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

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March 4, 2003
Presented at ISART 2003, Boulder, CO

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
**Sustaining vs. Disruptive Technology in a Regulated Industry**

**Useful Wireless Communications Technology**

- **Traditional capabilities**
- **Novel Capabilities**

- **Adaptive Systems**
- **VLSI**
- **Internet**
- **SS, UWB, DSSS**

**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”
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”

\[ C = W \log(1 + \frac{P}{N_0W}) \], 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?

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.
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

Space and Frequency Division

Guard band
Guard band

Growth rate
Slepian-Wolf

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

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?

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

$\sum$ bits from $s$ to $r$
$\sum$ distance from $s$ to $r$
“Spectrum capacity” model under static partitioning

Capacity (Bit-meters/sec) vs. Station Density

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
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
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

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
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.

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 extract the maximum capacity from the medium, 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
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

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
Internetworking problem

Distinct from wired Internet
Potential low cost gateways “everywhere”

Tightly coupled with problem of managing coexistence when partitioned.

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