Basic Principles for Assessing Compatibility of New Spectrum Allocations

A White Paper

Spectrum and Receiver Performance Working Group*

FCC Technological Advisory Council

Release 1.1

December 11, 2015

* Gregory Lapin (Principal Author and Co-Chair), Lynn Claudy (Co-Chair), Kumar Balachandran, Robert Dalgleish, Pierre De Vries, David Gurney, Dale Hatfield, Bruce Judson, Stephen Kuffner, Geoffrey Mendenhall, Robert Miller. FCC Liaisons: Matthew Hussey, Julius Knapp, Uri Livnat, Robert Pavlak.

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1. Executive Summary

Modern wireless transmission has become a substitute for wired quality connectivity rather than simply a means of reaching between two locations without wires. As such, expectations of availability and quality have been heightened. Fortunately, RF and baseband technology has also progressed, allowing more precise use of the spectrum resource compared to existing services. As frequency spectrum grows ever more crowded, the efficiency of frequency allocations for new services becomes dependent on increasing the effectiveness of spectrum utilization. Accordingly, new spectrum allocations featuring coexistence with current uses are likely to seek more value from the spectrum resource while simultaneously improving interference management. To aid the Federal Communications Commission in its task of spectrum allocation for new services, the Technological Advisory Council has developed a set of basic principles to be considered when making such decisions.

Basic principles of spectrum utilization are important for all involved parties to consider, not just the regulatory authorities. Realization of certain facts of communications technology will temper the expectations of the incumbent services using spectrum resources as well as the new services that are trying to gain entry into the spectrum.

The FCC faces a daunting responsibility when assigning frequencies to services; it must satisfy two or more conflicting interests. On the one hand, services, some of which spend large sums of money to gain access to their frequencies, desire to yield maximum use of their "property." On the other hand, the interest of society is that the frequency spectrum be used to its fullest potential. Thus, the FCC must at times choose to place services in close proximity to each other at the risk of interference between them. Much as with real private property, easements impinge across property lines for the good of the society. In a similar way, the FCC may have to choose to impinge on frequency channels. A set of nine principles introduced in this document addresses this concept so that all users of the spectrum can receive the maximum value from their allocations while still meeting the needs of society.

Continuing with the property analogy, the best interests of the society overall are met when neighbors go beyond what is required by law in order to get along. Such good neighbor policies are commonly found along property lines and it is logical to extend them to spectral boundaries.

The principles in this document have been divided into three functional groups. Principles 1-3 discuss realities of interference that everyone must accept. Principles 4-6 introduce the concept of responsibilities that services involved in potential interference situations have to mitigate their interaction with other services. Finally, principles 7-9 present requirements for, and actions that should be taken by, the regulatory authorities that make decisions regarding spectrum allocations.

Although these principles have been developed in order to aid the FCC in formulating policy, it is clear that the requirements of different services are varied. While some services require high reliability without regard for the excess cost of equipment capable of realizing this goal, other services have flourished in part because of the low cost of their equipment and, as such, have had to accept some service degradation. Clearly, "one policy fits all" is not possible with such disparate requirements of various services. Thus, though the principles espoused in this paper will help with development of policies related to inter-service interference, the authors are not suggesting that a concrete set of regulations will fit all services in the same way.

This paper presents and discusses the nine principles. Following this are examples of actual situations of how these principles can be applied to spectrum users, both in cases where harmful interference has occurred and also cases where it has been successfully avoided.

Definitions

FCC	United States Federal Communications Commission
TAC	Technological Advisory Council to the FCC
Interference	The effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radiocommunication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy.[1]
Harmful Interference	Interference that endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radio communications service operating in accordance with the Radio Regulations[2]
Service	A type of communications that uses the radio frequency spectrum
Incumbent Service	A service that is currently using the frequency spectrum
New Service	A service that is trying to gain access (new allocation or assignment) to the spectrum
Adjacent Channel	A frequency channel that is immediately next the frequency in use
Co-Channel	Transmissions in the same radio frequency channel
Frequency Band	A group of radio frequency channels
Propagation	The physical properties that cause a signal to move from one place to another
Intermodulation	An interaction between signals on different frequencies that results in the generation of additional signals on other frequencies
Spectrum Mask	The pattern of attenuation values at frequencies removed from a signal's center frequency
SNR	Signal to Noise Ratio, often expressed in dB

[1] Codified in 47CFR § 2.1.
[2] Codified in 47CFR § 1.907.

SINR	Signal to Interference plus Noise Ratio, often expressed in dB
BER	Bit error rate
dBm	A measure of signal power, using the logarithmic scale of decibels and comparing all values to 1 milliwatt (i.e. 0 dBm is equal 1 mW).
Spurious Emission	Signal energy that is not part of the communicating signal, which appears outside of the assigned frequency channel.
Interference Limit	The strength of an interfering signal at the input terminals of a receiver above which the interference is considered to be harmful. Described in the TAC White Paper, "Interference Limits Policy and Harm Claim Thresholds: An Introduction" [3]
Harm Claim Threshold	The level of an interfering signal measured at the antenna terminals of a receiver above which a service can request regulatory action to resolve the interference.

Harmful Interference

The wording in the official definition of Harmful Interference can be open to interpretation. This is a large part of the purpose of the nine principles that are being proposed.

Historically, the "harmfulness" of interference has been expressed as the amount of difficulty experienced by an individual attempting to accurately hear, view, or read the reproduced result of an original transmitted signal contaminated by interference or noise at the receiver. Such human-centric interpretations were founded on analog transmission of the original baseband information. Since the analog format allowed only real-time transmission, appreciation of interference was completely subjective.

As wireless systems grew to make two-way communication common, descriptive terms were used to categorize quality. An example of such an early measure was the R-S-T system[4], which employed numeric values representing the Readability, Signal Strength, and Tone (in the case of Morse code) signals as a description.

Although objective standards such as "quieting" and SINAD sensitivity later appeared to express receiver performance in the presence of noise, correlation with "on-the-air" interference to quantify an amount of "harm" remained difficult. Measurement of carrier-to-noise ratio evolved to become a primary metric of channel quality, where interference was included in the "noise" definition.

When analog picture and video transmission became pervasive, the terms "imperceptible," "perceptible, not annoying," "slightly annoying," "annoying," and "very annoying" were added to the lexicon[5] of subjective representation of "harms."

[3] Available at https://transition.fcc.gov/oet/tac/tacdocs/reports/TACInterferenceLimitsIntrov1.0.pdf
[4] *Arthur M. Braaten, W2BSR, "A New Standard System of Reporting Signals", QST Magazine, 1934*
[5] RECOMMENDATION ITU-R BT.500-13, "Methodology for the subjective assessment of the quality of television pictures", (Question ITU-R 81/6), (1974-1978-1982-1986-1990-1992-1994-1995-1998-1998-2000-2002-2009-2012)

When use of radio for critical control, remote measurement, radar, and safety applications proliferated, it became obvious that strong protection of these services was needed since many of these uses could be time-bound, require high accuracy, or be non-repeatable. Accordingly, the FCC coined the term "harmful interference."[6] Harmful interference is defined as "[a]ny emission, radiation or induction that endangers the functioning of a radio navigation service or of other safety services or seriously degrades, obstructs or repeatedly interrupts a radio communications service."

Today, any interference level other than "harmful" is deemed "non-harmful" and is viewed as an acceptable part of using a spectrum resource wirelessly. The ITU terms this concept "Permissible Interference: Observed or predicted interference which complies with quantitative interference and sharing criteria contained in these Regulations or in ITU-R Recommendations or in special agreements as provided for in these Regulations." The NTIA[7] uses the term Allowable Performance Degradation to define how much interference can be tolerated without affecting operations: Agreed-upon degradation in the performance of a radio communication system due to interference that is at a sufficiently low level such that the performance capabilities are not significantly compromised. The degradation is often referred to in terms of the percentage change in a key performance measure such as voice circuit noise, outage time, or target detection probability.

With the advent of digital information encoding, error rate was added to carrier-to-noise ratio in a given bandwidth as a fundamental metric of received signal "goodness" building on the information-theoretic work of Shannon. Digital coding also made it possible to transmit compressed versions of the original information, allowing less bandwidth than the original content to be used to convey material. However it further complicated subjective assessments of impairment, as errors produced different audio and visual artifacts depending on the compression type and the exact location of the encoding where the error occurred.

One of the problems going forward with newer digital transmission systems remains quantifying the extent of the "harm" judged by the receiving individual. Now that digitally encoded information is commonplace, reception through impaired channels using automated methods[8] to quantify quality may be needed to objectively measure QOE (Quality of Experience) in networking environments.

Until these methods become available, the current state of the art is likely to rely upon carrier-to-noise and error rate as fundamental pre-detection and post detection benchmarks, and harmful interference will be defined qualitatively as interference that causes substantial impairment of a communication signal. Such degradation can be quantified by a variety of techniques that must be subjectively judged in regard to the ability of systems to meet their service requirements, or by the ability of purveyors of associated services to effectively sustain their business goals. Such a definition of what constitutes harmful interference may, for example, be agreed to in bilateral or multi-stakeholder discussions

[6] FCC Regulations, 47CFR § 2.1

[7] NTIA Report 05-432, 2005

[8] Monitoring Video Quality Inside a Network, Department of Computer Science School of Information and Computer Science University of California, Irvine, AT&T Labs - Research, Amy R. Reibman, 2010.

between parties that will end up impacting one another, possibly in conjunction with regulatory guidance.

If appropriate messaging can occur successfully then any interference to a signal cannot be deemed to be harmful. Based on the needs of a signaling system, the definition of harmful will vary. For instance, a public safety message generally needs to be accurately understood without appreciable delay. In contrast the typical data transfer can tolerate delays and the typical video feed can tolerate small inaccuracies. Thus interference to a system that implements retransmission to correct erroneous data, thereby delaying its error-free reception for an appreciable amount of time, could be considered to be harmful in a public safety setting. Yet the same interference would be non-harmful to many data transmission applications. Likewise, for instance, occasional interference that causes 100 milliseconds of garbling of audio could make a crucial public safety message unintelligible and thus be considered to be harmful, while the same interference to a musical transmission could be non-harmful.

Interference Limits

The process of applying quantitative signal measurement to the determination of harmful interference has been described as Interference Limits Policy. Interference limits are set in specific cases to define a level of signal appearing at the antenna terminals of a service's receivers above which the interference to that receiver is considered harmful. This can be quite variable across services, depending on the requirements of a particular service and its system behavior. Once determined, interference limits can be used to define the minimum behavior of a receiver within a particular service, thus insuring harmful interference-free operation with a maximum efficiency of spectrum use. Interference limits were introduced in white papers by the FCC Technological Advisory Council and are discussed further in Section 4 of this document.[9,10]

2. Interference Realities

Various terms for Interference have been used in many settings and are not always in agreement. The severity of interference often is defined by one's point of view; understandably someone who is on the receiving end of interference tends to view it as more onerous than the person who is causing the interference, or even a third party. The person running the system that is trying to receive a message is usually intolerant of any interference while the interferer may not be able to communicate successfully without causing some form of interference to others. All parties in the wireless communications arena must go into this field with certain realities about interference in mind.

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[9] "Interference limits policy - the use of harm claim thresholds to improve the interference tolerance of wireless systems" published in 2013 and available at https://transition.fcc.gov/bureaus/oet/tac/tacdocs/WhitePaperTACInterferenceLimitsv1.0.pdf

[10] "Interference Limits Policy and Harm Claim Thresholds: An Introduction" published in 2014 and available at https://transition.fcc.gov/bureaus/oet/tac/tacdocs/reports/TACInterferenceLimitsIntrov1.0.pdf

<u>Principle 1</u>: *Harmful interference is affected by the characteristics of both a transmitting service and a nearby receiving service in frequency, space or time.*

"It takes two to tango" is a well worn phrase that can be related directly to the presence of interference in a wireless communications setting. In a system where frequencies are assigned to specific communicators, an unavoidable amount of energy leaks into every channel from every other channel. The amount of energy contributed by each transmitter on a different frequency can be controlled to some extent by the transmitting system. Likewise, the amount of energy outside of the assigned frequency channel that affects a receiver can be controlled by the receiver design. In addition, the strength of a potential interferer at a receiver can be affected by the distance between the two systems. As well, energy that could cause interference has no adverse effect if no one is listening at the time it is transmitted. Thus the parameters of frequency, space and time can be manipulated to decrease interference.

Take the case of a system that requires its receivers to be able to detect very weak signals. For example, in a narrow band system it is not unreasonable for the receiver to be able to hear far away transmitted signals that are heard at a level of -120 dBm. FCC regulations for many transmitters require that spurious emissions not be greater than -13 dBm (Regulations also specify -20 dBm for some narrow band transmitters and different levels for certain other services). Clearly, a -13 dBm signal will render a receiver that is listening for -120 dBm signals useless. However, all is not so bleak, as -13 dBm is measured close to the transmitting antenna and is usually considerably smaller as the distance to the other service's receiver increases. Also, even though a transmitter can have spurious emissions as large as -13 dBm they usually do not occur at all frequencies but more commonly at harmonics of the transmission frequency. In the unfortunate case where a spurious emission of a nearby transmitter falls onto a weak signal system's frequency, harmful interference occurs even though all regulations have been followed.

The most common parameter that has been used in the past to lessen interference has been frequency. Frequency channels were spaced farther apart than absolutely necessary to introduce "guard bands" between channels. Going forward, the presence of unoccupied guard bands is not compatible with societal need of more efficient use of the limited spectrum. As guard bands are decreased or even eliminated, other characteristics of all wireless communications systems must be optimized to avoid harmful interference.

<u>Principle 2</u>: *All services should plan for non-harmful interference from signals that are nearby in frequency, space or time, both now and for any changes that occur in the future.*

Interference is everywhere in nature, whether caused by man-made radio sources or natural ones. Even though radio services are assigned to frequency channels, effects from every radio signal can be found in all frequencies; the signal weakens significantly as it moves away from its source in both frequency and space but it never goes away entirely. Propagation effects can vary the signal strength that is seen in other channels, as well as the signal that reaches other areas; under unusual conditions of propagation signals may cause interference where they would not normally be detected.

Frequency reuse over distance is an effective method to maximize effective use of the available spectrum. With careful design and layout, considering typical propagation effects, different services can be collocated in frequency but positioned in space so that the signal from each is minimal at the others' locations. Depending on the characteristics of the frequencies used, various natural conditions, such as sunspots, meteor showers and atmospheric temperature inversion can extend the range of transmission. For such conditions that occur infrequently, it is not efficient to extend the distance between services so that they cannot detect each other under all conditions. Rather, the usual propagation is used to space services and then under unusual conditions the services may cause interference for each other. Services should expect that they will occasionally receive such interference and should plan to use whatever techniques are available to them to tolerate infrequent episodes of these conditions.

For example, two suburban police departments separated by 50 miles were assigned to operate on the same VHF frequency. The typical transmission distance of their signals was no more than a 15 mile radius from their police stations. However, this frequency range was susceptible to temperature inversion ducting, which could extend the distance of transmission as far as hundreds of miles. Although this atmospheric condition occurred infrequently, when it did the radio messages from one department were heard by the other and occasionally were disruptive to normal operations. By implementing the technique of Tone-Coded Squelch (CTCSS), with a different tone assigned to each system, when the rare ducting propagation occurred it would not cause the squelch of the other system to break and the distant transmissions were not heard.

It is also important to realize that conditions of interference today are unlikely to be the same as they will be in the future. There are many services that currently operate with no services assigned to adjacent frequency channels. If these systems are designed to operate under those conditions they may not work properly when other services are assigned to the adjacent channels in the future. It is important to design systems to operate effectively as if other systems occupied the adjacent channels.

Principle 3: ***Even under ideal conditions, the electromagnetic environment is unpredictable. Operators should expect and plan for occasional service degradation or interruption. The Commission should not base its rules on exceptional events.***

Propagation Variations

According to Maxwell's equations, the propagation of electromagnetic waves is influenced by the EM properties and the geometry of the propagation medium. Any boundary between different media or a gradient of media properties (e.g. permittivity, conductivity, etc) can alter the EM wave's direction, strength and polarization. Such boundary condition microscopic effects are generally captured in macroscopic behavioral models based on large scale parameters such as terrain variation and structure and foliage statistics which give a more static impression of propagation losses. In practice the propagation loss is constantly changing due to motion at one or both ends of the radio link as well as motion in the environment, ranging from passing traffic to wind turbine farms to atmospheric phenomena.

Familiar examples of propagation variation include fast and slow fading. A highly scattered EM environment can experience Rayleigh fading, while conditions with a dominant direct path will experience shallower Rician-like fades. For fast fading, movement on the order of a wavelength can result in a large variation (>20 dB) in propagation loss within a given coherence bandwidth on the channel. Slow fading is due to large scale (relative to a wavelength) environmental changes with movement such as diffraction around buildings or terrain or foliage loss through a grove of trees. Log-normal shadowing is often utilized to model longer term variations in signal strength due to RF shadowing. At the other extreme, atmospheric phenomena can result in propagation well beyond simple path loss predictions due to ducting and ionospheric variations.

The timescale of these propagation variations can typically range from milliseconds (e.g., for reflections off of low-flying aircraft or moving vehicles) to hours (e.g., for temperature inversions and their associated refractive properties to daily for ionospheric conditions) to months for seasonal atmospheric effects and foliage and building construction absorption and shadowing.

Temporary Intermodulation

Broadly speaking, intermodulation occurs when some function of the modulation of one signal gets transferred to another carrier. Classical intermodulation occurs when the modulation of two or more input signals gets transferred to a new third carrier frequency (which may or may not be in the set of input or desired signal frequencies). Classical cross-modulation has the modulation of one input signal getting transferred to the carrier of another input signal. In a receiver, strong signals (e.g., blockers) can result in desense of a desired signal by a variety of mechanisms. In practice, intermodulation based desense often refers to the interactive effects that stronger signals (e.g., blockers) have on a weaker desired signal due to non-linearities in the reception system.

Strictly speaking, intermodulation has occurred when a set of two or more signal frequencies at the input, once passed through a nonlinear effect, result in an expanded set of output signal frequencies or distorted desired signals. Generally, interest is limited to “local” terms, or terms that have the potential to result in desense to one or more desired signal terms (i.e., not harmonics). The prefix ‘inter-’ (between, among) is generally taken to mean the ‘modulation’ is due to the mixing of signals originating from two different sources (radios), though the same mechanism results in an expanded set of frequencies (though only one “carrier”) even when they come from the same source (e.g. an OFDM or other broadband signal). In transmitters, and even in receivers, these effects are often termed spectral regrowth. Another type of intermodulation that doesn’t result in an expanded set of carriers is cross-modulation, where a distorted copy of the envelope of the offending strong signal is transferred to the desired carrier frequency and becomes a relative-amplitude co-channel interferer. All three types of distortion (spectral regrowth, cross-modulation, and intermodulation) can simultaneously occur when multiple non-constant envelope signals are present.

The order of the nonlinearity will correspond to the sum of the absolute values of the frequency multipliers in an intermodulation calculation. For example, a fifth order intermodulation can result in local terms when the combinations of local frequencies are 3F1 – 2F2, 2F1 – 2F2 + F3, F1 + F2 + F3 – 2F4, etc. Clearly, when there are many interferers present in a dense environment, the opportunities for generating a potentially damaging intermodulation product (one that falls on the desired channel) grows rapidly. For similar reasons, these effects can come and go fairly rapidly (since they depend on the relative signal strengths of many signals). If there are only two offending signals present, the number of 3rd order intermodulation products is only two: 2F1 – F2 and 2F2 – F1. However, when the input set is extended to say N terms, a third order nonlinearity yields N(N – 1) double beat terms (of the form 2F2 – F1) and N(N – 1)(N – 2)/2 triple beat terms (of the form F1 + F2 – F3).[11] It is important to note that, since the offending signals all have a bandwidth if they are communicating information, the bandwidth of the Kth order intermodulation term is K-times wider, so the intermodulation term doesn't have to fall directly on channel to cause a problem; even falling on adjacent or alternate channels can result in desense if the distortion term's bandwidth is several channels wide, as might be seen for broadband interferers.

For a large set of blockers, each with random offered load, it can be shown that the probabilities and locations of the offending terms can fluctuate wildly. The desense potential (i.e., the temporary denial of "full" access to the channel) for the victim radio in a crowded spectral environment becomes similar to a queuing availability of a channel (i.e. the "number of 9's"), though the availability of the channel is not due to competition for that resource but instead due to interference from users competing for other resources, and is additionally dependent on the strength of the desired and undesired signals. Often intermodulation terms will be generated and fall on channel, but due to the actual (time dependent) signal strengths of the undesired signals, they may fall well below the receiver noise floor, or the desired signal may be high enough above the intermodulation product that there is no interruption of service. Thus it can be seen that the severity of an intermodulation product is highly contingent on the locations of and propagation conditions between the spectral occupants.

Such probabilistic intermodulation can become a more serious problem when the offered load on the various communications systems dramatically increases, such as during a natural or man-made catastrophe or other incidents that trigger an increased need to communicate. There can be high activity on many channels at such a time, increasing the probability of intermodulation terms, and there can also be a need for high probability of access to the channel (especially for public safety and utilities

[11] If there are $N = 10$ blockers present, there are 90 double beat terms generated and 360 triple beat terms, lots of opportunities for something to fall on the desired channel, the probability of which depends on the spread (in number of channels) of the original frequencies. Now if just one of those blockers is temporarily silenced, the number of double beat terms decreases from 90 to 72, the number of triple beats from 360 to 252. If two blockers are temporarily silenced, the terms drop even further to 56 and 168. The dependence is roughly N^2 and $N^3/2$, where the approximation is better for large N.

workers).[12] In addition, in OFDM communications systems (e.g., LTE), the actual usage of resource blocks (i.e., groups of subcarriers) is highly dependent on the time-varying load or data traffic on the system. This results in a very complicated interference environment.

In terms of intermodulation distortion and other related effects, such phenomena often arise from near-far issues, where dominant interferer(s) and a weaker desired signal are present. While these types of interference can be affected by numerous propagation effects mentioned above, they often arise in dense deployments (e.g., where base stations are not co-sited), or in cases with differing deployment densities (e.g., a very wide area PS system interspersed with a wide area macro-cellular system). Again, these types of interference can be hard to control without proper system (and inter-system) planning.

Service Outages

Whether from time-varying intermodulation interference, or other sources of interference (e.g., co-channel or adjacent channel interference), the net effects of interference can result in temporary service outages in a given location at a given time. Often times, statistical models are utilized to model the propagation effects for both desired and interfering signals (in addition to the other statistical effects mentioned above, such as signal fading). For example in DTV service, the propagation model utilized for computing a desired signal service contour is often the F(50,90) propagation curve (R-6602), which refers to a minimum expected field strength in at least 50% of locations at least 90% of the time. A more conservative F(50,10) curve is often used to model interference, or more detailed Longley-Rice calculations are utilized.

Regardless of the exact methods used in modeling interference and signal propagation, there may be cases where service becomes temporarily unavailable. This may be due to propagation effects (e.g., shadowing, fading, ducting, etc.) and the locations (in time, frequency and space) of desired or interfering signals. Related signal distorting events such as intermodulation also can play a key role in interference and outages. In some cases, services may be specified for a particular system availability or coverage reliability. Many factors (further described below) go into estimating system availability and coverage reliability.[13] The system availability (SA, expressed as a fraction of time the system should be available) or coverage reliability (CR, expressed as a fraction of locations that the signal should be receivable) may vary greatly depending on the particular system or service. For instance, a commercial cellular system may have a 90% coverage reliability requirement (e.g., be reliably receivable in 90% of locations in a given area), while a narrowband public safety system may have a 97.5% coverage reliability requirement, and an unlicensed (e.g., WiFi) hotspot in a crowded area may have a 80% coverage reliability due to interference. Similarly, a cellular system may need to be available 99.9% (0.999) of the time to meet customer requirements, while a public safety system may need to be available 99.999% (0.99999) of the time, while an unlicensed system may need to be available 90% (0.9)

[12] For example, an LMR base station could be exposed to a highly occupied spectrum with many opportunities for intermodulation products while it is trying to receive weak signals from public safety or utilities workers deep within buildings. In such cases, the cost of the intermodulation products could be quite high, even though the likelihood of such events is low.

[13] Coverage reliability may also be termed ‘service area reliability’ and is related to ‘bounded area percent coverage’.

of the time. Taken together, these figures can give an indication of overall outage probabilities.[14] In general, any newly introduced interference events should not significantly negatively impact the system availability or coverage reliability of existing systems, since these figures are often contractually or business driven.

As mentioned above, interference can be highly time-varying (due to dynamic propagation and system loading effects), with different effects on different systems (depending on modulation and coding schemes, interleaving, error-correction coding, transmission repetition schemes, etc.). Thus, there are no simple formulas for reliably predicting interference, other than the more obvious cases of interference (e.g., receiving a signal with a very poor signal to interference plus noise ratio (SINR)). Therefore, statistical models are often utilized in an attempt to quantify the overall effects of numerous interference sources. Often times, Monte-Carlo simulations are used to model the interaction between complex random variables, to study the overall effects on the system. Of course, such results are only as good as the underlying models and assumptions (i.e., the real world can indeed be a complicated place). For example, models that don't take into account complex intermodulation terms may miss important cases of interference.

In order to help estimate system performance in the presence of interference, several radio performance specifications are often utilized. Often times, radios are specified to tolerate given levels of co-channel, adjacent channel, and alternate channel interference. There are often specific in-band blocking specs and intermodulation rejection (IMR) tests in various systems. Some systems may also have spurious response rejection (SRR) specs or other related tests. Typically, these tests are specified with the desired signal some small amount above reference sensitivity (e.g., 3 or 6 dB). While this is highly useful, the performance of a receiver may change significantly as the desired signal (and interfering signal) strengths change, due to the non-linearities mentioned above.[15] Another complicating factor in these tests is that it is often hard to properly foresee which other systems may be placed next (in time and frequency) to an existing system. For example, a broadband LTE system may be placed next to a broadcast DTV system, or a broadband LTE system may be placed next to a narrowband (LMR) system, or in close proximity to satellite spectrum. This further complicates the specification problem, since it may be hard to predict which interfering systems (e.g., broadband, narrowband) an existing system may encounter. In general though, having a larger set of available radio performance specifications often results in more accurate interference and outage prediction.

3. Responsibilities of Services

Once a service has been assigned frequencies it may still have to make adjustments to its operations to avoid both creating and receiving interference from adjacent services. The FCC does not provide a brick

[14] Very generally speaking, the outage probability can be defined as (1-CR) in terms of locations, and (1-SA) in terms of time, though there may be interaction between the two effects. A more precise computation of service availability and coverage reliability is highly system dependent and highly statistical in nature, and beyond the scope of this paper. The interested reader can refer to the TIA TSB-88 document series for some examples of TIA approved calculations.

[15] Jacobsmeyer JM, Comments of Pericle Communications Company to FCC ET Docket No. 13-101, July 2013.

wall to separate services. Rather, the services are responsible to take whatever steps required to ensure that energy outside their channels does not become harmful interference to them and that they minimize the energy they transmit outside of their channels. These responsibilities are what would be expected of any good neighbor and may exceed what is required by FCC regulations.

<u>Principle 4</u>: *Receivers are responsible for mitigating interference outside their assigned channels.*

An ideal receiver accepts only the energy in its desired channel, and thus rejects all energy outside its channel. Actual receivers can only provide a finite amount of rejection of unwanted signals outside the assigned channel. These interferers are commonly referred to as *Blockers*. The ability of a receiver to reject unwanted signals is typically defined as a Blocking Mask, as shown in the Figure 3.1. Blockers that produce energy above the mask limit cause interference to the receiver.

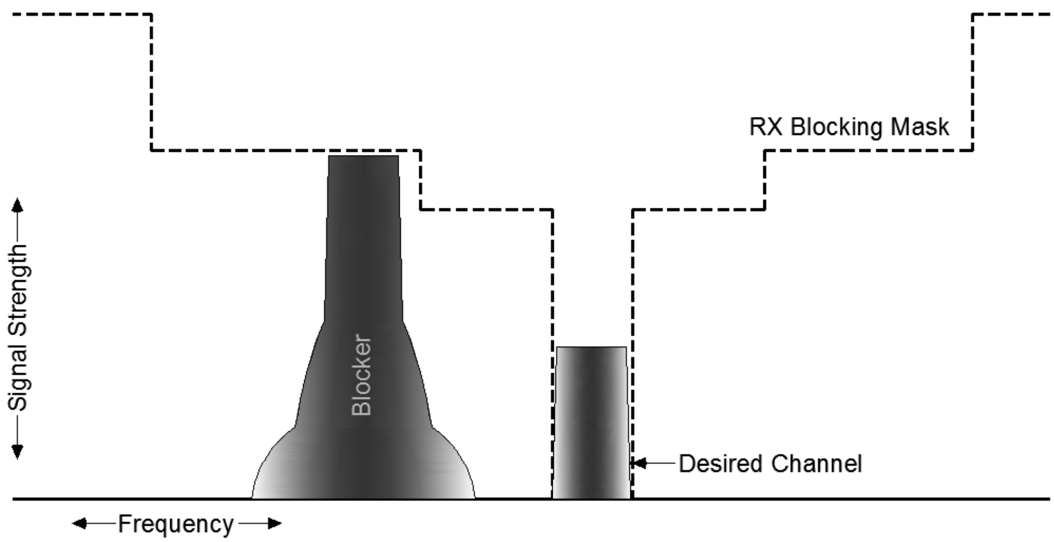

Figure 3.1   Receiver Blocking Mask

The Blocking Mask requirements are established by considering the RF environment in which the receiver is intended to operate, including Blocker levels, number of simultaneous Blockers, bandwidth and time characteristics. These are derived by reasonable operational scenarios and channel conditions. The ability of an actual receiver to reject Blockers is limited by practical considerations, such as power consumption, size and cost. Limitations of the receiver to reject Blockers include both linear, nonlinear and noise mechanisms. Linear mechanisms consist of filtering, both preselection and channel. Nonlinear mechanisms consist of intermodulation and mixing products. Noise mechanisms consist of both thermal and phase noise.

The Blocking Mask of a receiver will vary its dynamic range. This is because as the receiver's gain changes, so the component noise and intermodulation performance also vary.

<u>Principle 5</u>: *Systems are expected to use techniques at all layers of the stack to mitigate degradation from interference.*

There are techniques at different protocol layers to mitigate degradation from interference. Discussion of the Protocol Stack is generally limited to systems that process data digitally, however, in this setting the term "Stack" is being used to apply to all forms of communication, with non-digital and legacy systems only making use of the lower layers. For instance, in a legacy analog radio system, filtering appears in the Physical Layer and modulation occurs in the Link Layer. The following list of techniques is by no means exhaustive, and not all techniques will apply to all forms of communication. However, any form of communication can benefit from at least one of the listed techniques below, which are listed in order of their position in the Stack, from lowest to highest.

- Directional Transmission. Focusing the transmit energy in the direction of the user reduces interference to receivers in other areas. Lower transmit power may be a consequence of higher antenna gains. As the frequency of operation increases, the use of directional transmission may be required to maintain adequate link performance.
- Directional Reception. Directional antennas can be used by the receiver to increase gain in the desired direction while reducing gain in unneeded directions. A directional antenna combined with power control eases the ability to meet the link budget with reasonable power expenditure. Methods to achieve directional reception antennas include physical antennas with directional characteristics (e.g. parabolic dish antennas and Yagis) or by combining multiple antennas using a phased array, often in an adaptive manner. Optimal combining techniques can be used to maximize the receiver SINR, which inherently increases gain at in the desired direction or steers a null in the direction of interferers.
- Multi-input multi-output (MIMO) antenna systems – MIMO is a generic class of techniques that makes use of spatial differences in channels between the transmitter and receiver to achieve a number of system enhancements such as interference mitigation, improvement in diversity order of the system and consequently an increase in data rate, and finally an improvement in spectral efficiency in a distributed wireless system made up of many users, such as in a mobile system.
- Power Control – The receiver provides SNR feedback to the transmitter. When interference occurs, which lowers the receiver's SINR, the transmitter increases its output power to maintain the desired SINR. Power control is also used to reduce the dynamic range requirements of the receiver, thus preventing desensitization of receivers that have to discriminate between transmitters that are far away and those that are close to the receiver.
- Frequency hopping or spreading can be used to combat frequency-selective or narrowband interference.
- Adaptive Modulation and Coding – The system can select the modulation order and type and the rate of communication based on the receiver's observed channel quality, nominally the SNR, or more detailed channel state information such as the spatial characteristics of the desired channel. If the receiver experiences degradation in SNR due to interference, the system switches to a lower order modulation which is suitable for the degraded SNR level.

- Channel Codes – A lower rate of communication is usually associated with a lower rate channel code, corresponding to a greater amount of structure in the transmitted waveform and a higher effective energy per transmitted bit. The use of lower rate channel codes allows the receiver to operate at lower SNR levels, and without compromising the ability of the receiver to recreate the transmitted bits beyond a desired error rate.
- Advanced receivers – Such receivers will compensate for impairments and disturbances in the channel using a variety of techniques such as knowledge of the channel, the color of interference statistics, structure of interfering signals etc. Such receivers would implement equalizers of appropriate complexity and may use a variety of spatial, temporal or frequency-based signal processing techniques to improve the performance of the receiver as well as adapt to changes in the channel.
- Time Interleaving – time interleaving is the spreading of information in time (e.g. Block Interleaving), and is usually used to convert bursty interference into randomly distributed events. The use of interleaving is sometimes necessary to allow error correction to be more effective.
- Retransmission – the receiver requests that the data be transmitted again when the original information is improperly received. Retransmission can occur at lower or upper protocol layers. In Type II hybrid ARQ systems, retransmitted information is encoded in a way in which the energy of the prior transmission is not lost, and prior transmissions are used along with successive transmissions to effectively lower the code rate and thereby increase the effective SNR of the combined transmission. A type of channel code design known as rate-compatibility may be used to derive individual channels codes used for each attempt as punctured bit or symbol sequences of a parent code of suitably lower rate.
- Scheduling is used in mobile systems to transmit information over the channel over opportune temporal or frequency domain resources. It is typically useful under varying channel conditions or varying interference conditions. The scheduler typically operates using rules that aim to insure a certain level of service.

Some of these techniques trade system performance for a robust and reliable radio link. For example, switching to a lower order modulation will decrease throughput, and Error Coding adds additional bits. In reality, many interference sources are statistical in nature. When considering this, the resulting degradation in overall system performance is minimal while achieving a reliable link, which is critical. An example of the successful implementation of many of the above mitigation techniques is modern cellular networks, where simultaneous reliable links are achieved in challenging RF environments.

Good standard engineering practice dictates that deployed radios can operate in the environment for which the operating and neighboring spectrum is allocated. The term ‘operating’ includes both the receiver being subjected to reasonable Blocking levels from authorized services, as well as the transmitter not interfering with neighboring services. For example, if neighboring spectrum is allocated for Fixed Link Service, a deployed radio should be able to accommodate both current and potential future fixed link installations, within reason. Assuming good engineering practice, a receiver would be deployed with proper filtering and dynamic range to accommodate future expansion of the spectrum, as it was intended for. Deploying a receiver without proper filtering or dynamic range because no neighboring systems are located nearby at the time of installation would be considered poor engineering practice, and future interference can be expected. Some of the mentioned interference mitigation techniques could be considered as optimization techniques to legacy systems. For example, directional antennas, power optimization, modulation and scheduling may be practical features available to legacy systems to support the mitigation of interference as the spectrum usage grows.

Looking forward, we know that spectrum usage will continue to increase and service allocations will change to better serve the public. The mitigation techniques above are successfully used over a wide range of radio applications (i.e. military, industrial, commercial and consumer), acknowledging that not all are suitable for a given system and other more applicable techniques may exist. There are strong practical pressures for the radio system, such as cost, size and power consumption. The realities of current and future spectrum usage prescribe the need for a robust radio system. Given these realities, the incorporation of practical mitigation techniques into the radio system would be considered good engineering practice.

Principle 6: ***Transmitters are responsible for minimizing the amount of their transmitted energy that appears outside their assigned frequencies and licensed areas.***

An ideal transmitter emits energy in the desired channel and none elsewhere. Actual transmitters generate energy outside of their channels. This is referred to as emissions, usually out-of-channel or out-of-band emissions. Transmitted emissions are typically specified in terms of an emission mask, as shown in Figure 3.2.

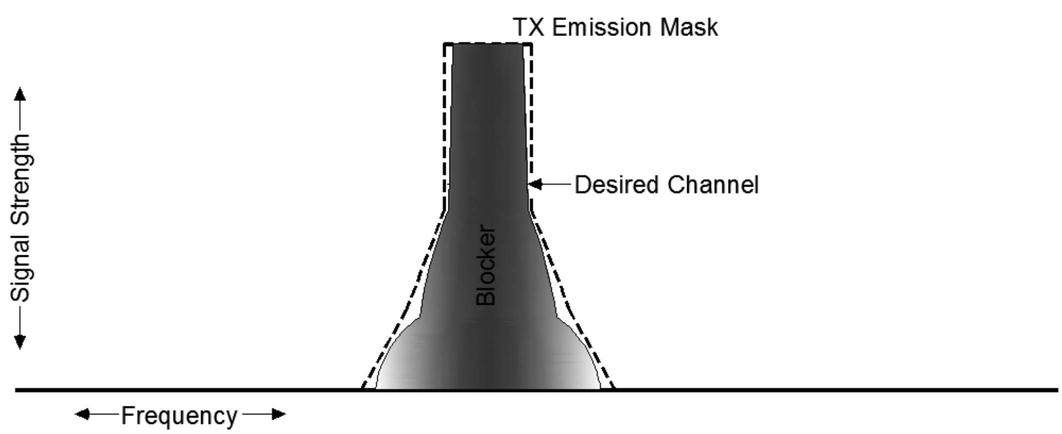

Figure 3.2 TX Emission Mask

Emission masks are typically defined in Federal Regulations and Industry Standards. The mask is determined by the needs of neighboring systems and operational scenarios. Figure 3.3 shows an example of a transmitted emission falling into a receive channel causing interference (referenced to the receiver's input).

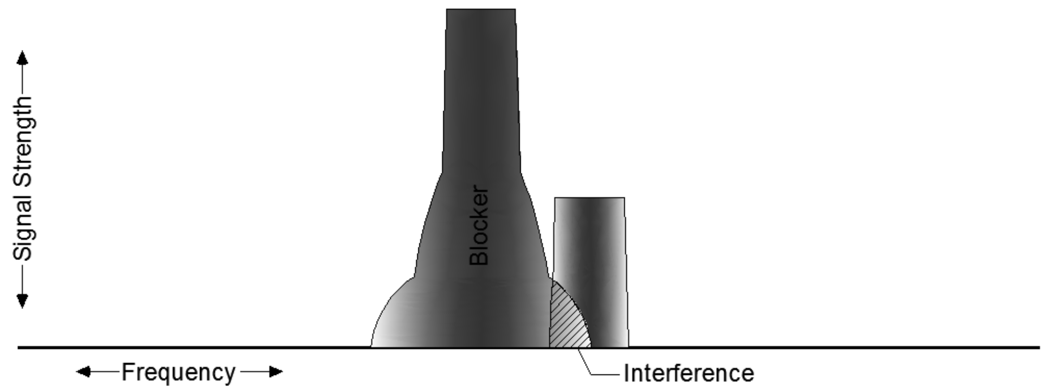

Figure 3.3 Interference due to TX Emissions

Transmitted emissions are due to practical considerations in the transmitter, such as power consumption, cost and size. Transmitted emission sources include both linear, nonlinear and noise mechanisms. Linear mechanisms consist of filtering, both in the channel and following the power amplifier. Nonlinear mechanisms consist of intermodulation and mixing products. Noise mechanisms consist of both thermal and phase noise. The actual transmitted emissions vary over the transmitter's dynamic range.

4. Regulatory Requirements and Actions

To make informed decisions about frequency allocations that maximize efficiency of spectrum use while still minimizing interference interactions between services, the FCC must be supplied with all of the tools that make prediction of levels of interference possible. In order to successfully do this, the Commission needs sufficient technical details about all of the affected services. This includes detailed information about the operations of such services, a prediction of the level at which interference will become harmful to each service, and quantitative modeling about the interactions between services over a wide variety of expected conditions.

Principle 7: ***Services under FCC jurisdiction are expected to disclose the relevant standards, guidelines and operating characteristics of their systems to the Commission if they expect protection from harmful interference.***

Prior to assignment of frequencies, the FCC needs to determine the compatibility between services in adjacent channels. The determination of compatibility requires information about the transmitters and receivers, as well as systems communication parameters. Typical questions that must be asked are: What is the maximum signal power needed for a successful link? What level of blocking immunity do the receivers have? What tools are available at the system level to correct for interference? What are the performance requirements for each system, such as maximum tolerable bit error rate, the minimum acceptable throughput, the maximum latency? With an appropriate list of such parameters, the Commission can decide on the compatibility of neighbor services to avoid harmful interference and also determine who is at fault if harmful interference does occur.

Transmitters and receivers need to provide their spectrum masks. Receivers should specify their level of protection from generating intermodulation, such as IP3. Locations of operation for both transmitters and receivers are important for estimates of potential levels of interference.

The FCC has traditionally required that transmitters utilizing a spectrum resource provide the important characteristics of the station, such as emission type, power level, height above average terrain, antenna gain, pattern, etc. as part of the licensing process. The information is usually made available as part of the public record. This information, aside from assuring compliance with a license, has provided information useful for enforcement and reconciliation of interference situations. When the transmitter details are compared to a receiver system at a "victim" location, it is possible to estimate whether the transmitter is operating within its license limits and what might be done to ameliorate harmful interference. Remediation has customarily taken the form of direct negotiation between the transmitting and impacted parties, occasionally with the assistance of the FCC.

Supplying additional detailed information about the operation of the receiver and the system may be considered to be proprietary by some services. To these entities it has to be made clear that the FCC can only work to prevent interference if they are given sufficient information. A spectrum user that refuses to provide such information cannot expect the Commission to provide as much protection from interference as it could with all of the details.

Increasing Automation of Interference Resolution

With full disclosure of information about system operation, neighboring services would also have the tools to solve interference issues, often without involving the FCC. The evolution of spectrum management toward sharing of resources among disparate uses, services, and operators and the necessity for increased security by some of the operations suggests the establishment of a more responsive "clearinghouse" repository for new band allocations. Such a repository could contain transmitter and receiver information with security and rapid access in which affected users could participate in a private Internet-based interactive measurement and resolution process.

With the advent of ubiquitous Internet connectivity, many transmitters (producing non-trivial power levels) and base, fixed, or nomadic receivers either have or can easily arrange for access to a real time clock and the capability to connect to a secure URL. In such an arrangement, a "victim" receiver could identify and contact a putative transmitter via the clearinghouse to set up a schedule when the transmitter operation could be temporarily modified while the affected receiver simultaneously determines interference presence or impact.

Such a quick-response interference management process could shift much of the reduction effort to the licensed user community and could include automated applications. This would speed interference determination, measurement, and resolution among users while providing more security for services that may reject making all detailed information available openly. It could also reduce the FCC enforcement load as the number of users engaged in new spectrum increases.

<u>Principle 8</u>: *The Commission may apply Interference Limits to quantify rights of protection from harmful interference.*

Harmful interference is affected by the characteristics of both an interfering (transmitting) service and an affected (receiving) service. For example, receivers that cannot reject interfering signals transmitted outside their assigned frequencies can preclude or at least constrain new allocations in adjacent bands. Efficient allocation therefore involves making trade-offs between receiver and transmitter performance.

While radio systems are entitled to protection from harmful interference, they must be able to reject non-harmful interference. The Commission therefore needs a way to communicate the limits of the protection to which systems are entitled. One way is to mandate receiver performance specifications; however, this has been very rarely used. Another way, recommended by the TAC[16], is *interference limits*, that is, quantitative descriptions of the interference environment in which a radio systems needs to operate successfully without being able to make a claim of harmful interference.

Interference limits provide benefits to both the Commission and wireless system operators by providing greater clarity about the entitlements that are, and are not, entailed in assignments. This will be particularly useful in bands with many, diverse and frequently emerging new technologies.

Interference limits can be promulgated by stating the out-of-band and in-band interfering signal levels that must be exceeded before a protected system can make a harm claim. Since the electromagnetic environment is unpredictable, interference limits will be statistical by their nature, for example being given as received signal levels not to be exceeded for more than some small percentage of locations and times, along with a confidence level at which signals exceeding the threshold would have to be demonstrated.

Interference limits policies have recently been adopted by the Commission: (1) as one of the conditions presumed to constitute harmful interference to SDARS operations from WCS operation[17] ; and (2) as the so-called Reception Limits that specify the amount of adjacent channel and in-band blocking interference that Priority Access Licensees must accept[18] .

Interference limits state the interference at the antenna input and make no reference to receiver operating characteristics; that is, they are not receiver performance specifications. Manufacturers and operators are free to determine whether and how to build receivers – and more generally, design their

[16] FCC TAC Receivers and Spectrum Working Group (2013). Interference limits policy - the use of harm claim thresholds to improve the interference tolerance of wireless systems. FCC Technological Advisory Council. http://transition.fcc.gov/bureaus/oet/tac/tacdocs/WhitePaperTACInterferenceLimitsv1.0.pdf

[17] 47CFR §27.64(d)(2)

[18] 47CFR §96.41(f)

systems of transmitters and receivers – that can tolerate such interference. An interference limit gives an operator the flexibility to decide best how to deal with the levels of interference it needs to tolerate, whether by improving receiver selectivity, deploying more base stations, using internal guard bands, or accepting occasional degradation in receivers that are not designed to operate effectively at interference levels below the limit.

The use of interference limits may require special consideration where receivers are not controlled by a license holder, or for life-safety systems like aviation and public safety. Alternative or additional measures may be required to ensure that devices that are brought to market in these cases can operate successfully in the presence of interference up to the specified limit.

The roll-out of interference limits to protect a particular service might follow a three step process. First, the Commission would identify frequency allocation boundaries where interference limits would bring value. Second, the Commission would encourage a multi-stakeholder consultation process to work out boundary issues and implementation choices, such as the parameters required, methods for determining interference limit levels, and enforcement mechanisms in cases of dispute. Third, if necessary, the Commission would use the record developed by the multi-stakeholder process as the basis for a Notice of Proposed Rulemaking to enshrine in regulation the interference limits agreed by the parties.

Determining Interference Limits

Interference limits would be determined on a case by case basis for new allocations; different bands would have different interference limits. Performance degradation as a result of interfering signals is system and scenario dependent; limits can be chosen to incorporate the needs of services being protected.

If the bands adjacent to a new allocation are already in use, and that use is not expected to change, the interference limit for the new allocation could be calculated (by measurement, modeling, and/or reference to industry standards) to reflect the characteristics of the current neighboring use. This will ensure that the neighboring incumbents' operations will not be deemed to be harmful under the new allocation's interference limit.

If one or both of a new allocation's adjacent bands are radio quiet (i.e. result in low signal levels at affected receivers) but are planned to be converted to more intensive use – for example, a band where an existing noise-limited service will relocated elsewhere, and be replaced by terrestrial mobile communications – the Commission would define interference limits that reflect the anticipated future interference environment, i.e. relatively higher signal levels. This would help licensees in the new allocation to set appropriately their expectations about future interfering signal levels that the Commission will deem to be non-harmful.

While interference limits are not receiver specifications, the ability of the system in the new allocation to tolerate interfering signals, including but not limited to the performance of affected receivers, will influence the level at which the limits are set. The 2013 TAC white paper on interference limits policy[19] discussed how interference limits (called harm claim thresholds in the paper) interact with receiver performance specifications; see Section 3.5 in that white paper and Figure 4.1 below. In short, interference limits are one of many inputs to a system design process and receiver performance specifications are an output.

As the dotted lines in Figure 4.1 indicate, the regulator's choice of an interference limit will most likely take account of the current or expected interference environment, which is in turn influenced by the deployment of transmitters in the same service, as well as transmitters in the interfering service.

Interference limits and the expected RF interference environment are two inputs to determining the RF interference that a system must tolerate. In the absence of interference limits, today's status quo, system designers have to estimate the likely interference environment around their receivers by making inferences from uncertain data like the likely transmit power of interferers and the likely deployment density of transmitters. However, as the figure shows, there are other design inputs that include quality of service requirements, cost constraints, industry standards and service rules such as maximum allowed transmit power. These factors are combined to yield an inter-related set of specifications for transmitter and receiver performance, transmitter deployment, etc.

The connection between receiver performance specifications and interference limits is indirect since receiver specifications refer to isolated devices, whereas interference limits apply to an RF environment. For example, receiver standards might specify the adjacent channel selectivity (ACS) of the receivers of the system that is seeking the protection of an interference limit. However, the ACS is usually specified at a single, relatively low received power level, and there is no indication of how often a receiver will be exposed to such a situation in practice; the specification therefore provides little guidance in determining an interference limit framed as the interfering level not to be exceeded for more than specified percentage of locations and/or times.

[19] FCC TAC Receivers and Spectrum Working Group (2013). Interference limits policy - the use of harm claim thresholds to improve the interference tolerance of wireless systems. FCC Technological Advisory Council. http://transition.fcc.gov/bureaus/oet/tac/tacdocs/WhitePaperTACInterferenceLimitsv1.0.pdf

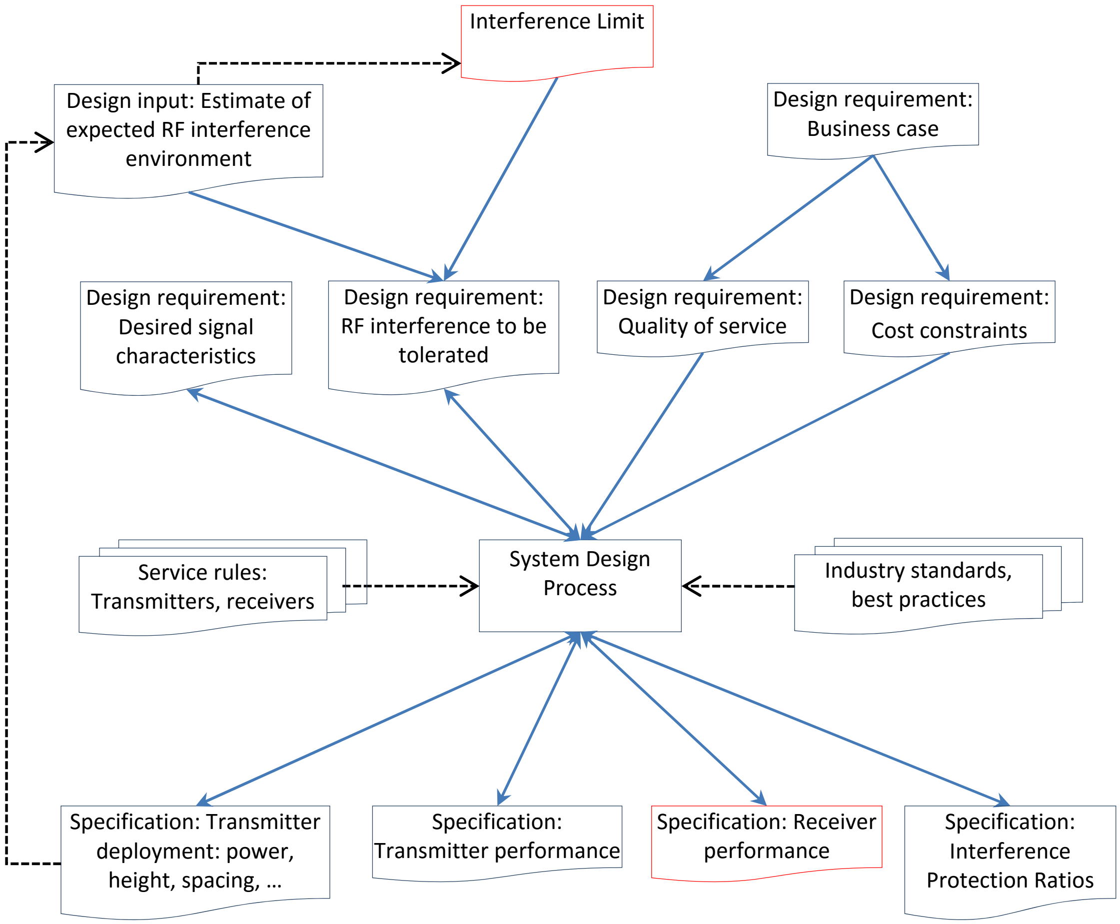

Figure 4.1: Relationship between interference limits, receiver performance and other factors

<u>Principle 9</u>: ***A quantitative analysis of interactions between services shall be required before the Commission can make decisions regarding levels of protection.***

Quantitative studies of the interactions between radio services in order to set interference limits, or to conduct inter-service coexistence or compatibility analyses more generally, require the development and assessment of often highly complex models. These models, or combinations of models, are based upon empirical, computational, and statistical techniques. For example, a model for predicting the strength of interfering signals at the antenna input of a receiver might involve models or assumptions for the transmission line losses at the transmitter, models for predicting the gain of the transmitting antenna based upon its physical and electric characteristics, and propagation models for estimating the signal attenuation between the transmitting antenna and the receiving antenna. The propagation model, in turn, may utilize inputs specifying the characteristics of the intervening terrain and/or clutter. Differences between models and their associated inputs used by the FCC and by diverse stakeholders may lead to widely different interference results and produce disputes leading to costly delays. To take a simple example, the model for predicting the strength of interfering signals just described may produce widely different results depending upon the assumptions regarding clutter along the intervening path(s), even if the model is otherwise identical.

Recommendation: Transparency & Reproducibility

As explained in more detail below, transparency and the reproducibility that it enables is (a) the essence of the scientific method, (b) a cornerstone of evidence-based decision-making and (c) critical to the improvement and refinement of interference models and studies including more sophisticated consideration of risk.

Reproducibility and thus credibility requires transparency about all the key elements of an analysis, including assumptions, model structure (e.g. formulas), data sets, and computation (e.g. computer code). It also applies to other technical activities such as testing, where the repeatability and verifiability of a testing regime and the results obtained can contribute to confidence in the regulatory outcome.

Given the ever-growing importance and complexity of these empirically-, computationally-, and statistically-based interference modeling techniques, the TAC therefore recommends that the FCC improve the transparency and reproducibility of the interference analyses underlying its major spectrum management policy and regulatory decisions.

Similarly, the TAC recommends that the FCC require or otherwise incentivize stakeholders and other participants in major spectrum management proceedings to provide comparable transparency and reproducibility in their pleadings and deliverables. As part of its work on Risk Informed Interference Analysis (RIIA), the Spectrum and Receiver Performance Working Group of the TAC discovered a lack of transparency in some of the past interference studies that regulators and policymakers have relied upon in making important spectrum allocation and assignment decisions. While this lack of transparency does not necessarily mean that the results of the studies or the decisions that relied upon them are flawed, the absence of adequate transparency produces at least two problems:

First, the essence of the scientific method is reproducibility. That is, enough information should be provided about an experiment or analysis so that the results can be validated by other researchers. Without adequate empirical, computational, and statistical information[20] on the research, it is difficult or impossible for other researchers to validate the results of the interference studies even though the results may have serious impact in terms of economic and social consequences and the safety of life and property. In short, in spectrum management, fact- or evidence-based policymaking is dependent upon transparency.

Second, transparency is critical to improving and refining models and studies that are based upon the empirical, computational, and statistical techniques described immediately above. With transparency, other researchers have the ability to identify, e.g., through sensitivity analyses, areas where

[20] For a more complete discussion of these terms see Victoria Stodden, *2014: What Scientific Idea is Ready for Retirement?,* EDGE, (November 2, 2015), https://edge.org/response-detail/25340.

improvements in interference models would have the greatest impact and, as in the case of the Working Group's efforts on RIIA, where the risk of harmful interference is particularly high or low. In short, transparency is essential in promoting improvements in interference analysis techniques.

Based upon these two findings, the Working Group came to the initial conclusion that the FCC should improve the transparency of the interference analyses underlying its major spectrum management policy and regulatory decisions and, similarly, that it require stakeholders and other participants in major spectrum management proceedings to provide comparable transparency in their pleadings. In reaching this initial conclusion, the Working Group observed that opaque (rather than transparent) differences between models, their embedded algorithms, and their associated inputs as used by diverse stakeholders with varied interests have led to widely different interference results and produced bitter disputes leading to costly delays.

While the Working Group recognized that the primary role of the TAC is to provide technical rather than legal analysis and advice, it did observe that its conclusion regarding transparency appeared to be consistent with the Office of Management and Budget (OMB) Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of Information Disseminated by Federal Agencies.[21] For example, the OMB Guidelines are intended to ensure that influential scientific, financial, or statistical information disseminated by agencies is sufficiently transparent in terms of data and methods of analysis that it would be feasible for a replication to be conducted.

In the Guidelines, OMB observes that:

> The primary benefit of public transparency is not necessarily that errors in analytic results will be detected, although error correction is clearly valuable. The more important benefit of transparency is that the public will be able to assess how much an agency's analytic result hinges on the specific analytic choices made by the agency. Concreteness about analytic choices allows, for example, the implications of alternative technical choices to be readily assessed. This type of sensitivity analysis is widely regarded as an essential feature of high quality analysis, yet sensitivity analysis cannot be undertaken by outside parties unless a high degree of transparency is achieved. The OMB guidelines do not compel such sensitivity analysis as a necessary dimension of quality, but the transparency achieved by reproducibility will allow the public to undertake sensitivity studies of interest.

In reviewing the OMB Guidelines, the Working Group noted that the FCC's implementation of the Guidelines reflected the same notions of transparency and reproducibility.[22]

[21] Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of Information Disseminated by Federal Agencies; Final Guidelines (corrected), 67 Fed. Reg. 8452 (February 22, 2002), *available at* https://www.whitehouse.gov/sites/default/files/omb/fedreg/reproducible2.pdf.

[22] *Implementation of Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of Information Pursuant to Section 515 of Public Law No. 105-554,* FCC 02-277, Information Quality Guidelines (adopted Oct. 4, 2002), *available at* https://apps.fcc.gov/edocs_public/attachmatch/FCC-02-277A1.pdf.

The Working Group also observed that its conclusions regarding the benefits of transparency is entirely consistent with the Commission's existing policies of requiring that advocates provide detailed information about cost models in the context of Universal Service. That requirement arises from the 2011 *USF/ICC Transformation Order,* which encouraged stakeholders to participate in the process of determining the design and operation of the cost model governing Phase II of the Connect America Fund (CAF).[23]

In the referenced Order, the Commission also cited a previous statement it had made that "all underlying data, formulae, computations, and software associated with the [cost] model must be available to all interested parties for review and comment. All underlying data should be verifiable, engineering assumptions reasonable, and outputs plausible."[24] Finally, the Order promised that before the cost model to be used was implemented, the Wireline Competition Bureau (WCB) would "ensure that interested parties have access to the underlying data, assumptions, and logic of all models under consideration, as well as the opportunity for further comment."[25] It also directed the WCB to "request … parties to file models for consideration in this proceeding consistent with this Order," implying that advocates of a particular cost model must also make their underlying data and computations available for analysis.[26]

The Working Group found that Universal Service reform and improved spectrum management are two of the Commission's most important efforts and that transparency and the broad public interest benefits it produces are equally important in both contexts. The Working Group also noted that if, for some reason, the Commission was hesitant to require transparency and reproducibility in the spectrum management/interference analysis context, it could, in an interference dispute, simply note that it would give more weight to evidence presented in a transparent and reproducible form. Doing so would incentivize stakeholders and other participants in major spectrum management proceedings to provide comparable transparency in their pleadings.

5. Examples

It is instructive to consider examples of communications services that have followed the concepts of the principles presented in this paper as well as those that have not.

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[23] *Connect America Fund, A National Broadband Plan for Our Future, Establishing Just and Reasonable Rates for Local Exchange Carriers, High-Cost Universal Service Support,* WC Docket Nos. 10-90, 07-135, 05-337, 03-109, GN Docket No. 09-51, CC Docket Nos. 01-92, 96-45, WT Docket No. 10-208, Report and Order and Further Notice of Proposed Rulemaking (adopted Oct. 27, 2011), *available at* https://apps.fcc.gov/edocs_public/attachmatch/FCC-11-161A1_Rcd.pdf [hereinafter USF/ICC Transformation Order].

[24] *State Forward-Looking Cost Studies for Federal Universal Service Support,* CC Docket Nos. 96-45, 97-160, Notice, 12 FCC Rcd 8915 (1998), *available at* https://transition.fcc.gov/Bureaus/Common_Carrier/Public_Notices/1998/da980217.txt.

[25] *USF/ICC Transformation Order,* ¶ 192.

[26] *USF/ICC Transformation Order,* ¶ 192.

Example 1: ***The Cellular Near-Far Problem***

An example of services on adjacent frequency channels working together to minimize the interference between them is found in the cellular industry with regard to the near-far problem. In this case both service providers readily acknowledge the presence of interference with their neighbors and work cooperatively to minimize its effects.

The received signal level of a cellular handset is a function of its location within a cellular system. An example of levels (assuming a 3G system), is shown below;

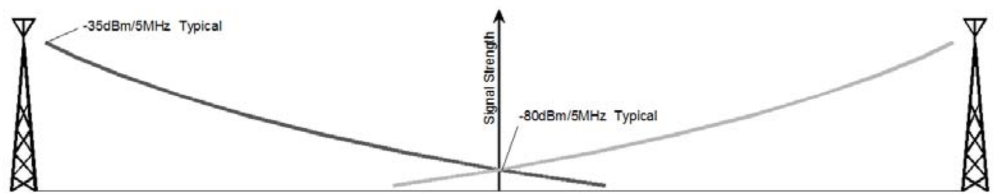

Figure 5.1: Influence of two cellular base stations on a handset located between them.

Cellular spectrum is usually divided into blocks, which are allocated to multiple operators in the same region. An example is the US 800 MHz Cellular Band, which is divided in two portions, Block A and Block B, as shown below;

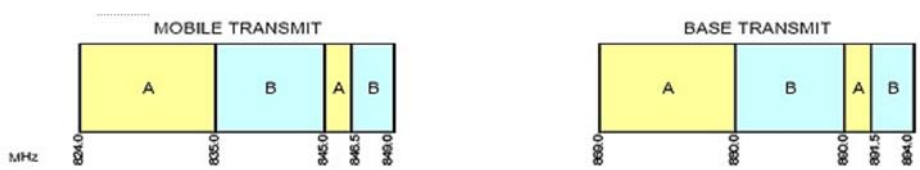

Figure 5.2: The layout of the 800 MHz Cellular Band

Cellular Handsets are limited in their ability to reject signals (i.e. Blockers) on adjacent channels. This is termed Adjacent Channel Selectivity (ACS) and defines the Receiver's Blocking Mask in adjacent channels. The typical ACS value for a consumer handset is 33dB. Higher ACS performance impacts the handset cost, size and power consumption (i.e. talk time & standby time), all very sensitive and visible parameters to the consumer and operator.

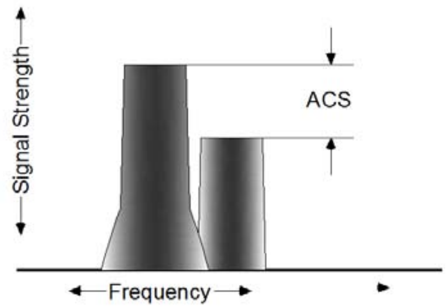

Figure 5.3: A cellular telephone's ACS in the presence of a strong adjacent channel signal.

The potential for exceeding the Handset's ACS ability in split cellular bands can be a common occurrence. An example of such a scenario is shown below, using the heavy black lines to denote the desired signal (from the Handset's perspective) and light gray lines as the service on the adjacent channel.

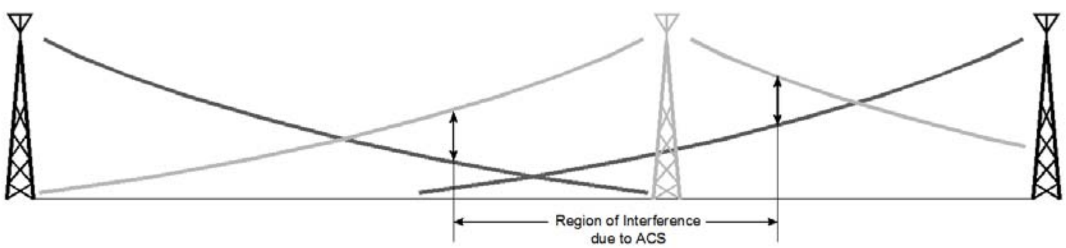

Figure 5.4: An example of how a cellular telephone's ACS can be exceeded. Whenever the telephone is located nearer to a cellular base station that is transmitting on the adjacent channel than to the cellular base station that is transmitting on the telephone's channel, the potential for interference exists.

This interference is commonly referred to as the "Near-Far Problem," where the Handset is far from the serving transmitter and near the Transmitter on the adjacent channel. This can occur at the boundary between allocated blocks.

The solution used in the cellular industry is to co-locate the transmitters as shown below. Service providers with adjacent channel allocations negotiate the location of their base stations in order to minimize the near-far problem.

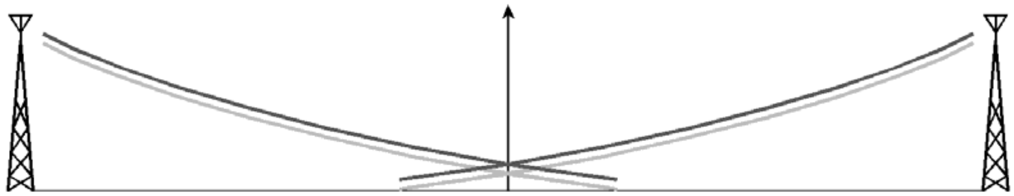

Figure 5.5: An example of how cellular providers cooperate to avoid telephone ACS interference.

Example 2: ***Aggregate Interference Analysis for Coexistence***

Some coexistence scenarios need evaluation of aggregate interference to determine the ability of a service to coexist with another in a co-channel or an adjacent channel situation. A recent example of this is the AWS-3 uplink band, where the LTE uplink occupies the same band as the receivers on earth stations belonging to the meteorological satellite service. This situation was analyzed by NTIA CSMAC WG-1 and has been re-evaluated in a study within the Spectrum and Receiver Performance working group of the FCC TAC. In that situation, the analysis has resulted in the definition of protection zones around the earth stations, such that the sum total of expected interference represented as an I/N ratio from all mobiles connected to AWS-3 base stations operating in the 1695-1710 MHz band has been below an acceptable threshold.

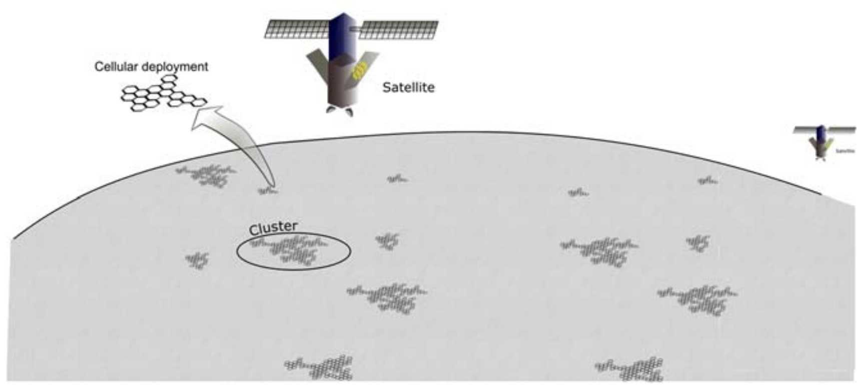

Figure 5.6 Aggregate interference effects in aeronautical and satellite services have to account for the effect of multiple co-channel transmitters

More complex scenarios may be imagined for aggregate interference situations. A particularly interesting one is the situation involving the operation of mobile services in the same band or a band adjacent to the aeronautical services or satellite services, where the high altitude receiver is used for receiving ground transmissions or inter-platform communications. In the case of 5G systems, mobile services may be allocated in the Ku band, in proximity to satellite services or in a co-primary sharing arrangement. Many bands of interest to existing mobile services also coincide with, or are in proximity to bands allocated to aeronautical sensing and telemetry or satellite services. 5.6 provides an illustration of a typical scenario where city-scale or town-scale clusters of mobile cellular deployments are distributed on the surface of the earth, these deployments appearing in view of a satellite or airborne platform. A satellite may have a view of large parts of a country, while a high altitude platform like a drone may be able to receive radio signals from thousands of square kilometers. The aggregate effect of a single cluster on the ground would be to act as a composite secondary antenna that appears at some height in the atmosphere above the deployment. There are many ways to model the effect of many uncoordinated radiators though and the ease of modeling the coexistence scenario must be accounted for. The equivalent virtualized transmitter would have characteristics that must account for the following effects:

1. The effect of ground clutter and terrain at the surface, including the variation in deployment density due to population density,
2. The expected traffic density in the near term and the expected growth over time,
3. In the case of indoor systems, the possible effect of wall loss or the effect of radiators that have a view of the external environment through windows,
4. The effect of antenna down tilt, the use of beam forming or sectorization, and the subsequent signal attenuation in directions towards the satellite systems,
5. The impact of deployments in cities where intentional radiators may be installed in high rise buildings and the azimuthal orientation of radiators towards the orbits of the satellites or airborne platforms.
6. The variation in loading due to realistic traffic models, resulting in a fraction of the deployments radiating energy.
7. Atmospheric effects due to low elevation angles from the surface,
8. The normalization of propagation models used for the terrestrial system and the high-altitude systems so that there are no discontinuities in the assumptions.

It is essential to bring realism into modeling of coexistence scenarios. The Commission can play a very important role in balancing the biases that creep into analyses provided by vested interests in the industry and to impose a rational approach to risk assessment. Industry can likewise help by providing technical expertise to coexistence studies hosted by the FCC after initial notices of inquiry, where points of disagreement are eliminated and specific agreements reached regarding evaluation methodology. In all these matters, it is useful to have the FCC influence the course of discussions in a way where worst case analyses, when applicable, are used only to determine the consequences of harmful interference, and tested statistical techniques to assess risk are used to perform a thorough assessment of the impact of mixing different services in the same or nearby bands.

6. Summary

We have presented nine basic principles that, when followed while making frequency allocations, will lead to more efficient and effective use of the spectrum. It is in the best interests of both society and users of the spectrum that this be implemented wherever practical.

The nine principles are categorized into three groups. The first group contains realities of communications physics with respect to interference. If users of the spectrum accept these facts then they are less likely to have unreasonable expectations. The principles make clear that interference is not simply one signal impinging another but is a more complicated relationship between a transmitted signal, the characteristics of a receiver, the frequencies on which both devices operate, the spatial distance between them and the times at which they operate. A very important realization that spectrum users should have is that operating conditions are rarely constant and even if little interference is detected today, varying propagation conditions and new frequency allocations can change that in the future. Systems should be designed to be able to operate properly under expected conditions even if they are not evident right now.

The second group of principles deals with responsibilities of the different services to minimize the effects of interference with each other. The FCC has regulations that require transmitters to limit the amount of their energy that goes outside of their assigned channels. However, such requirements are upper limits of allowable spurious signals. If a transmitter is capable of further decreasing the levels of its spurious emissions then it should do so in order to be a good neighbor to other services. The FCC does not have regulations that require a receiver to reject any other signals in the spectrum but it is in the receiver user's best interest to make use of current technology to minimize interference. Improvements to both types of devices are often expensive to implement, and cost is a valid consideration when planning communications systems. However, if it is decided that interference avoidance now as well as in the future is more important than the additional cost then such design changes should be performed. System design techniques that may not lead to much additional hardware cost can also be considered in order to deal with current or potential future interference. Such techniques affect the operational aspects of the communications and may affect such things as data throughput but if such concessions are acceptable then the ability to withstand interference is enhanced.

The third group of principles is directed toward the FCC. In making decisions about allocating frequencies to services the Commission must consider the capabilities of incumbent services as well as those of the new services. To properly perform their tasks, the regulators need to know as much information about the services as possible. With specific definitions of the operating requirements and behavior of the equipment and systems being used, an optimal choice of frequency allocations that will avoid harmful interference can be made. With sufficient information the FCC can choose the optimal frequency and physical spacing between systems so that maximum use is made of the spectrum while at the same time systems will operate as expected in the presence of the inevitable interference. To protect the services from harm, the same information can be used to calculate interference limits, which would then be used as an objective measure for enforcement purposes.

Considerable calculation is required to arrive at these goals. Many different modeling algorithms exist to help with this process. Every modeling program requires that operating assumptions be made in order to arrive at a prediction of the behavior of systems. The large number of choices of modeling and assumptions often leads to considerable variation in the results. For the FCC to effectively make use of modeling results, the methods and values used to arrive at the results must be presented transparently.

The interaction between two services cannot be accurately determined if each service provides modeling results that were arrived at in different ways. However, with full transparency of the modeling methods, the results can be combined and reproduced to confirm the expected operation once the systems are realized.

The application of these principles does not preclude operational harmonization between users in adjacent channels. Despite the best efforts of modeling before a system is deployed, it is sometimes difficult to account for effects on systems once they are placed in different environments. Effects such as reflections from structures, terrain variations, and seasonal changes to flora can result in the signal levels not being as predicted during the design phase of a system and interference to adjacent channels may occur unexpectedly in certain locations. If a user finds that it must impinge on the frequency space of its neighbor because of unexpected effects of the environment, the two services can enter a form of Coasian bargain and agree to modify their operations as necessary to prevent harmful interference from occurring.

Through the application of these nine principles, we can expect that the spectrum will be used in an efficient and effective manner. This does not mean that a standard set of regulations can be adopted to realize this goal. The many differences between the requirements of various types of systems that use the spectrum will not permit such standardization of regulations. Yet the same principles can be applied to all systems to result in an optimal solution for each service.

Acknowledgements

The Principal Author would like to thank the following co-authors who provided text for this document: Kumar Balachandran, Pierre De Vries, David Gurney, Dale Hatfield, Bruce Judson, Stephen Kuffner and Robert Miller.