Start Presentation

Spectrum Issues: A Different Perspective

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The 21st Century: The Age of Wireless

- **The 21st Century is evolving into an "age of wireless"**

- **People want and need bandwidth -- in far more places than we can ever run fiber or copper**

- **Expectation of constant access to help, (Hence, requirement for mandatory E-911 on cell phones) constant connectivity, constant availability**

- **Exponential growth in use of devices that use radio signals -- including cell phones, pagers, even watches that synchronize to WWVB!**

- **In this wireless age, the ability to innovate and to engage in many businesses depends on access to an unusual, abstract sort of "turf" known as "spectrum"**

- **Many argue that the current regime has created artificial scarcity, "haves," and "have-nots"... and is hindering progress**

- **Congress has now "balanced" tax cuts with revenue**

from sales of scarce spectrum

- **As large corporations buy and aggregate spectrum, small operators are literally in danger of becoming "spectrum sharecroppers" -- or "spectrum serfs"**

- **It therefore behooves us to take a step back and ask: What is this "turf," really? How was it "created?" How can it be shared? Are the economic and political problems the result of poor design?**

My Background and Experience

- BSEE Case Institute of Technology (now Case Western Reserve University) 1981
- MSEE Stanford 1985
- Chip designer, programmer, author, magazine columnist, consultant
- "Lone Eagle" (Moved to rural Wyoming as the Internet made it possible to work from afar)
- Founder of LARIAT.NET -- the first and longest continuously operating wireless broadband provider
- LARIAT.NET was originally LARIAT.ORG -- a nonprofit (501(c)(12)) rural telecommunications company taken private at members' request

LARIAT.NET's Spectrum Travails

- **First 10 years were great.... With only a few easily resolved conflicts over spectrum (e.g. with Metricom, which sought to monopolize 900 MHz)**
- **Now being affected by "tragedy of the commons" on unlicensed bands**
- **While LARIAT.NET does what it can to engineer superior unlicensed solutions, it is now being crowded off the unlicensed bands by everything from cordless phones to baby monitors**
- **Many gigahertz of unused spectrum in our area, but we cannot use it**
- **Other potential bands, such as 3650 MHz, tied up in political red tape**
- **Our analysis shows that licensed spectrum -- even at FCC's minimum bid (5 cents per MHz per unit population) -- is so expensive that a savings account has better ROI than broadband operation on auctioned spectrum**
- **Most other providers are in same situation: Spectrum scarcity hinders deployment of reliable**

services that people want and need

- **How did we get into this mess? Is there a way out of it?**

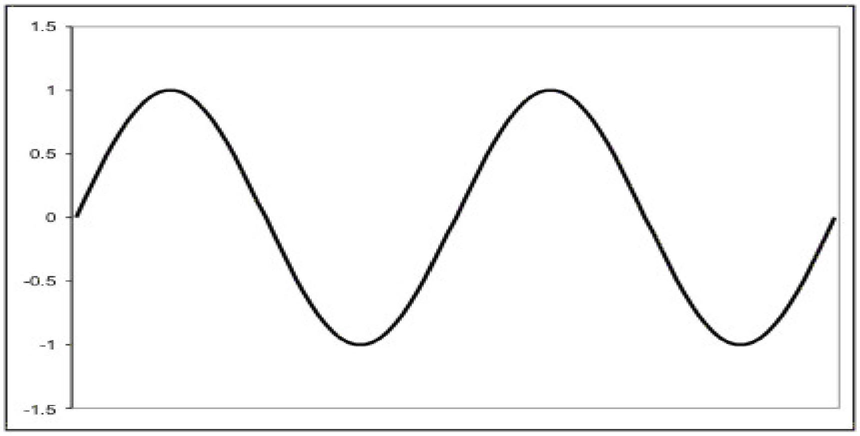
Alexander Graham Bell's Revolutionary Invention (No, not the telephone)

- **In the late 1800's, Alexander Graham Bell and rival Elisha Gray worked on an invention that would revolutionize communications.... The Harmonic Telegraph**
- **Telegraph wires were scarce and expensive; number of available pairs limited the number of messages**
- **Harmonic Telegraph coupled tuning forks -- via coils not unlike guitar pickups -- to telegraph lines**
- **Each tuning fork would send a unique frequency over the wire, causing sympathetic vibrations in its "mate" at the other end**
- **First known application of Frequency Division Multiplexing (FDM) -- sharing of a communications medium among different signals via partitioning by**

frequency

- **The Harmonic Telegraph was eclipsed by the telephone, but with the development of vacuum tube amplification and analog filtering, FDM resurfaced in analog carrier systems -- and in the world of radio**

Sines of the Times



- **Development of electronics in the late 19th and early 20th centuries focused largely on processing, transmission, and reproduction of audio with good "fidelity" as perceived by the human ear**

- **As active elements such as vacuum tubes and then transistors were developed, they were quickly molded (via negative feedback techniques) into linear amplifiers, which preserve frequency distributions and hence the "quality" of audio. THD (Total Harmonic Distortion) became a key measure of amplifier quality**

- **Signals were filtered by passive tuned circuits -- coils and capacitors -- which, like tuning forks, naturally filter by frequency and produce sine waves when they resonate**

- **Early radios (crystal sets, regenerative receivers, superheterodyne) likewise "tuned in" signals by frequency**

- **Fourier's Theorem (proved by and named for Jean-Baptiste-Joseph Fourier in the mid-1800s) stated that any signal could be decomposed into a unique linear**

combination of sine waves of various phases, frequencies, and amplitudes... in short, EVERY signal could be thought of as being composed of sine waves!

- **Before long, we were living in a world based on sine waves... and have barely looked back**

Classical Signal Processing 101

- **Classical signal processing (studied by every second year Electrical Engineering student) generalizes Fourier's Theorem:**
  - **Any signal can be represented by a vector in an abstract space, with an infinite number of dimensions. The "dimensions" consist of a family of signals called an "orthogonal basis set"**
  - **The signal can therefore be decomposed into a unique linear combination of the signals in the basis set**
  - **The set of all sine waves (at all possible frequencies, phases, and amplitudes) qualifies as an orthogonal basis set**
  - **Therefore, every signal has a unique Fourier transform which represents the combination of sine waves necessary to reproduce it**

- **A radio receiver (or any device which receives signals from a shared communications medium) works by:**
  - **Starting with everything it "hears"**
  - **Rejecting portions which fall outside the desired subset of the basis set (noise and interference)**
  - **Decoding what remains (the signal)**

- **The Shannon-Hartley Theorem (AKA Shannon's Law) dictates the maximum amount of information that can be transmitted without error if noise falls within the desired subset of the basis set or if filtering is imperfect**

- **The instructor usually mentions -- but only in passing -- that the set of all sine waves is only one possible orthogonal**

basis set. There are an infinite number of others, including:

- **Square waves (Walsh Transform)**
- **"Sampling" functions (e.g. sinc(t))**
- **Wavelets and wave packets**

...all of which leads to two very vitally important but generally overlooked revelations....

Two Important Revelations

Revelation #1: When we wrangle over spectrum, we are really squabbling over something very abstract: how to divvy up a basis set (Or, to be more precise, how to divvy up a vector space representing an orthogonal basis set.)

Revelation #2: There are an infinite number of other possible ways to do it -- some of which may be better

Are Sine Waves the Best Choice? Pros and Cons

Pro	**Con**
• Easy to construct physical oscillators and filters (from tuning forks to tuned circuits consisting of capacitors and inductors) • Corresponds, intuitively, to aspects of human perception such as color and pitch. (The cochlea is, in fact, a real time audio spectrum analyzer.) • Technology for separating and distinguishing signals by frequency is now well developed • Narrowband antennas are simpler to construct and better understood than wideband antennas (at least today) and "naturally" filter by frequency • Frequencies of signals are relatively easy to shift via mixing with sine waves ("heterodyning") and then filtering	• "Heisenberg uncertainty principle" dictates that frequency cannot be exactly determined at any point in time; therefore, no filter can be perfect and no slice of spectrum is 100% usable (there's always waste at the edges; hence the need for "guard bands") • Disconnect from reality: All real life signals are time limited. What's more, a signal that's time limited cannot truly be frequency limited • Some frequencies have characteristics (e.g. "skip") which can cause unexpected interference at a great distance • Systems designed for a specific frequency are not easily "re-tunable" to others, making reallocation difficult (not only on the fly, but even with long

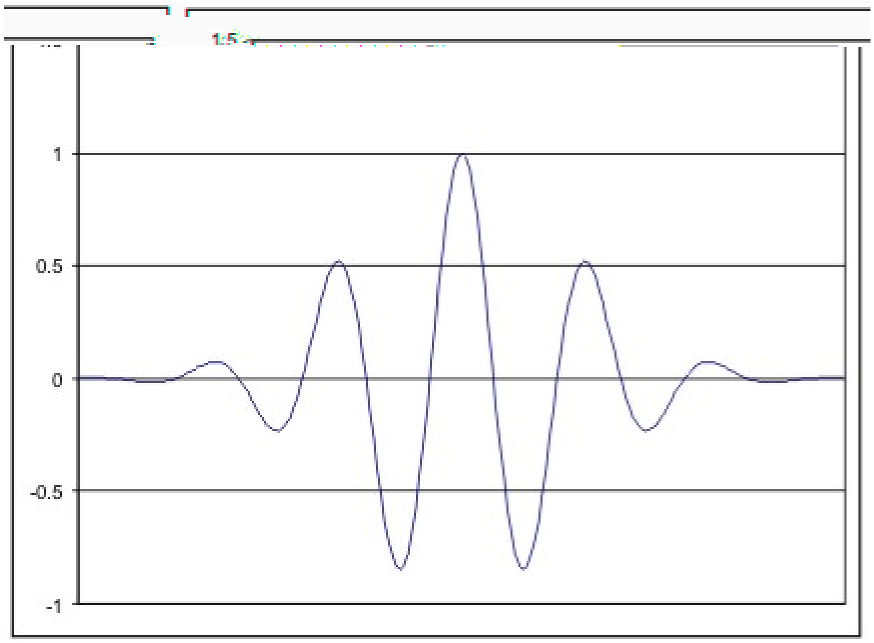
• Confining signals to a limited space (e.g. indoors) is easier if absorption spectra ofmaterials can be exploited • It's tough to change now, due to massive investment in the existing regime!	notice) and expensive • Varying absorption spectra of materials (air, water, buildings) cause some frequencies to be "beachfront property" while others are of limited use. A different basis set could equalize the practical value of different allocations, eliminating some of the artificial scarcities caused by allocation by frequency • Some alternative schemes could make "sharing" of the airwaves easier, due to increased agility, etc.

The (Probable) Folly of SETI

- **SETI (the Search for Extra-Terrestrial Intelligence) is a massive distributed computing project which searches for narrowband radio signals from space as a sign of intelligent life**
- **Millions of computers throughout the Internet contribute computing power to process massive amounts of raw radiotelescope data**
- **Key assumptions:**
  - **Alien technology developed in the same way as human technology**
  - **Aliens squabbled politically over spectrum and divided it up into narrow slices just as we did; and**
  - **To do this is a sign of intelligence (!)**
- **The fact that the project has adopted this anthropocentric viewpoint with so few objections from the scientific and engineering communities shows just how inculcated the notion of sine waves as a basis set has truly become**

Can we think outside the box?

- Would other basis sets afford better utilization or fairer allocation?



Morlet Wavelet (Product of sine wave and Gaussian envelope)

- Could other schemes coexist with existing ones (perhaps by retaining some bandwidth limitations) either during a transition or indefinitely?

- What other insights and/or productive policy decisions might result from reframing spectrum issues as contention for portions of an abstract signal space?