Spectrum Sharing and Spectrum Efficiency

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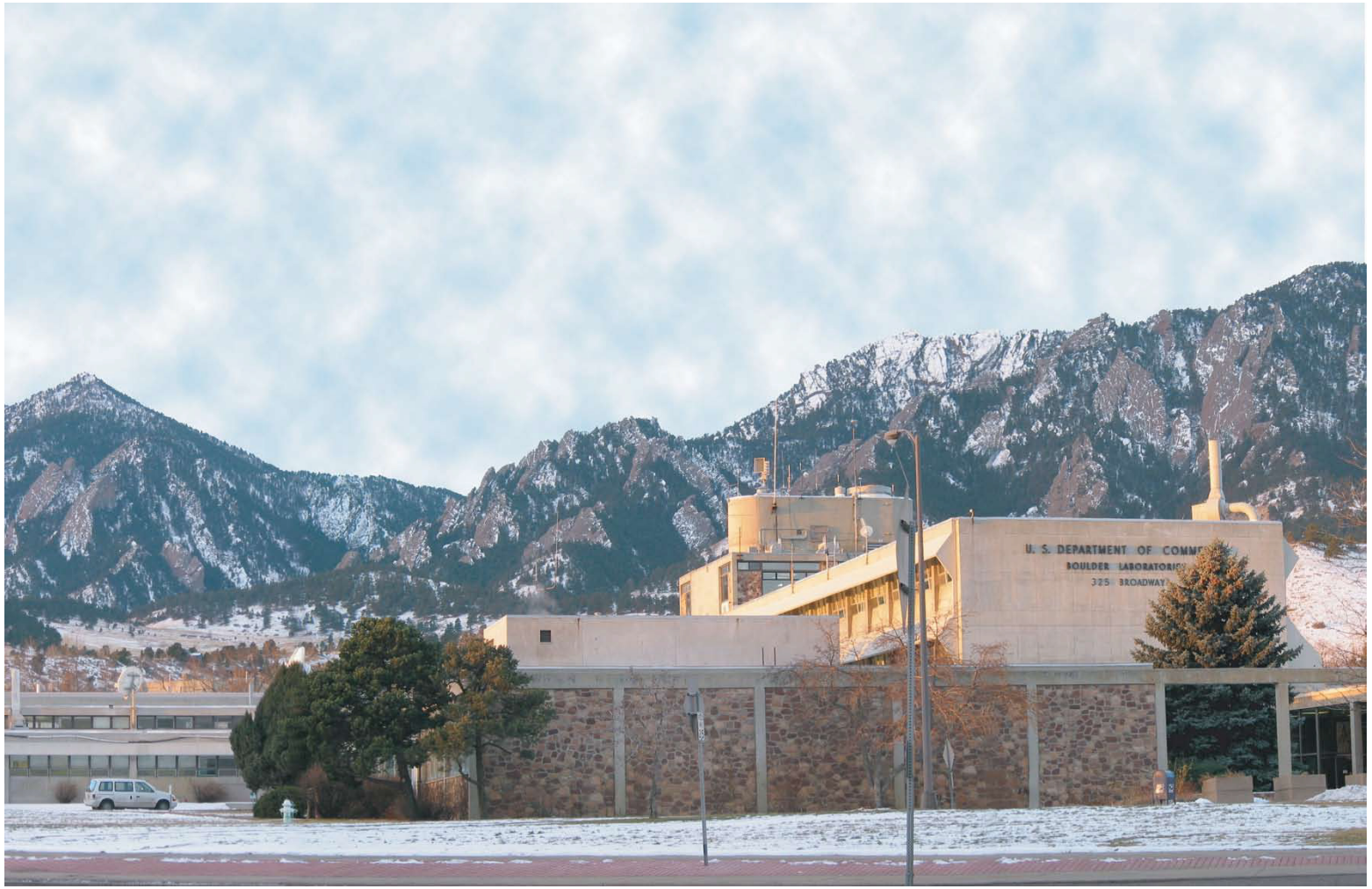
Institute for Telecommunication Sciences (ITS)

- The Institute for Telecommunication Sciences (ITS) is the U.S. government's premier telecommunications laboratory
  - Located in Boulder, Colorado
  - 100-year history of telecommunications research
- ITS mission:
  - Perform the research and engineering that enables the U.S. Government, national and international standards organizations, and many aspects of private industry to manage the radio spectrum
  - Ensure that innovative, new technologies are recognized and effective
  - Serve as a principal Federal resource for solving the telecommunications concerns of other Federal agencies, state and local governments, private corporations and associations, and international organizations

DoC Laboratories in Boulder, CO



Spectrum Demand

- Demand for radio frequency spectrum is exploding
  - Proliferation of wireless devices
    - In 2014, Americans used 4.1 terabytes of data over 355.4 million cellular devices[1]
    - 69% of adults access the Internet on a smartphone[2]
    - Nearly half of U.S. homes have only cellular phones[3]
    - By 2019, 11.5 billion "smart" devices will connect to mobile networks [4]
  - Increasing demand for bandwidth hungry data such as video
    - Standard definition -> high definition -> 4K
- But, spectrum is a physically limited asset
  - Exclusive rights to spectrum is not sustainable
  - Spectrum sharing is the new reality

[1] http://www.ctia.org/your-wireless-life/how-wireless-works/annual-wireless-industry-survey
[2] http://www.leichtmanresearch.com/press/120315release.html
[3] http://www.cdc.gov/nchs/data/nhis/earlyrelease/wireless201512.pdf
[4] http://www.cisco. com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white_paper_c11-520862.html

U.S. Objectives for Spectrum

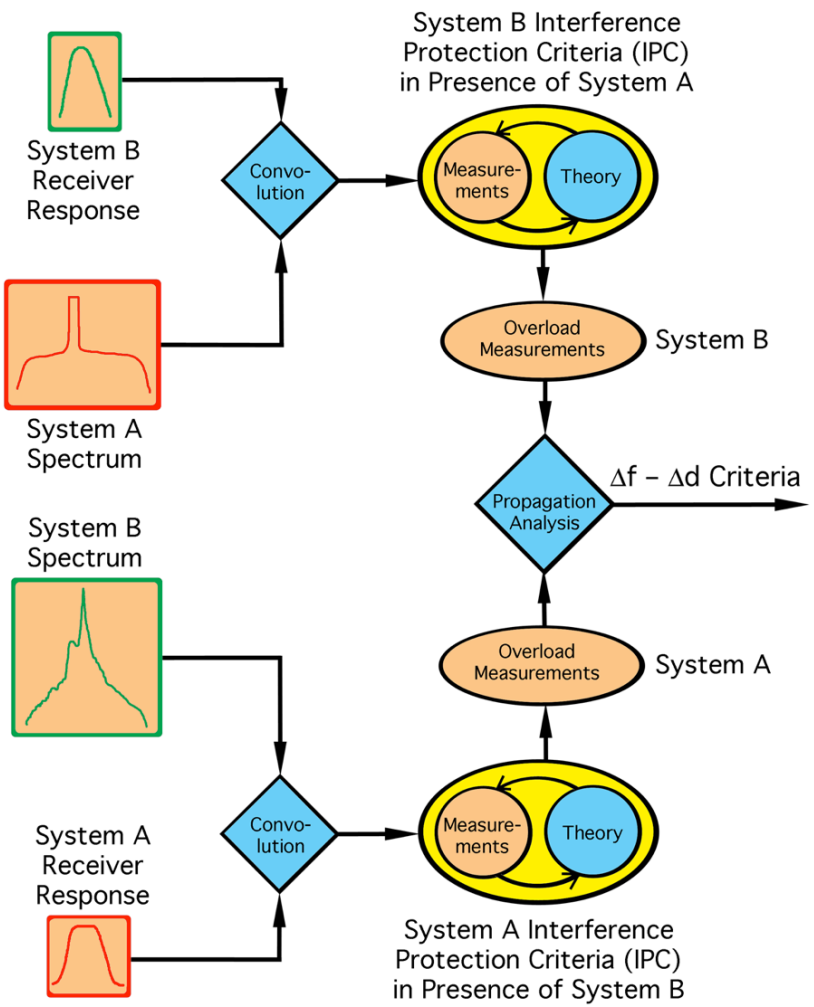
- *Unleashing the Wireless Broadband Revolution* – Presidential Memorandum 2010
  - Make available 500MHz of Federal and non-federal spectrum by 2020
  - Ensure no loss of critical existing and planned government capabilities
    - E.g., national security, emergency communications, aviation, maritime, weather, …
- Sharing is required to meet the objectives
  - Between Federal and non-federal systems
  - Across combinations of space/time
  - Dynamically
- Sharing is a *strategic imperative*
  - Exclusive use of spectrum will be the exception in the future

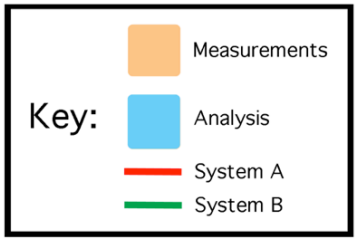
Spectrum Sharing

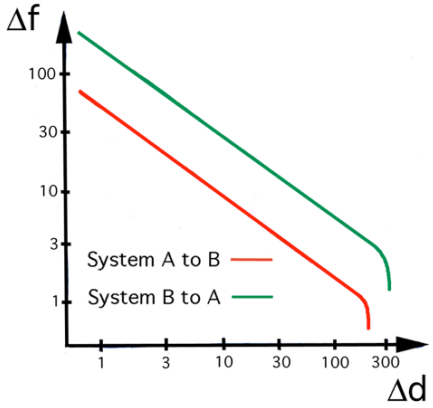
Four Basic EMC Analysis Pieces Needed

- Emission spectra for both systems
  - OOB and spurious levels as measured in the respective systems' receiver bandwidths
- Receiver selectivity for both systems
- Interference protection criteria for both systems
  - Requires interference-effects measurements, modeling, or both.
  - Needs to be done in terms of either I/N or S/(I+N), as appropriate.
- Overload characteristics of receivers
  - Only needed if either system can put overload power into the other system's front end

Use Those Pieces to Draw Δf – Δd Curves



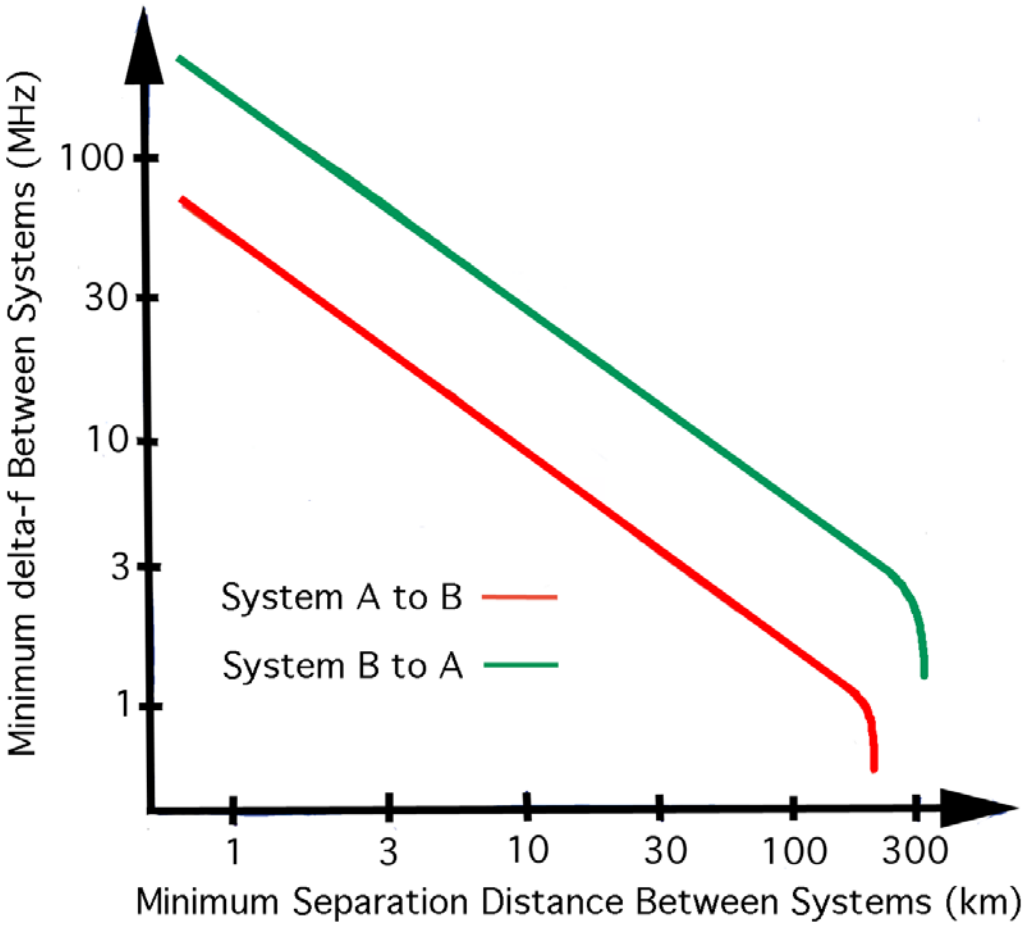




Δf – Δd Criteria for System A to B and System B to A

Δf – Δd Curves Determine Coordination Criteria

- The most restrictive Δf – Δd curve determines coordination
- In this case, System B to System A



Case Study:
5 GHz Dynamic Frequency Selection (DFS)

- In the late 1990s
  - Perception that some spectrum used by radar was underutilized
  - Unlicensed National Information Infrastructure (U-NII) developed to share spectrum with incumbent radar systems
  - 5250-5925 MHz band was selected in U.S.
    Primary focus: FAA Terminal Doppler Weather Radars (TDWRs)
- The basic idea:
  - U-NII Rxs would detect radar signals and not operate in those frequencies
  - Radars would have primary allocation status; U-NII systems would operate on a not-to-interfere basis
  - Prior to commencing operation, a U-NII would verify that no signals were present on a candidate frequency
  - If, during operation, a radar signal was detected on the same frequency, the U-NII system would vacate that frequency and shift to another

5 GHz DFS Spectrum-Sharing Experience

- Deployment: Reports of interference to radars began in 2008-09
- NTIA and FAA spent a year identifying the cause(s) and finding technical solutions
- Problems identified:
  - Some test-and-certification protocols needed improvement
  - Some deployed DFS devices were accidentally set up with DFS functionality disabled (non-USA country codes activated by users)
  - DFS device emission spectra needed to be measured (none had been available when DFS was being devised)
  - Using those spectra, criteria had to be developed for the amount of off-tuning needed when radar signals were detected
- Frequency-distance separation criteria were established: 30 MHz of off-tuning for DFS devices within 35 km of FAA weather radars.

J .E. Carroll, G. A. Sanders, F. Sanders, R.L. Sole, "Case Study: Investigation of Interference into 5 GHz Weather Radars from Unlicensed National Information Infrastructure Devices, Part 3," NTIA Technical Report TR-12-486.

Lessons Learned: 5 GHz DFS Spectrum-Sharing

- Don’t underestimate challenges of developing new & untried spectrum sharing technology
- Challenges include technology, funding, and time
- Development time-scale can be years (like, 5-10)
- Test-and-certification of spectrum sharing approach needs adequate resources (funding and staffing)
- Verifying proper functionality of a new sharing approach requires significant time and funding
- Some interference problems are probably unavoidable when any new, non-trivial spectrum-sharing technology is deployed
- Allow for funding and staffing to resolve interference when it occurs

Spectrum Efficiency

Definition of Spectrum Efficiency

- 53 years of spectrum efficiency studies[1]
- Minimization of spectrum blocking is the starting point for spectrum efficiency
- Basic spectrum efficiency metric:
  Ratio of (effective spectrum use) to (blocked frequency bandwidth × blocked space × blocked time)

$$\xi = \rho / (b \times s \times t), \text{ where}$$

ξ is spectrum efficiency
ρ is useful throughput
b is bandwidth blocked
s is space (volume) blocked
t is time blocked

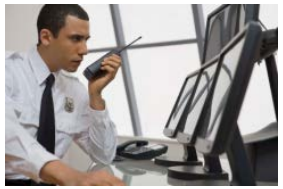
- Consensus emerging to only compare efficiency of like systems [2, 3, 4]

[1] F. H. Sanders, K.E. Davis, and K.D. Gremban, "A 53-Year History of Spectrum Efficiency Studies and Recommendations for Future Work," NTIA Report 18-530
[2] International Telecommunications Union Radiocommunication Sector (ITU-R), "Definition of Spectrum Use and Efficiency of a Radio System," Recommendation ITU-R SM.1046-2, Geneva, May 2006.
[3] Commerce Spectrum Management Advisory Committee, Working Group 1 (CSMAC WG-1), "Definitions of Efficiency in Spectrum Use," October 2008.
[4] Federal Communications Commission (FCC) Technological Advisory Council, Sharing Work Group, "Spectrum Efficiency Metrics," FCC Whitepaper, Washington, DC, Sep. 2011. https://www.fcc.gov/oet/tac/2011

Quality of Experience (QoE)

Engineering Metrics Must Be Linked to QoE

- "I need at least 80% of my customers to rate this good or excellent."
- "To do my job, I need usable images least 99% of the time."
- "I need to understand at least 95% of the words."





- "I need at least -90 dBm"
- "I need least 8 dB C/I"
- "I need 16 kbit/sec and less than 5% BER"

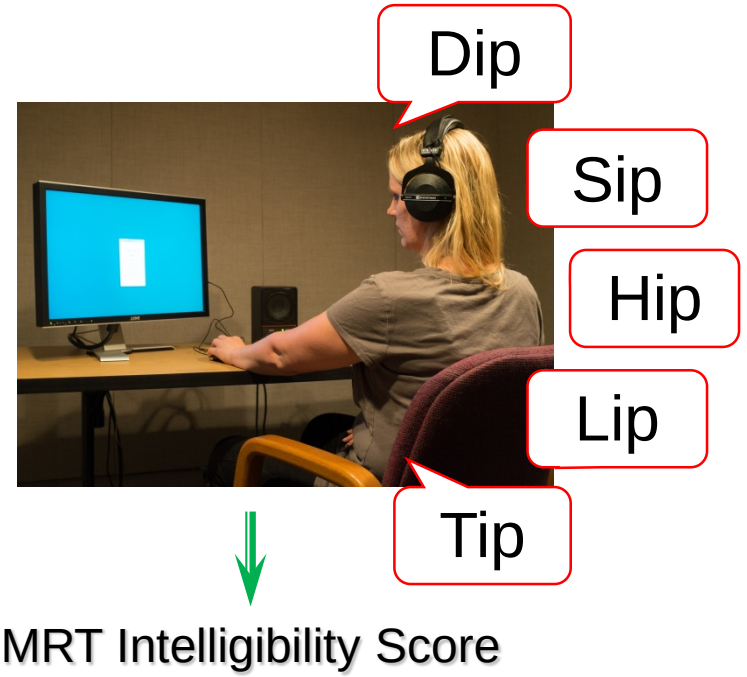




Harms Claim
Assignment
Sharing Auction
Allocation
Spectrum
Exclusion Zone Reuse
Protection Incumbent
Reframing
Efficiency

One Tool - Modified Rhyme Test (MRT)

- Speech samples
  - Phonemes in the English language
  - Transmit through radio system
  - Inject different levels and type of noise
- Panel of subjects
  - Every trial classified as “success” or “failure”
  - Calculate average success rate
- MRT Intelligibility Score (range 0 to 1)



Varied and Abundant Toolkit, More Tools in Development

MRT by Digital Signal Processing Algorithm

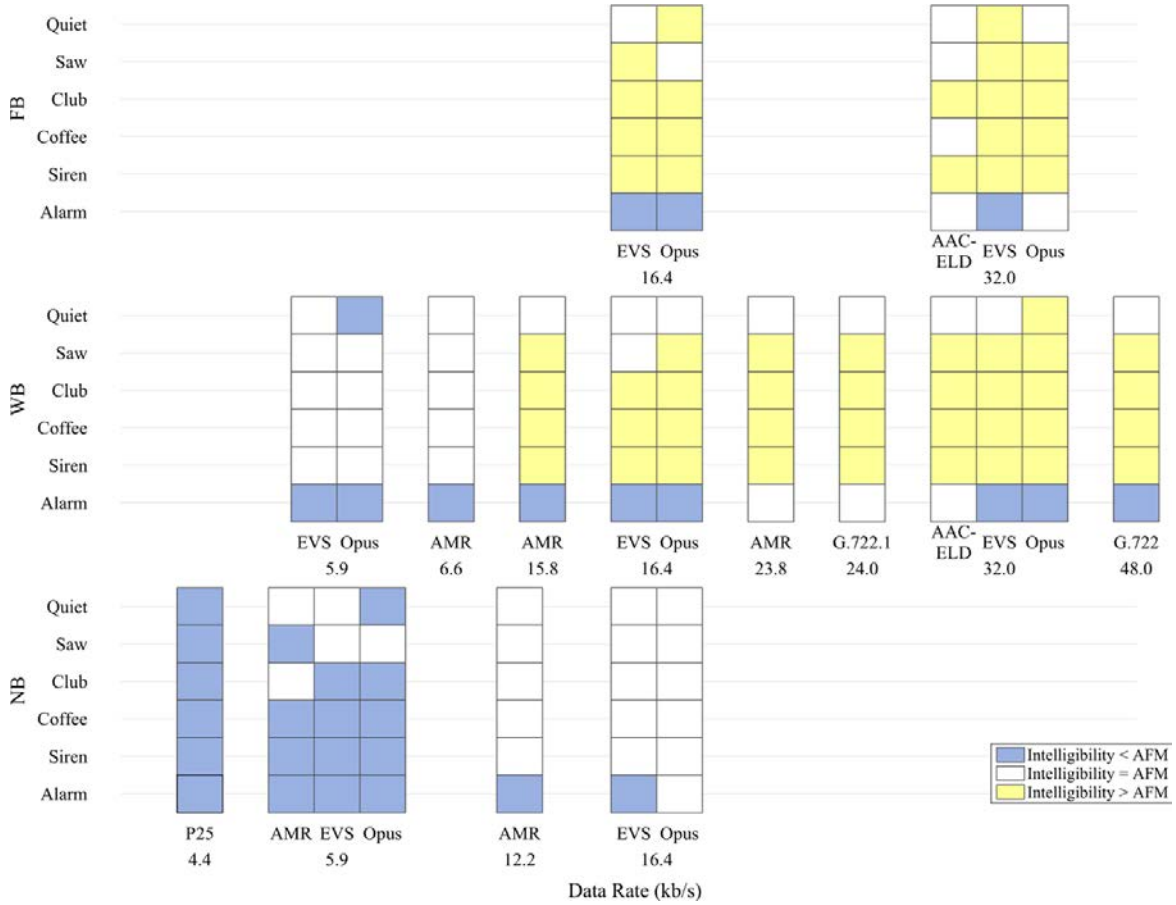
MRT in Cloud by Crowd

MRT in Lab

Post Processing

Speech Intelligibility Evaluation

- Speech intelligibility linked to bitrate and noise level



S.D. Voran, A.A. Catellier, "Speech Codec Intelligibility Testing in Support of Mission-Critical Voice Applications for LTE," NTIA Technical Report TR 15-520.

Questions?