An Evening with David Reed: Bits are not Bites! Balkanizing spectrum creates scarcity.

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With special guests: Tim Andrews (Moderator) and Tim Shepard (Commentator)

Summary

David P. Reed's aphoristic double entendre put another way is "**Bits are a measure of entropy. They are not their container.**" So when you deliver a stream of bits into a medium you're not necessarily taking a significant bite out of the information capacity of that channel. Reed's presentation[1] to the MIT Wireless Forum detailed his vision for adaptive radio architectures. He believes that the use of adaptive radio architectures will eventually enable a **massive increase in usable "spectrum capacity**."

A bit is a bit.
– Claude Shannon

Bits are bits.
– Nicholas Negroponte

A bit is not a bite.
– David Reed

The current structure of U.S. and international radio spectrum regulation has enforced an **architectural model of narrow band fixed power broadcasting and a market for spectrum**. This made sense with the state of technology in 1912. Given recent advances in information theory and radio communication techniques (e.g. Ultra Wide Band) it is no longer viable. The arguments in support (as well as against) new spectrum allocation schemes take on technical, economic, and political dimensions. For example, Lawrence Lessig and Yochai Benkler have argued that if the information capacity is effectively unlimited our current spectrum allocation process could be declared unconstitutional.[2]

Reed believes that **over the next 10 years a revolution is inevitable** and acknowledges there are many entrenched interests and faulty metaphors to negotiate before this can occur. The most important confusion to clear up is in the distinction between bandwidth, channel capacity, and spectrum capacity. The talk provided clear and applicable metaphors by which to understand spectrum usage, channel capacity, bandwidth, and so on, and he laid out regulatory and architectural frameworks for the new era of adaptive wireless technology. Reed also detailed his ongoing efforts to influence FCC regulatory activity in accordance with his vision and to educate industry and government leaders on the true issues.

The event attracted a large audience with a number of individuals flying hundreds of miles to attend the session. The next section contains some unstructured notes.

Selected Notes

David Reed mentioned two articles by Ronald Coase, "The Federal Communications Commission" (October, 1959) and "The Interdepartment Radio Advisory Committee" (October, 1962) which present the "classic" argument that because the frequency spectrum is a scarce resource the best method of allocating the resource is to **create a market in frequencies**.

Reed points out that the classic argument is based on a pre-Shannon[3] understanding of information theory and communications. Reed suggests we measure the utility of spectrum in terms of **information capacity** and **the options to connect** rather than the number of frequency channels. When you do this, the scarcity argument no longer applies. The conclusions of Reed's arguments are counter-intuitive and the explanations are qualified by uncertainty.

The key issue is cooperation vs. balkanization. Reed suggests that the capacity and value of the network will increase with cooperation, with capacity roughly proportional to the number of nodes. On the other hand, the current scheme of balkanizing spectrum destroys value, with capacity remaining constant or worse. Reed referenced Tim Shepard's research[4] that offers a convincing argument that a self-organizing packet radio network may scale to millions of stations within an urban area with raw per-node data rates in the hundreds of megabits per second. If this is so, there **is no technical justification for the current strategy for spectrum allocation**. While Reed remains diplomatic on this point, we expect the NAB and their cronies will find many 'experts' to say this is not so.

So what should we do? The FCC is looking into this. Reed and others suggest that our centrally designed and regulated system must be replaced by a self-regu-

lating system over time. Just like the Internet, we should move towards cooperation and internetworking and away from balkanization.

The heart of the talk focused on an explanation of the **end-to-end argument**,[5] that advocates: (1) a "stupid network," (2) systems that support dynamic adaptation, i.e. a society of "Cognitive Radios," (3) Open Architecture, and (4) a plan for evolution and obsolescence. The current regulatory regime does not support this new approach other than within small areas of unregulated spectrum. Much like the evolution of the Internet, there are no guarantees to investors. On the other hand, the collective economic rewards and impact on innovation are immense.

Reed is credited with putting the slash in TCP/IP. The end-to-end argument calls for "**radical simplification**" in the design of the Internet and this led to the split of TCP into TCP and IP, thus putting the slash in TCP/IP. The argument suggests, "**functions placed at low levels of a system may be redundant or of little value when compared with the cost of providing them at that low level**." Examples include error recovery, encryption, duplicate message suppression, and delivery acknowledgement. Reed claims that low-level mechanisms to support these functions are justified only as performance enhancements. This approach is illustrated with the "Hourglass Model." In the talk Reed advocated the **application of these design principles to wireless communication**. This will yield dramatic improvements in terms of scalability and ability to evolve gracefully as new technologies and uses are introduced.

Does spectrum have a capacity? According to Michael Gallagher, spectrum is "a non-depleting but limited resource." Shannon defined the bit and the channel[6] in the late 1940s but these revolutionary concepts have yet to be used in radio. Cerf, Kahn et al. in the 1970s took Shannon's ideas and suggested we don't need a channel for each service. Just use a single medium (e.g. the internet) but still, these ideas have had no real impact on radio. Eventually they will.

Decentralized communication challenges the current "mainframe communication" infrastructure. If you take a look at the mainframe to PC evolution we learned that decentralized computing eliminated barriers to innovative uses, enabled new technologies, drove the cost of innovation down precipitously, and made it easier to introduce new capabilities. For example: user-interfaces, sound, interactivity, etc. Likewise, the transition from mainframe communications to decentralized communications eliminates barriers to innovative uses (e.g. 802.11, currently the healthiest part of computer industry). And similarly it enables new capabilities (pervasive communication and computation with wireless).

Scalability is starting to matter. The big problem we now face is the scalability of current wireless communication systems. This is driven by many factors, primarily that pervasive computing must be wireless. Demand for connectivity that changes constantly must scale. Capacity and response time expectations are evolving exponentially. So the important question becomes, "Can we really scale with wireless?"

If you take a look at Reed's slides[7] he points out "standard" channel capacity is for one sender, one receiver. This model says nothing about the most important case: many senders, many receivers. The system does not take advantage of geographical distribution of senders. Noise is considered to be "other signals." Reed said, "The capacity of multi-terminal systems is a subject studied in multi-user information theory, an area known for ... open problems and counterintuitive results." **Information loss is a systems design and architectural issue, not a physical inevitability!** Theorists talk about "confusion" when they think of radio interference. Lawyers twist it into "damage."

Repeater networks offer a major architectural improvement. Transport capacity is the important measure of radio network capacity. The common assumption that lots of cell phones won't work in the same space due to interference or spectrum saturation is wrong. Capacity is limited by the number of network access points in the area. The traditional, intuitive "spectrum capacity" model is limited in the number of bits of channel capacity in the room. Energy/bit is reduced by 1/hops if nodes can play a role in helping each other. Many paths can operate concurrently. Everyone shares space in a helpful way, as repeaters in the Internet.

What is the capacity of a repeater network? Grows as the square root of the number of nodes, not the number of nodes or worse as with the current approach. Architectural improvements include spatially organized waveforms, BLAST (diffusive medium & signal processing), exploiting multi-path via cooperative signal regeneration, etc. Multi-path reflections actually become additional information which can all be used to improve the signal. This leads to the security implication that if a weak signal is being transmitted to near neighbors and forwarded to the ultimate receiver, a small number of intermediate receivers will not have enough information to reconstruct the signal.

Counterintuitive results from multi-user information theory: (1) multi-path, repeating and mobility increase capacity, (2) repeating reduces energy, increases battery life and reduces health concerns, (3) channel sharing decreases latency and jitter, (4) network capacity under cooperation likely to scale linearly w/demand. David Reed is currently exploring these issues as a visiting scientist at the MIT Media laboratory.

Many economic utilities scale beneficially as a result of network architectures. Value grows because of "optionality" (Real Options[8]), the number of possible connections (Metcalfe's Law[9]), and the possibility of forming groups (Reed's Law[10]).

Cooperation Gain vs. Tragedy of the Commons. Markets in property rights attempt to prevent the "tragedy of the commons" by allocating a valuable, scarce commodity to its most valuable uses. But property rights and "tragedy of the commons" assume the valuable commodity is conserved. Yet **capacity increases with use in a cooperative network!** New technology transforms the tragedy of the radio frequency commons into a cornucopia of the commons.

There are many interesting start-ups in this area, among them are Discrete Time Communications and Ember.

Discrete Time[11] has developed an Ultra Wide Band radio architecture implemented with CMOS that is highly scalable, in power, frequency of operation and bit rate. The current design is intended for very low power wireless networking products that require low bit rate and multi-year battery lifetime. They are also developing products for very high bit rate, short-range applications for multimedia networking.

Ember[12] has developed EmberNet, a self-organizing, self-healing wireless embedded networking platform based on patented mesh networking algorithms. Ember claims that wireless networks based on a star topology (e.g. 802.11 and Bluetooth) are vulnerable to physical obstructions, radio interference, single points of failure and bottlenecks. In contrast, EmberNet use a decentralized, multi-hop mesh topology in which each node is in direct communication with its neighbors. If a single node fails (e.g. strong RF interference) packets are automatically routed through alternate paths. The current implementation is suited for sensing and control applications that require low bit rates and nodes with low power requirements. EmberNet may be implemented with a variety of radio technologies.

Meeting notes by Phillip Apley <pga@alienlanding.org> and David Tamés <davidt@alum.mit.edu>, December 9, 2002, revised December 13, 2002.

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[1] D. P. Reed, Open Spectrum web pages at http://www.reed.com/OpenSpectrum (has links to many of the articles and resources mentioned during the presentation). The presentation itself may be downloaded directly from: http://www.reed.com/OpenSpectrum/MITWF%20slides.pdf

[2] Y. Benkler & L. Lessig, "Will technology make CBS unconstitutional?" *The New Republic,* Dec. 14, 1998, http://www.thenewrepublic.com/archive/1298/121498/benklerlessig121498.html

[3] C. E. Shannon, `"A mathematical theory of communication," *Bell System Technical Journal* 27, July and October, 1948, http://cm.bell-labs.com/cm/ms/what/shannonday/paper.html

[4] T. J. Shepard, "A Channel Access Scheme for Large Dense Packet Radio Networks," *Computer Communication Review,* ACM SIGCOMM 26, 4, October 1996, http://www.acm.org/sigcomm/sigcomm96/papers/shepard.pdf

[5] J. H. Saltzer, D. P. Reed and D. D. Clark, "End-to-End Arguments in System Design," *ACM Transactions in Computer Systems* 2, 4, November, 1984, pp. 277–288, http://web.mit.edu/Saltzer/www/publications/endtoend/endtoend.pdf

[6] C. E. Shannon, ibid.

[7] D. P. Reed, ibid.

[8] Whenever an organization makes an investment in physical assets, research, product development, etc. they are acquiring options: opportunities to make decisions in the future based on the outcome of activities that are uncertain today. The authors call these "real options" (to distinguish them from option contracts traded in financial markets) that are valuable when there is uncertainty. Their value derives from the upside potential. There is value in having options to change tactics or update strategy in the future. See: M. Amran & N. Kulatilaka, *Real Options: Managing strategic investment in an uncertain world*, Harvard Business School Press, 1999, http://www.real-options.com

[9] Bob Metcalfe said, "I made this law up. It is called Metcalfe's Law. I did not call it Metcalfe's Law, but I am delighted that other people are. And it says that the value of a network grows as the square of the number of users. Well, if that law is even remotely true, subdividing the Internet, for whatever reason, cuts into its overall value. Because it inevitably detracts from the connectivity that we are seeking. So rather than build our own separate intranets, we should be fixing the Internet. That is the general premise. " Quote from "The Internet After the Fad," Remarks of Dr. Robert Metcalfe the University of Virginia, May 30, 1996, http://americanhistory.si.edu/csr/comphist/montic/metcalfe.htm#me7

[10] Reed suggests Metacalfe's law understates the value created by group-forming networks. As they grow the value is based on the number of possible groups those members could form rather than the number of possible connections. See D. P. Reed, "That Sneaky Exponential—Beyond Mecalfe's Law to the Power of Community Building," *Context,* Spring, 1999, http://www.contextmag.com/archives/199903/DigitalStrategyReedsLaw.asp.

[11] See Discrete Time's Ultra Wide Band white paper available at: http://www.discretetime.com/papers/white-paper.pdf

[12] http://www.ember.com

URL of this document: http://kino-eye.com/docs/MITWF-02-Dec-Reed.pdf