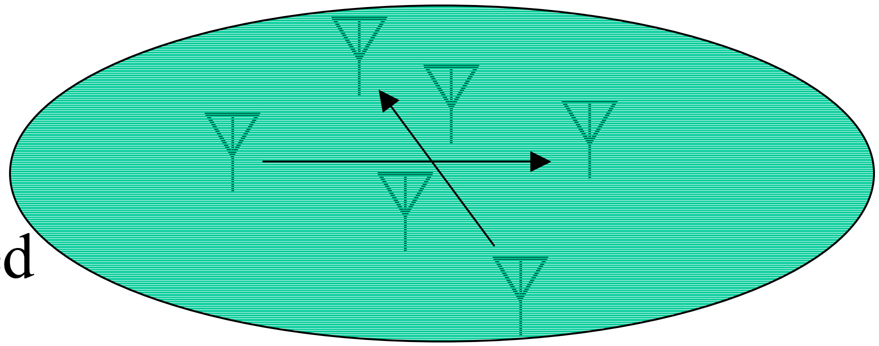


- Regulatory interference = damage
- Radio interference = *superposition*
- No information is lost
- Receivers may be confused
- Information loss is a design and architectural issue, not a physical inevitability



Capacity, Architecture, and Scaling Laws

- Network of N stations (transmit & receive)
- Scattered randomly in a fixed space
- Each station chooses randomly to send a message to some other station
- What is total capacity in bit-meters/second?



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

Capacity of a radio network architecture

N – number of stations

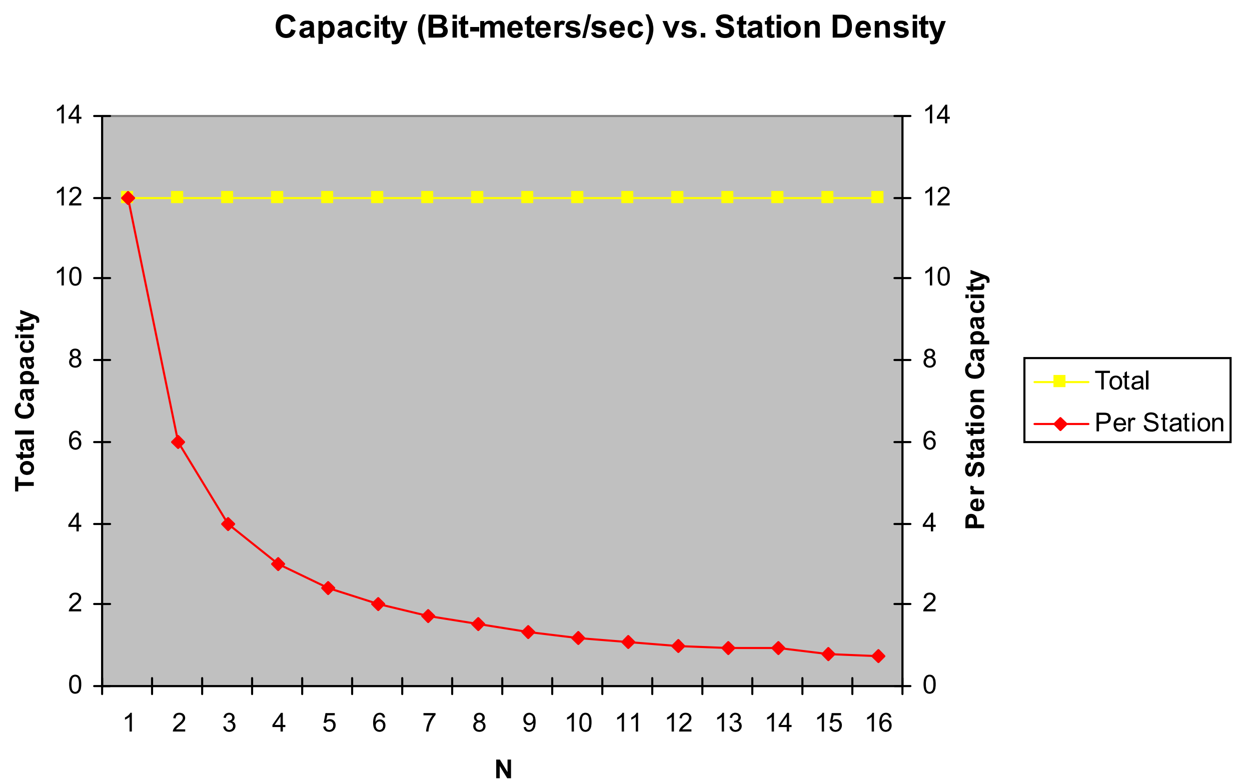
B – bandwidth

$C_T(N, B)$

increases linearly in B

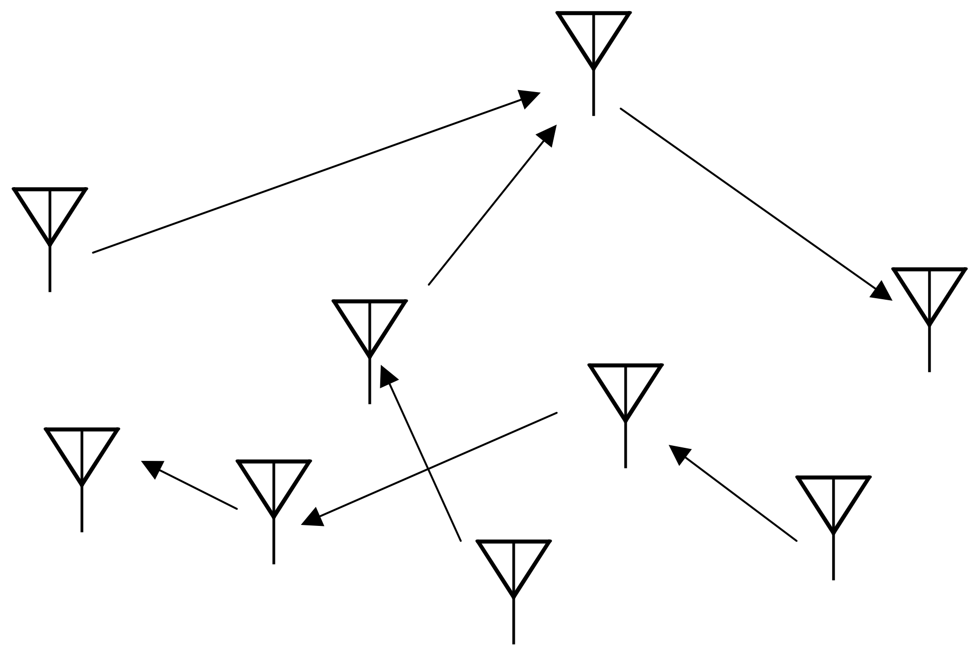
but what function of N?

Traditional, intuitive "Spectrum capacity" model



Repeater networks

If nodes repeat each other's traffic then transmitted power can be lower, and many stations can be carrying traffic concurrently – what is capacity?



C_T(N, B) depends on technology and architecture

Tim Shepard and Gupta&Kumar each demonstrate that C_T, measured in bit-meters/sec grows with N if you allow stations to cooperate by routing each others' traffic

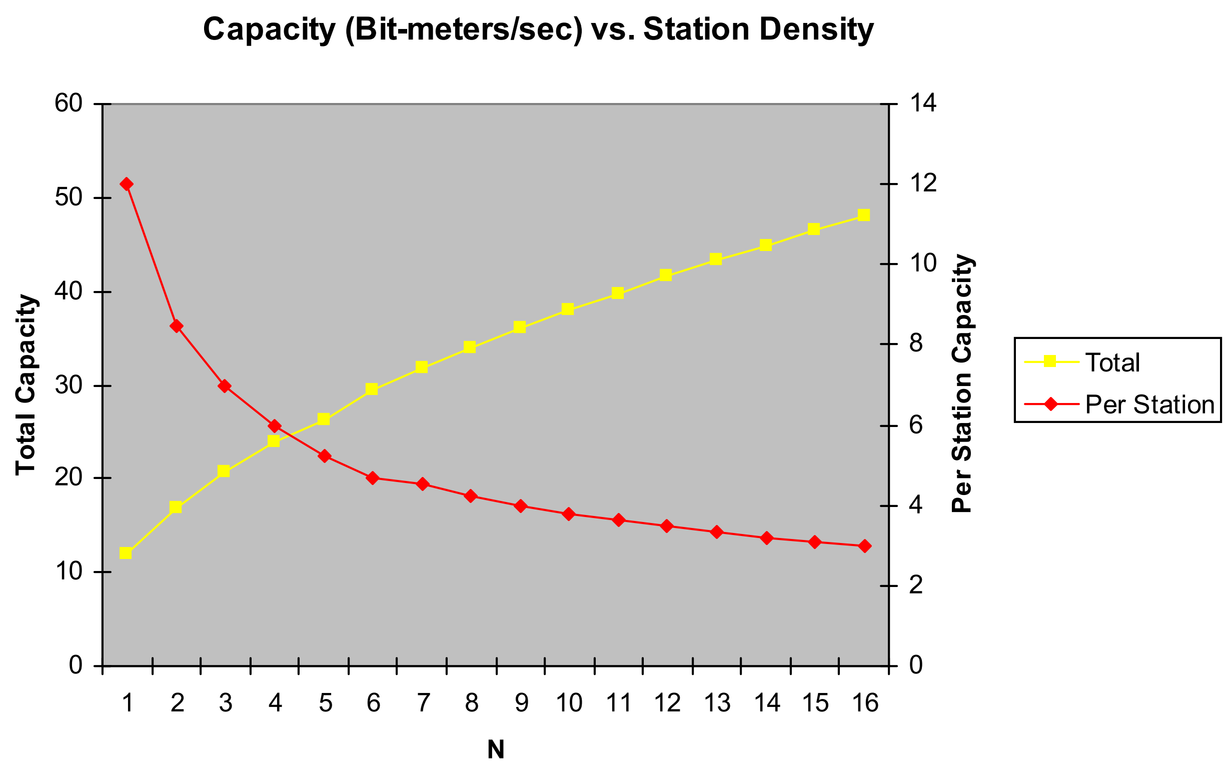
$$C_T(N,B) \sim \sqrt{N} \text{ (planar)}$$

$$C_T(N,B) \sim N^{2/3} \text{ (volume)}$$

But that is a *lower bound* – because other potential approaches may do better.

* *Total* system radiated power also declines as N increases: incentive to cooperate, safety benefits

Repeater Network Capacity



Better architectures

Cellular, with wired backbone network:

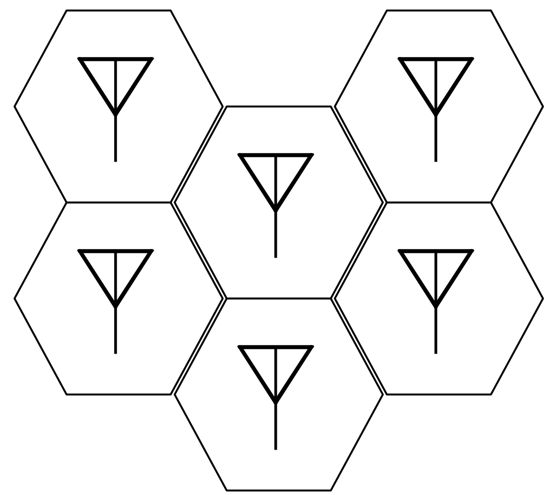
C_T grows linearly with N

Space-time coding, joint detection

C_T can grow linearly with N

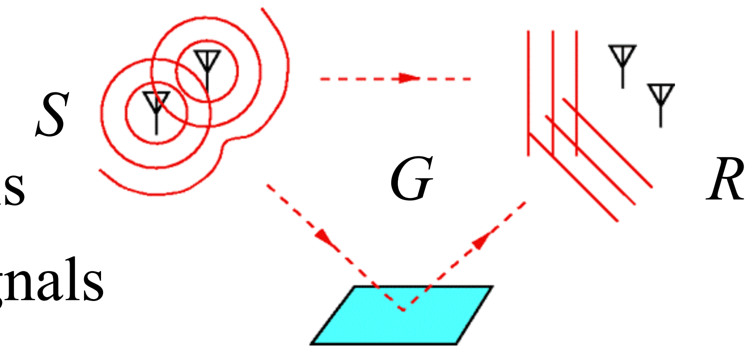
Cellular with wired backbone

Add cells to maintain constant number of stations per backbone access point



Space-time coding

BLAST (Foschini & Gans, AT&T Labs) – diffusive medium & signal processing



$R = [R_1, R_2, ...]$ received signals

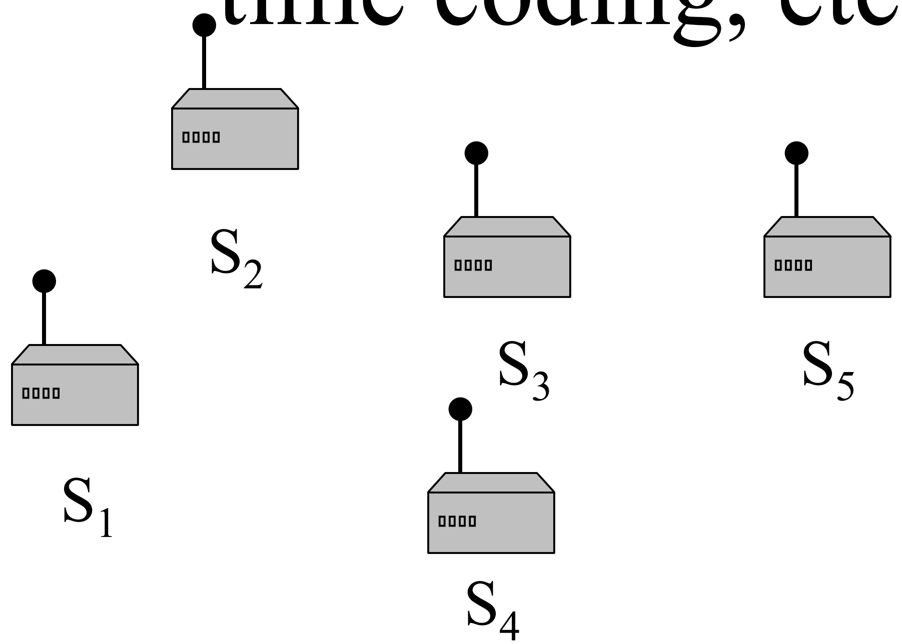
$S = [S_1, S_2, ...]$ transmitted signals

$G =$ impulse response matrix

$R = S \times G$

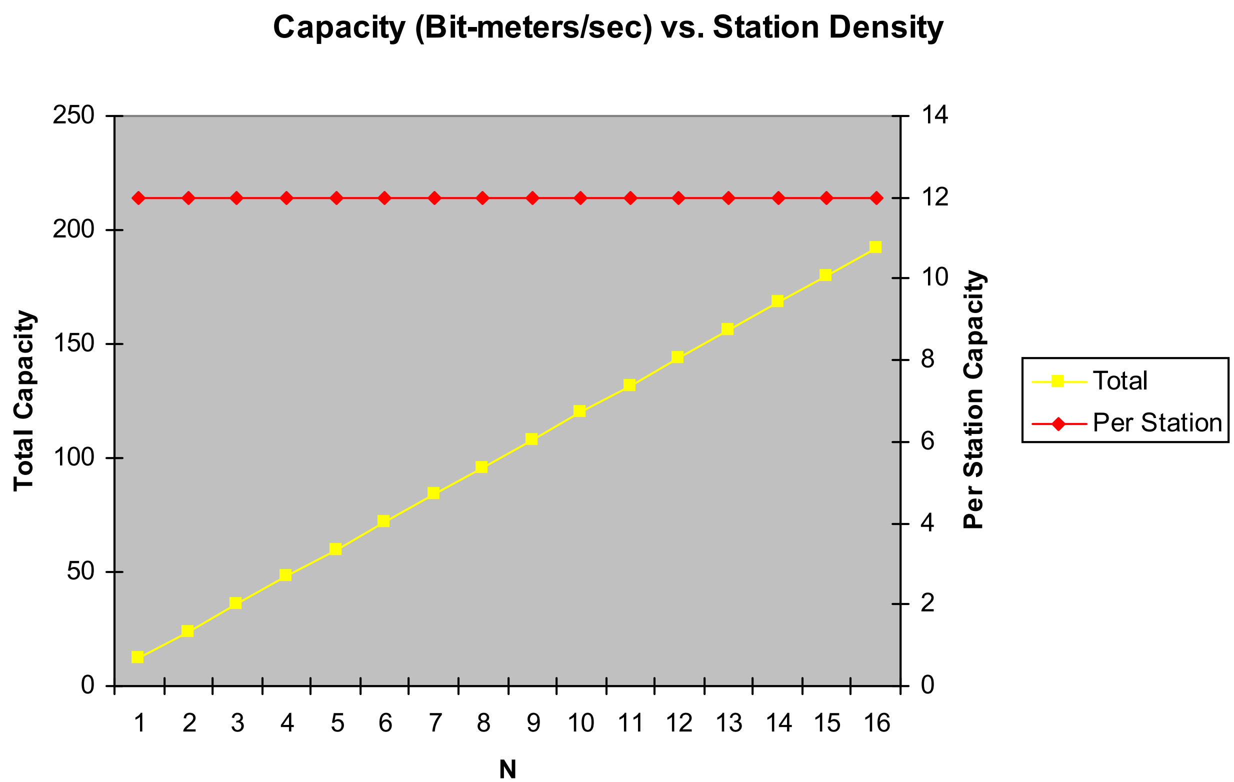
$S = R \times G^{-1}$

Combining relay channels, space-time coding, etc.



Potential C_T proportional to N or better?

Network Capacity Scales w/Demand



How do networks create value?

- Value depends on capacity
- But also on “optionality”:
  - Flexibility in allocating capacity to demand (dynamic allocation)
  - Flexibility in “random addressability” (e.g. Metcalfe’s Law)
  - Flexibility in group forming (e.g. Reed’s Law)
- And security, robustness, etc.

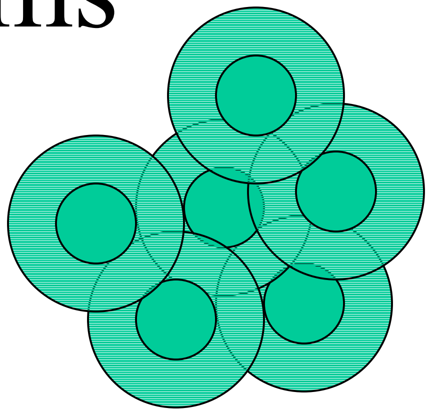
Economics and “spectrum property”

Property rights are a solution to the “tragedy of the commons” by allocating property to its most valuable uses

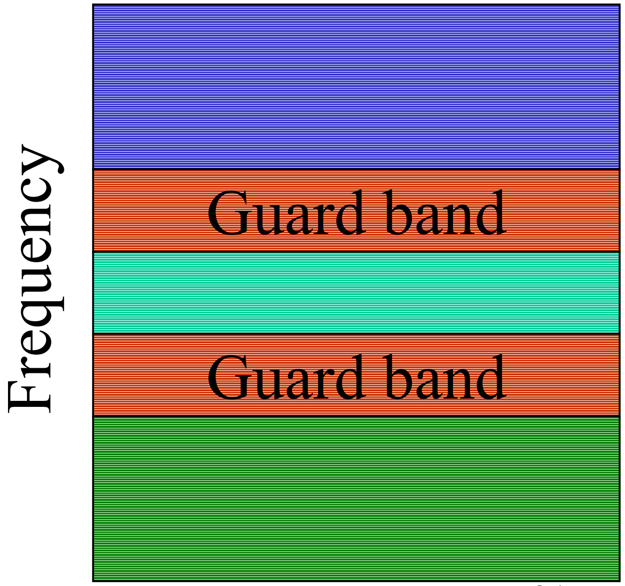
But property rights assume property is *conserved*

Yet spectrum capacity increases with the number of users, and if proportional to N, each new user is self supporting!

Partitioning problems



- "Guard bands" – each time a band partitioned in space or time, capacity wasted
- Partitioning impacts flexibility value:
  - Burst allocation capped
  - Random addressability & group-forming value severely harmed
- Robustness reduced, security reduced.



Increasing returns

- Increasing returns + spectrum ownership lead to "winner takes all" where scale trumps efficiency
- Having "taken all" winner has reduced incentive to innovate rather than just raise prices.

Calls to action

- Research needed to create efficient wireless architectures that are based on networks that cooperate dynamically in spectrum use
- New incentive structures (regulatory or economic) need to be in place to encourage use of efficient architectures. Property models (e.g., auctions, band management) likely incompatible with dynamic cooperation needed for dense scalability
- Architectures for cooperation -- “hourglass”-like Internet -- enabling variety of underlying technologies and variety of services/apps to be under constant innovation and evolution