Radio Spectrum Pollution: Facing the Challenge of a Threatened Resource
A Silicon Flatirons Conference
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Reading List
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This Conference brings together academics, policymakers, spectrum users, and advocates to examine the extent of, and trends in, radio noise pollution and to suggest how the associated policies and regulations might need to be adjusted to reflect changes in radio noise levels.

This Reading List offers participants background reading and references, organized in reverse chronological order, under *Recommended Readings* and *Additional Readings*:

Recommended Readings:

J. A. Wepman and G. A. Sanders, "Wideband Man-Made radio noise measurements in the VHF and low UHF bands," NTIA, Tech. Rep. TR-11-478, Jul. 2011. [Online]. Available: http://www.its.bldrdoc.gov/publications/2553.aspx

- Conducts man-made radio noise measurements in a 1.16-MHz bandwidth at 112.5, 221.5, and 401 MHz at two residential and two business locations in the Boulder/Denver, Colorado, area and presents data collected as a complex baseband noise data record every 10 minutes over a 24-hour period for each frequency and location.
- Provides a background on the description of noise parameters, man-made noise models, and previous noise measurements, identifying that "having an accurate model of man-made noise at very high frequency (VHF) and ultra high frequency (UHF) is of interest in the design and evaluation of radio communication systems and wireless networks." Further, it identifies that the current model for man-made noise is outdated and based on measurements that were taken in the 1960s and 1970s, which was "before the proliferation of computers, cellular telephones, wireless networks, and other electronic devices as well as increases in spectrum crowding, aging of the power distribution infrastructure, and enhancements to auto ignition systems."
- Introduces a new, wideband noise measurement system suitable for measuring man-made radio noise in bandwidths more comparable to those used in modern wideband communication systems, highlighting noise measurement location selection, noise measurement frequency and bandwidth selection, noise measurement systems, and noise measurement procedure.
- Presents results from initial man-made radio noise measurements taken at VHF and UHF and compares them to the current ITU model, recording (1) Time Domain Characteristics and APDs of Individual Noise Data Records; (2) Median, Mean, and Peak Noise Power

Analysis; (3) Complementary Cumulative Distributions of Hourly Median Noise Power; (4) Statistics of the Hourly Medians of Mean Noise Power; and (5) Comparison of Measured Results with Models.

- Finds that the measured values are larger than the values predicted by the International Telecommunication Union's (ITU) man-made radio noise model but still within one standard deviation of the predicted values.
- Recommends further noise measurements in a greater number of locations to provide more statistically significant results.

C. Bianchi and A. Meloni, "Natural and man-made terrestrial electromagnetic noise: an outlook," Annals of Geophysics, vol. 50, no. 3, Jun. 2007. [Online]. Available: http://www.earth-prints.org/bitstream/2122/3674/1/11bianchi.pdf

- Describes the natural and man-made electromagnetic noise in the NIR band.
- "Natural noise comes from a large variety of sources involving different physical phenomena and covering a wide range of frequencies and showing various propagation characteristics with an extremely broad range of power levels."
- "Due to technological growth man-made electromagnetic noise is nowadays superimposed on natural noise almost everywhere on Earth. In the last decades man-made noise has increased dramatically over and above the natural noise in residential and business areas. This increase has led some scientists to consider possible negative effects of electromagnetic waves on human life and living systems."
- "Accurate measurements of natural and man-made electromagnetic noise are necessary to understand the relative power levels in the different bands and their influence on life."

A. J. Wagstaff and N. P. Merricks, "Autonomous interference monitoring system, phase 2. final report, volume 1: Summary report," Ofcom, Tech. Rep. MC/SC0585/REP016/1, Mar. 2007. [Online]. Available: http://stakeholders.ofcom.org.uk/binaries/research/technology-research/aims2_1.pdf

- Describes phase 2 of AIMS used as a tool for measuring spectrum quality and usage.
- Interference Measurement Study: Measures interference levels to prove the performance and effectiveness of the new interference measurement mode. Uses the subspace-based I+N algorithm for interference monitoring. Mostly, the I+N levels were fairly flat during the day and showed only small amounts of diurnal variation.
- Licence-Exempt (LE) Measurement: There is increased demand for LE usage and LE bands are getting more congested. However, results showed that LE bands are in general not heavily used. "The band displaying the highest general use is the 458 - 459.5 MHz band" and "little use was found of WLANs in the 2.4 GHz band." Further, faulty light fittings (especially fluorescent tubes) can have an environmental noise over a significant part of the whole spectrum.

- Man-Made Noise Measurement: White Gaussian Noise (WGN) and impulsive noise components of Man Made Noise (MMN) were separated into different components and estimated and recorded. Found that the possible empirical relationship between *Mw* and *Sw* lead to the concept of measuring impulsive noise levels in terms of *Mw*.
- Conclusions: The new algorithm successfully measured the WGN component of MMN (*Fa*), allowing measurements to be taken in the presence of weak signals, which greatly simplifies the measuring process in the field. However, impulsive noise measurements yielded very large variations over time, making it extremely difficult to prove any link between *Fa* and *Mw*. Finally, although "the Weibull fitting method can produce good estimates of impulsive noise levels, it requires a lot of data, is difficult to calibrate and does not differentiate impulsive noise from low duty cycle signals."

Additional Readings:

Mitchell Lazarus, "Bulbs Behind Bars II: FCC Goes After Hair Salon Lighting Fixture," CommLawBlog, Oct. 29, 2013. [Online]. Available: http://www.commlawblog.com/2013/10/articles/enforcement-activities-fines-f/bulbs-behind-bars-ii-fcc-goes-after-hair-salon-lighting-fixture/#more

- Notes a situation where FCC issued a citation against a Texas hair solon for using fluorescent lights that interfere with AT&T, Inc.'s 4G service.
- "Hair dressing does not come among the FCC's responsibilities. But radio interference does. The salon's fluorescent lights emitted a stray radio signal at 705 MHz, part of a band licensed to AT&T for the delivery of 4G service to smartphones and tablets. This particular frequency is used for transmission from a mobile device to a cell tower, such as the cell tower that rises up directly behind the Perfect Cuts Salon."
- "Radio interference from non-radio devices has been popping up lately. We saw another lighting-fixture case just a few months ago that also involved 4G frequencies, and before that, a problem with a well pump."
- "There are no technical standards for these kinds of devices, as regards radio interference. In practice, though, in the aggregate, they probably cause more trouble than do the closely-regulated transmitters and digital devices."

J. Riihijärvi and P. Mähönen, "A model based approach for estimating aggregate interference in wireless networks," in *CROWNCOM 2012, 7th International Conference on Cognitive Radio Oriented Wireless Networks*. IEEE, Jun. 2012. [Online]. Available: http://www.inets.rwth-aachen.de/fileadmin/templates/images/PublicationPdfs/2012/2012-CrownCom-GibbsAggregateInterference.pdf

- Discusses the problem of estimating aggregate interference in large scale wireless networks, which is that "the commonly used approach of approximating transmitter locations within a uniform distribution or a homogeneous Poisson point process can result in significant approximation errors."

- Develops a methodology that reduces approximation errors (using techniques from spatial statistics) and can be used to both aggregate interference estimation within individual wireless networks and between two or more wireless communications systems.

K. Woyach, P. Grover, and A. Sahai, "Near vs. far field: Interference aggregation in TV whitespaces," in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*. IEEE, Dec. 2011, pp. 1-5. [Online]. Available: http://www.eecs.berkeley.edu/~kwoyach/papers/globecom11Extended.pdf

- Investigates the behavior of aggregate interference with a grid and Poisson model for placement of whitespace devices.
- Finds that "a behavioral phase change occurs depending on the relationship between the distance between whitespace devices and the distance from these devices to the primary receiver." Specifically, "the decay of the observed interference falls with r_n changes depending on whether we are operating in near field or far field."
- Suggests that "in designing rules for whitespace devices, the FCC rules may have to be sensitive to whether the situation is one of near field or far field."

K. W. Sung, M. Tercero, and J. Zander, "Aggregate interference in secondary access with interference protection," *Communications Letters, IEEE*, vol. 15, no. 6, pp. 629-631, Jun. 2011. [Online]. Available: http://dx.doi.org/10.1109/lcomm.2011.040711.110272

- "This paper presents a derivation of the probability distribution function (pdf) of the aggregate interference in a secondary access network where multiple secondary users cause interference to a single primary user. The derivation considers a practical interference protection mechanism that the transmission of each secondary user is regulated by an interference threshold. Analytic pdf of the interference from a secondary user is obtained. Then, the distribution of the aggregate interference is approximated based on its cumulants. The derived pdf shows a good agreement with Monte Carlo simulation."

R. Jantti, J. Kerttula, K. Koufos, and K. Ruttik, "Aggregate interference with FCC and ECC white space usage rules: case study in Finland," in *New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on*. IEEE, May 2011, pp. 599-602. [Online]. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=05936252

- Conducts a case study on how much white space is available in Finland and how well the current FCC and ECC rules protect the TV receivers.

- Computes whitespace capacity for the cellular secondary system and covers Finland with secondary cells and in each cell uses only the frequencies and transmission powers allowed by FCC or ECC rules.
- Discovers "that only for a low secondary transmitters' density, the TV reception will not be disturbed" and concludes "that current white space usage rules are not adequate for protecting the TV receivers."
- Suggests "constraints that consider not only secondary transmission powers but also transmitters' density."

A. Rabbachin, G. Baldini, and T. Q. S. Quek, "Aggregate interference in white spaces," in *Wireless Communication Systems (ISWCS), 2010 7th International Symposium on*. IEEE, 2010, pp. 751-755. [Online]. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5624264

- Provides "a comprehensive analysis of aggregated interference by opportunistic radios accessing the white spaces of the digital television taking into account the 'hidden node' problem."
- Proposes "a new statistical interference model for opportunistic networks using the DTV bands based on the amplitude aggregate interference, which accounts for the parameters related to the sensing procedure, spatial reuse protocol employed by secondary users, and environment dependent conditions like channel fading including the hidden nodes problem" that is "capable of analyzing the interference level in any point of a given area and therefore can be used to accurately measure the effect of secondary networks displaced in a particular environment."
- Provide data to "help understand secondary network interference in the TV white space context for successful coexistence between the licensed system and opportunistic networks,"

ITU-R, "Radio noise," Recommendation P.372-10, Oct. 2009. [Online]. Available: http://www.itu.int/rec/R-REC-P.372-10-200910-I

- Provides information on the background levels of radio-frequency noise in the frequency range from 0.1 Hz to 1000 GHz; takes account of noise due to lighting, to man-made sources, to the galaxy and to the temperature of the lower atmosphere; and gives noise figures or temperatures to provide a basis for the estimation of system performance.

Microsoft and Shared Spectrum Company, "The impact of man-made noise on protection requirements for wireless microphones," Tech. Rep., Oct. 2009. [Online]. Available: http://www.sharedspectrum.com/wp-content/uploads/ms-ssc-20091026.pdf

- States that "difficulty in obtaining data on wireless microphone use has led regulators towards an unnecessarily conservative approach that does not account for real-world conditions found at major venues." Provides the example of "man-made noise, which

has a significant if not dominant effect on the operation of wireless microphones in the field."
- Identifies that "by neglecting the impact of man-made noise in the calculation of wireless microphone protection requirements, regulators have arrived at technical criteria which overprotect microphones and unnecessarily impede new applications of white spaces."

Akira Sugiura,"Radio Noise Measurement and related Standards," Presentation at Tohoku University, Japan, May 30, 2003. [Online]. Available: http://transition.fcc.gov/realaudio/mt053003.ram (RealPlayer required)

- Explores various kinds of receivers, examining the standards for measuring receivers.
- Identifies that there is not a good instrument to detect maximum communication systems and that degradation in communication systems is caused by noise.
- Antenna positioning: "It is difficult to position antennas," and the distance must be measured at the center of the measuring antenna, so "depending on the source position, you get a different measurement for the antenna."
- Antenna calibration methods: standard antenna and reference antenna method (depends on antenna height and calibration), and standard site method. But the antenna factor varies and the calibration method yield is based on many exceptions, for example the height of the antenna.
- A serious and fundamental problem is what is the accurate e-field (there are a wide variety of antennas and there is calibration for various frequency heights and polarization). Also, what is the accurate received voltage?
- Akira Sugiura presents long-term city noise measurements in Japan from 1971-1982 and concludes that measurements are needed for future communication systems. He suggests that measurements are made with APD functions, above 1 GHz, at in indoor environments as well as outdoors.
- Importantly, the Japanese stopped collecting data in 1982, but since then, cell phones and the IBM computer prompted major changes in the electromagnetic environment.

A. D. Spaulding, "The natural and man-made noise environment in personal communications services bands," NTIA, Tech. Rep. TR-96-330, May 1996. [Online]. Available: http://www.its.bldrdoc.gov/publications/2362.aspx

- The fact that natural and man-made noise and interference determine the limiting performance of radio systems "has become more and more significant as the radio spectrum becomes increasingly crowded, and noise-producing devices proliferate."
- "It is important that the real world electromagnetic environment be appropriately modeled so that correct system design and analysis can be carried out."
- Presents "available measurement information on the level and statistical characteristics of the background noise environment in the frequency range of 1-3 GHz…," covering "the proposed frequencies for the new personal communications services," including natural and man-made unintentional radiations (both the general overall background noise and noise from individual sources."
- Finds that "the urban noise environment in this frequency range is due primarily to automotive ignition system."
- Identifies that generally, "the noise is non-Gaussian in character, but not highly impulsive." And concludes that "the nature of the interference being, in many cases, highly non-Gaussian, seriously degrades most conventional systems designed for optimal or near-optimal performance against white-Gaussian noise."

A. D. Spaulding, "Technical evaluation of the 2.45 and 5.8 GHZ ISM bands for intelligent vehicle highway systems," NTIA, Tech. Rep. 1995. [Online]. Available: http://ntl.bts.gov/lib/jpodocs/repts_te/10404.pdf

- A report investigating the suitability of the 5.8 GHz and 2.45 GHz ISM bands for IVHS Electronic Toll and Traffic Management (ETTM) and related systems by examining the natural and incidental radiation devices in these bands.
- Looks at the spectrum usage (intentionally radiated signals) in and near these two bands, giving various measurement examples. "It is the combination of all these radiations, natural, incidental, and intentional, that combine to form the interference environment in which the new (e.g. ETTM) systems must operate."
- Finds that the main source of interference from licensed emitters is from radars located above the 2400-2500 MHz band and below the 5725-5875 MHz band and analyzes the effects of the radars on the system in order to determine under a worse case situation the distance separation required from the out-of-band radars.
- "In order to analyze or design communications systems for the real world non-Gaussian interference, such as exists in the two ISM bands, an appropriate interference model is required."
- The report includes a summary of a model designed to represent the entirety of the interference background, measurement techniques required to specify the physical-statistical parameters of the model, and examples of generic system performance.

A. D. Spaulding and R. T. Disney, "Man-Made radio noise – part i: Estimates for business, residential, and rural areas," NTIA, Tech. Rep. OT-74-38, Jun. 1974. [Online]. Available: http://www.its.bldrdoc.gov/publications/2736.aspx

- The report provides an accumulated database of man-made radio noise measurements in the frequency range from 250 kHz through 250 MHz taken in a number of geographical areas; an analysis providing estimates of the expected characteristics of man-made radio noise in business, residential, and rural areas; and examples of amplitude and time statistics of the received man-made radio noise process.
- "The interference environment present at a receiving terminal of a telecommunications system is one of the factors determining whether or not that link of the system will perform satisfactorily….In spectrum management, not only is information on the effect of the interference environment on the proposed system necessary, but also the change in the environment caused by the proposed system must be considered….The interference environment will consist of all discrete signals present other than the desired signal (usually referred to as unwanted or undesired signals), broadband impulsive noise, the receiver's own internally generated noise, and various other unintended radiations."
- "In order to estimate the behavior of a telecommunications system at some future time, two types of interference information are required. One is the determination of the effect of all of the various kinds of interference environments on the system under consideration, and the other is the estimate of the interference environment that will be present at the time and place of actual system operation. The latter involves a prediction process for estimating the characteristics of the environment within some degree of accuracy."