Multi-Objective Joint Optimization of the Transmission Hypercube

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The Claim

Spectrum is scarce and getting more so.

REALLY?

What is the Transmission Hypercube?

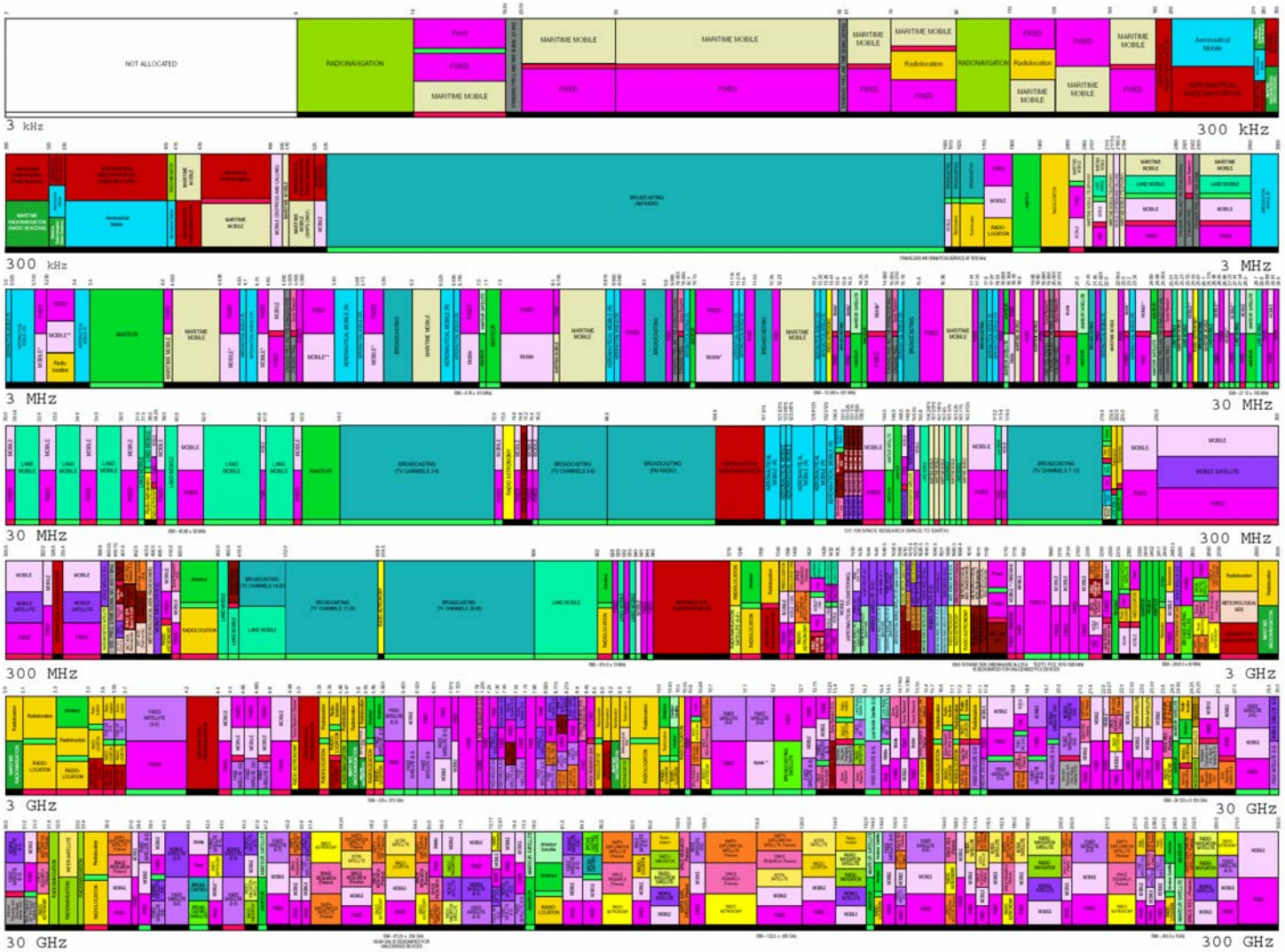
An **electromagnetically occupied volume** bounded in all dimensions.

(Time, Space, Frequency,
Code/Modulation, MIMO, Polarization)

Conclusions

- Frequency (spectrum) is only one dimension in the transmission hypercube
- Frequencies are NOT scarce, but are horribly inefficiently managed.
- The solution to the problem of “spectrum management” is a Jointly Optimized Transmission Space (JOTS)
- This is a VISION. I *DO NOT* have all the answers.
  - BUT, Barring a major paradigm shift (Quantum Comm), it seems necessary.
- Build it and they will come

NTIA Spectrum Chart (3 kHz - 300 GHz)



Section 301, Communications Act of 1934

- September 4, 2002

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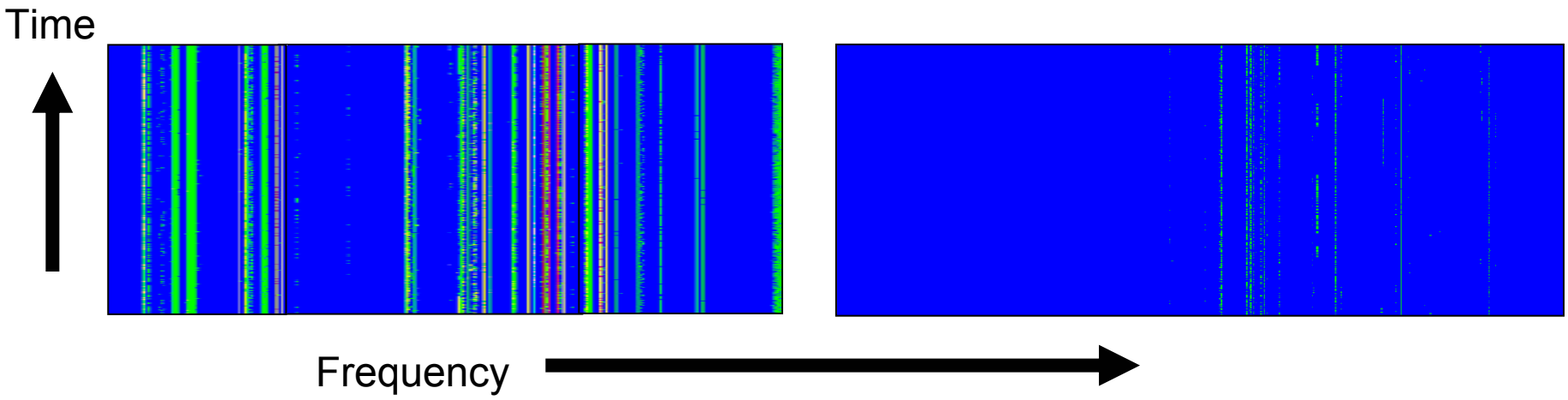
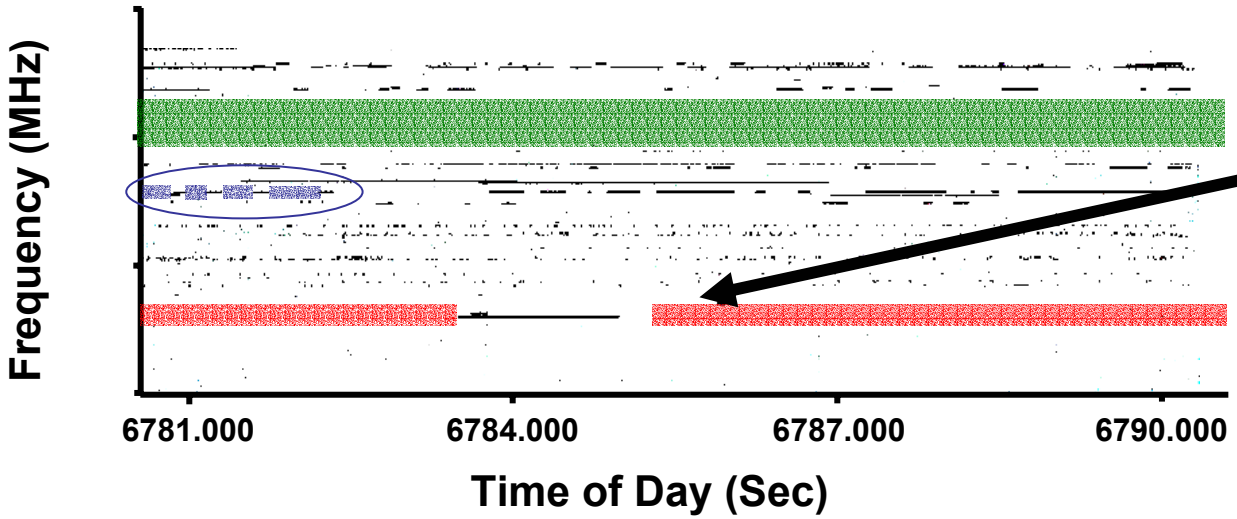
- **WILLIAM FLIPPO SENTENCED TO 15 MONTHS CONFINEMENT AND $25,000 FINE FOR UNLICENSED OPERATION ON AMATEUR RADIO FREQUENCIES AND INTENTIONALLY INTERFERING WITH AMATEUR RADIO COMMUNICATIONS.**

“10% Rule”

- **“We only use 10% of our brains”**
- **“NOT TRUE; We use 100% of our brains.” (**Dr. Eric H. Chudler; Dept. Anesthesiology, BOX 356540; University of Washington; Seattle, WA 98195-6540) http://faculty.washington.edu/chudler/tenper.html
- Other sources:
  - Ten Percent and Counting - BrainConnection.com
  - 90% of a Brain is a Terrible Thing to Waste - The New England Journal of Skepticism
  - "What is the Capacity of the Brain," a Brain and Mind Journal Brainstorming article
  - The Ten-Percent Myth from the Skeptical Inquirer
  - Don't Believe It! - Common Myths and Misconceptions Exposed
  - B.L. Beyerstein, Whence Cometh the Myth that We Only Use 10% of Our Brains? in *Mind Myths. Exploring Popular Assumptions about the Mind and Brain* edited by S. Della Sala, Chichester: John Wiley & Sons, pages 3-24, 1999. *This chapter is required reading for anyone who wants more information on the 10% myth.
- HOWEVER!
  - “10% of the spectrum” is TRUE.
  - Actually, it’s even less than that!

Real Spectrum Snapshots





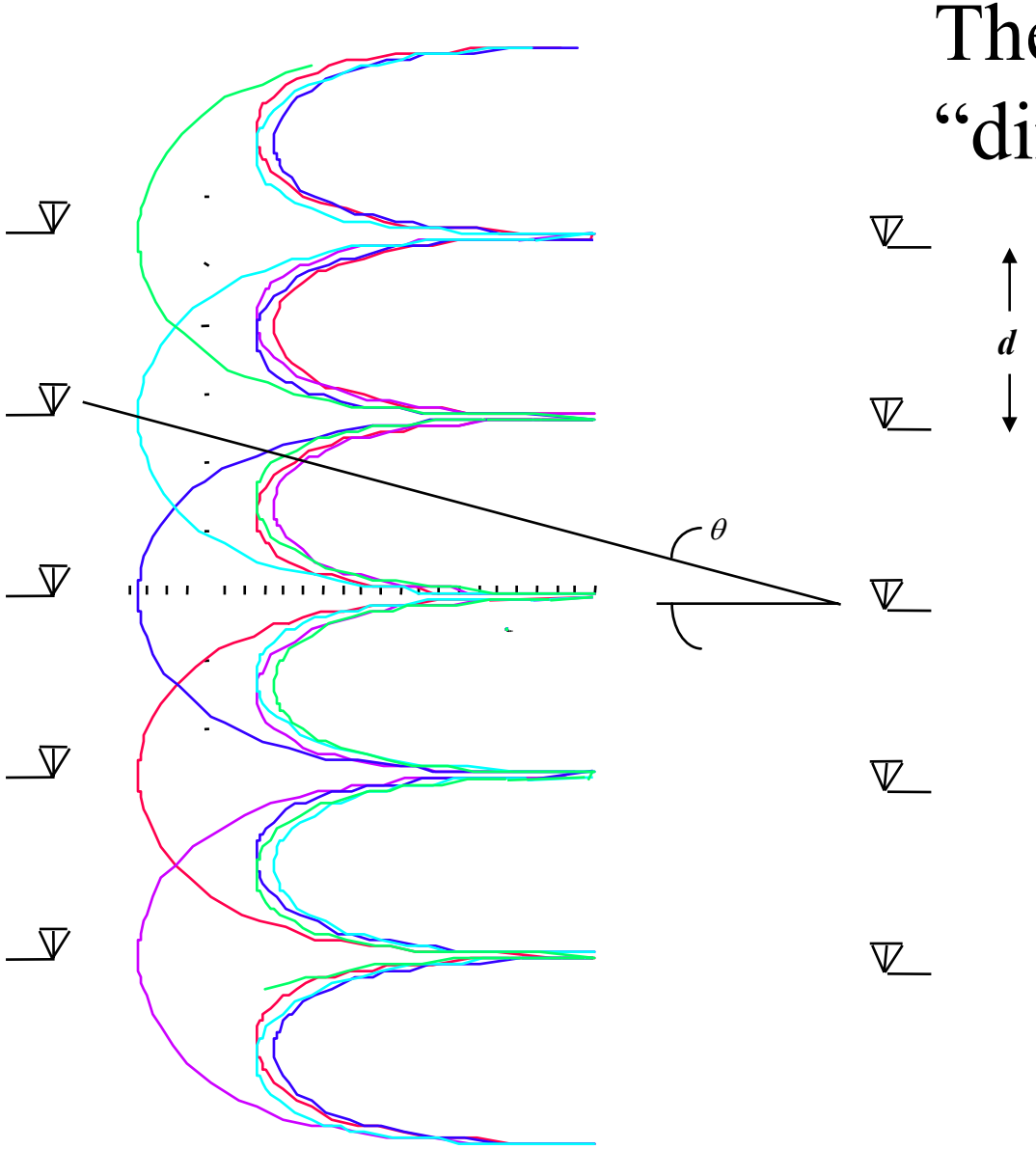
The MIMO "dimension"

$$g(N,u) = \frac{1}{N}\left(\frac{\sin(Nu)}{\sin(u)}\right)^2$$

$$u \equiv \pi \frac{d}{\lambda}\sin(\theta) - \frac{\psi}{2}\ ,\ \psi_k = \frac{2\pi k}{N}$$

$$\Delta\theta \cong \frac{\lambda}{Nd}$$

$$C_{EE} = N\log_2\left(1+\rho\frac{N}{N}\right)$$



Free Space Resolving Arrays for Equal Eigenvalue Capacity
N=5, d=1.5 λ, Δθ=7.6º

Multi-element Antenna Array Channel Capacity (Gans)

$$C = \log_2\left[Det\left(\mathbf{I}_{n_R} + \frac{\rho}{n_T}\mathbf{H}\mathbf{H}^{\dagger} \right) \right] \qquad \text{Bits / second / Hz}$$

H is the Transfer Matrix from n_T (columns) transmit elements to n_R (rows) receive elements, normalized so that the average value over the n_T x n_R elements of the square magnitude, $|H_{ij}|^2$, is unity. ρ is the SNR at each receive element if all the transmit power is radiated from a single transmit element, averaged over all pairs of transmit and receive elements. Capacity is reciprocal if one adjusts the total transmit power to maintain a fixed power per transmit element, because **H** becomes $\mathbf{H}^{\mathrm{T}}$.

Only one non-zero eigenvalue, Dyad case, Keyhole:

$$C_d = \log_2\left(1 + \rho n_R\right), \lambda = n_R n_T$$

All equal eigenvalues, largest capacity case:

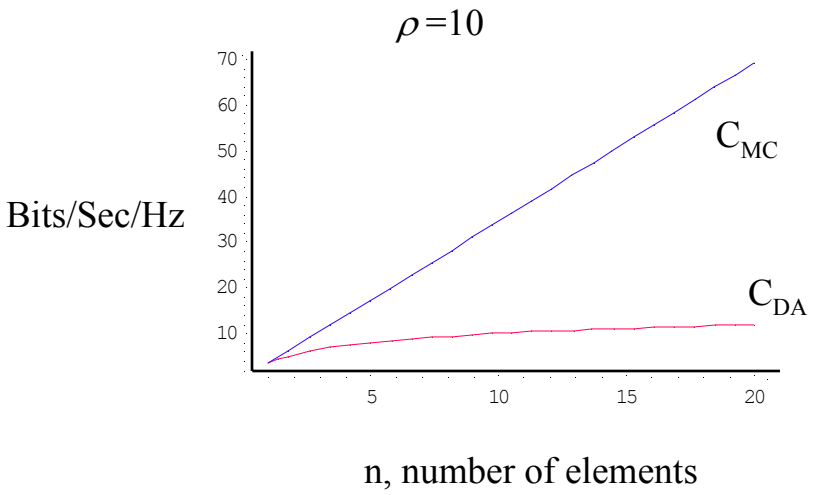
$$C_{EE} = \begin{cases} n_T \log_2\left(1 + \rho\dfrac{n_R}{n_T}\right), \lambda = \dfrac{n_R n_T}{n_T} = n_R, \text{if } n_R > n_T \\ n_R \log_2\left(1+\rho\right), \lambda = \dfrac{n_R n_T}{n_R} = n_T, \text{if } n_R < n_T \end{cases}$$

Channel Capacity

Shannon: $C = \log_2(1+\rho)$ Bits/Sec/Hz

Directive Antenna Arrays ($n_T=n_R=n$)**:** $C_{DA} = \log_2(1+n*n*\rho) = \log_2(1+n^2\rho)$

Multichannel: $C_{MC} = n\log_2\left(1+n\frac{\rho}{n}\right) = n\log_2(1+\rho)$



On the Napkin

Assumptions:

- 10% of spectrum is currently occupied with energy at any time
- Constrain discussion to below 30 GHz.
- Assume entirely digital modulations and a dismal 1 bit/sec/Hz bandwidth efficiency.
- Allow for 10% of total spectrum devoted to guard bands.

Spatial Reuse Approximation

200 Major Metropolitan Areas in US

$(30 \times 10^9$ Hz/space) x (1 bit/sec/Hz) x (60 sec)
x (200 spaces) x (.8 waste factor) x (10 MIMO gain)

= **2880 Terabits**

of information throughput across the system.

Every minute. Gone forever.

And this last 7 second sentence just cost another **336 Terabits**.

That's Permanent Enformation Waste

(yes I know it's mispelled, but the acronym works better)

(PEW)

In the course of one full day, the PEW factor is a mind boggling

4.14 Exabits nationwide.

- Or 14 Gbits for every man woman and child in this country every day.
- Using more realistic numbers for the PEW factor approximation would add at least three to six orders of magnitude to this number.
- This is average consumption. Some would use lots more, others would use lots less.

Bottom Line

- There is no spectrum scarcity
- There is flagrant spectrum management inefficiency.
- OK. So you're mad about the waste. Take a bad and make it a good …

Waveform Diversity is …

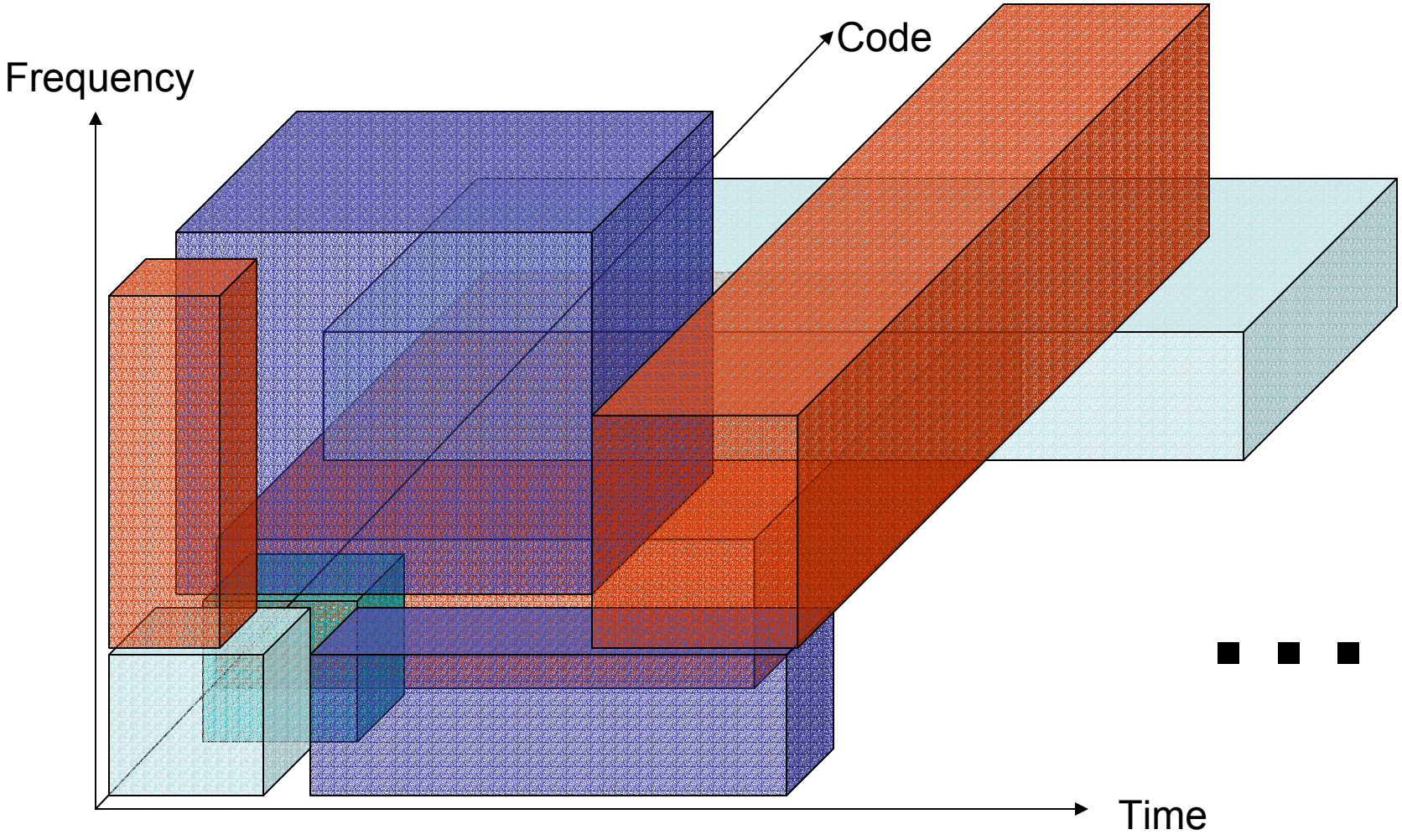
- First of all
  - Parametric agility of any transmission signal in multiple domains (*time, frequency, space, code, MIMO, polarization*)
- Second of all
  - Highly complex and heavy on signal processing.

“Managed RF Resources” The Vision

- Imagine a cube (in more than three dimensions) called the RF Resource Cube or Transmission Hypercube that is constantly changing with “cells” of signals that have applied for, received, used, and returned, their transmission coordinates.
- When you want to transmit, you ask for the coordinates, do your thing, and go off air.
- Next time you need a cell – same thing.
- This negotiation happens imperceptably fast.
- Everyone else uses the same system, which manages the utilization to optimize a cost function (one MAJOR area of R&D).

Geometric View

(Constrained to 3-D)



"Managed RF Resources"
Multiple Objectives, Joint Constraints

- Dynamic assignment
- Centrally managed
- On-demand
- Open access
- Priority/preemption enabled
- Decentralized local management nodes

- Optimally allocating all resources for:
  - transmit power
  - Throughput
  - bandwidth efficiency
  - spatial localization
  - battery draw
  - Latency
  - etc.
- Does one function
  - Hand out two 5-tuples
  - Possible 2nd function of enforcement

R&D Potential

(an organizational *"investment rationale"*)

- PROGRAM: <u>Multiobjective Optimization for RF Transmission Space Utilization</u>
  - Ripe for basic phenomenological research
    - 6.1 story is there
  - Ripe for current prototypical applied development
    - 6.2 story is there
  - Ripe for immediate demonstration with Software Defined Radios
    - 6.3a story is there
- BUILD IT AND THEY WILL COME…

What's Happening at High Levels

- White House recently tasked the Commerce Dept. (Don Evans) to solve the "spectrum management" problem in one year.
- FCC Spectrum Task Force recently motivated real change in spectrum policy
  - Required significant philosophical transformations
- NTIA and FCC have MOU to work together on evolving spectrum policy
- Defense Science Board is making strong recommendations on "shared RF resources"
- OSD is hot on the topic of spectrum management and are actively shifting paradigms pursuing "spectrum sharing" ideas
- NSF is beginning the process of organizing a coalition of academics to build a program on "the future of spectrum"
- Spectrum is being heralded as scarce resource from every direction.
- National and International governments, university researchers, and commercial enterprises all need VISION…

Recommended Reading

- Defense Science Board Task Force on DoD Frequency Spectrum Issues, November 2000
  http://www.acq.osd.mil/dsb/spectrum.pdf
- Federal Long-Range Spectrum Plan, DOC-NTIA report, September 2000
  http://www.ntia.doc.gov/osmhome/LRSP/Final-LRSP.pdf
- Air Force Scientific Advisory Board's "Spectrum Management Quick Look Study, April 2000"
  https://wwwmil.acc.af.mil/sc/scc/sccf/certs/AFSAB_SpectMgt-Final.pdf
- US Spectrum Management Policy: Agenda for the Future, NTIA report, 1991
  http://www.ntia.doc.gov/osmhome/91specagen/1991.html
- US Air Force Instructions on Radio Frequency Spectrum Management
- AFI 33-118, 3 April 2002
  http://www.afrc.af.mil/AFEPLTEMP/STDPUBS3/pubs/af/33/afi33-118/afi33-118.pdf
- AFI 33-120, 3 April 2002
  http://www.afrc.af.mil/AFEPLTEMP/STDPUBS3/pubs/af/33/afman33-120/afman33-120.pdf
- SDR Forum Regulatory filings and FCC actions:
  http://www.sdrforum.org/regulatory/filings.html
- DARPA/ATO Program - NeXt Generation Communications
  http://www.darpa.mil/ato/programs/xg.htm
  http://www.if.afrl.af.mil/div/IFK/prda/prda0201.html

Summary

- Fundamental AXIOM
  - The issue is **NOT** frequency spectrum, at least not independently
- The issue is joint optimization of *frequency, time, space, code, MIMO port, polarization, others*.
- A better term is **Transmission Hypercube** or **RF Resource Space**
  - Direct departure from the term “spectrum” avoids potential confusion with less novel concepts.
- Remainder of this discussion is built on this foundation.
  - ***Unifying visionary solution***
  - All action items can be addressed from this base.