Interference Limits Policy

The use of harm claim thresholds to improve the interference tolerance of wireless systems

White Paper

Receivers and Spectrum Working Group*

FCC Technological Advisory Council

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1. Executive Summary

In order to meet the growing demand for wireless service, the number of wireless systems that operate in close proximity in frequency, space and time needs to increase. Closer packing brings many benefits, including increased access, new services, and device innovation. However, tighter proximity also increases the risk of service disruptions due to inter-system interference.

Increased density requires more care in optimizing the whole wireless system structure, particularly regarding the interactions between transmitters and receivers on either side of band boundaries. Increased signal strength from transmitters allows better service, but requires receivers to be able to reject unwanted signals outside their allocated frequencies, and such interference tolerance comes at a cost. Further, as regulators strive for more intensive use, they no longer have the luxury of always being able to place like services with like services; they increasingly need to place new services in bands not previously allocated to that category of service. Thus, receivers that cannot reject interfering signals transmitted outside their assigned frequencies can preclude or constrain new allocations in adjacent bands. A holistic system view that facilitates trade-offs between receiver and transmitter performance requirements is needed. However, radio operation has traditionally been regulated solely based on using limits on transmitters, with few if any explicit constraints on receivers.

Receivers can be brought into the policy picture with minimal regulatory intervention by introducing an "interference limits" policy; that is, the establishment of ceilings, called *harm claim thresholds*, on in-band and out-of-band interfering signals that must be exceeded before a radio system can claim that it is experiencing harmful interference. Manufacturers and operators are left to determine whether and how to build receivers that can tolerate such interference, or even determine that they will choose to ignore these limits. Harm claim thresholds thus allow the FCC to provide guidance on the optimization of receiver performance without unduly restricting technical and commercial choice.

While transmit rights are usually defined in terms of radiated power (specified in watts or, using logarithmic units, dBW or dBm) and an emission mask that defines the relative power of out-of-channel emissions, interference limits would be defined in terms of field strength density or power flux density (dBμV/m per MHz or dBW/m^2 per MHz, respectively) at a percentage of locations and times within a service area, units similar to those used for television service contours. The limits would be defined both over a service's assigned frequency range, and some range of frequencies outside it. Limits represent threshold conditions for claims of harmful interference, and are not intended to capture specific interference situations. Performance degradation as a result of interfering signals is system and scenario dependent; limits can be chosen to reflect incumbent needs, and services would then make their own system design decisions that take the limits into account.

Harm claim thresholds provide benefits to both the FCC 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, provided that the new technologies do not exceed assumptions, such as peak to average power ratio built into the thresholds. They can facilitate the transition to more intensive frequency use by providing service providers with more clarity about the baseline regulatory and radio interference context going forward. The approach also delegates decisions about system design, including receiver performance, to manufacturers and operators. It 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 given their choice of receiver design. The private sector will play a key role in developing receiver specifications and standards that ensure adequate performance given the harm claim thresholds of a particular allocation.

Application of harm claim thresholds may require special consideration in cases where receivers are not controlled by a license holder or for life-safety systems like aviation and public safety. Alternative measures may be required to ensure that large numbers of devices, or safety critical devices that are not operating within their prescribed harm claim thresholds, do not prevent the introduction of adjacent channel services compliant with the harm claim thresholds.

The roll-out of interference limit policy-related rules and regulations might follow a three step process. First, the FCC would identify frequency allocation boundaries where harm claim thresholds would bring immediate value. Second, the FCC would encourage a multi-stakeholder consultation process to work out boundary issues and implementation choices, such as the parameters required, methods for determining harm claim thresholds, and enforcement mechanisms in cases of dispute. Third, if necessary, the FCC would use the record developed by the multi-stakeholder process as a thorough basis for a Notice of Inquiry and/or Notice of Proposed Rulemaking defining what would be the harm claim thresholds to the rules for a new assignment.

We recommend that the FCC begin to evaluate the harm claim thresholds policy approach. The following actions can be implemented in parallel:

1. The FCC should encourage the formation of one or more multi-stakeholder groups to investigate interference limits policy at suitable high-value inter-service boundaries.
2. The FCC should issue an appropriate request for input on the implementation of the interference limits policy.
3. The FCC should, where necessary, develop the expertise and gather the relevant data to facilitate the establishment of harm claim thresholds at high value inter-service boundaries.

The rest of the paper is structured as follows: Section 2 provides an introduction to the topic by surveying U.S. receiver policy to date; more detail on prior work and the role of receivers in interference management is given in the Appendix, Sections 9.1 and 9.2. Section 3 describes the principles, benefits and limitations of interference limits policy. Section 4 provides brief examples of how interference limits policy would be applied by describing how harm claim thresholds could be developed for cellular, television and satellite services; more detail is given in the Appendix, Section 9.4. Section 5 outlines the institutional actions that could be used to implement such a policy approach, and Section 6 discusses how the policy would be enforced. Section 7 outlines alternatives to setting harm claim thresholds, and Section 8 provides recommendations for FCC action. The appendices in Section 9 include material on prior work, interference mechanisms, receiver performance specifications, a comparison with interference temperature, an analysis of the 800 MHz SMR/public safety interference case, and some background on Multi-stakeholder Organizations.

2. Introduction

To meet the rapidly increasing demand for wireless capacity, wireless systems must operate in ever closer proximity in frequency, space and time. In addition, closer proximity of potentially dissimilar services increases the risk of service interruptions. Degradation of system performance is caused by insufficient interference tolerance in a system's receivers as much as by higher desired and undesired energy radiated by an adjacent system's transmitters.[1] In the United States, operation has traditionally been regulated using limits on the radiated power of transmitters, with few if any explicit requirements on receiver operation. However, receivers that cannot reject moderate interfering signals transmitted outside their licensed frequencies can preclude new allocations in bands adjacent to them, as the U.S. experience with the AWS-1/AWS-3 and GPS/mobile satellite service bands has shown.

Achieving the critical socio-economic objective of maximizing the value of wireless operation by closer packing of diverse services in a limited range of highly desirable frequencies is thus obstructed by the absence of ways to explicitly make cost-benefit trade-offs among transmitters and receivers in adjacent operating bands. Receiving systems that cannot reject interfering signals transmitted outside their licensed frequencies can preclude or constrain new allocations in adjacent bands. This paper proposes a way to bring receivers into the regulatory picture by using harm claim thresholds, a specification of the interfering signal levels that receivers need to be able to tolerate in order to work properly in a densely populated spectral environment.

Increased density requires more care in optimizing the whole system, particularly the interactions between transmitters and receivers on either side of band boundaries. For example, increased signal strength from transmitters allows better service, but requires receivers to reject unwanted signals outside their allocated frequencies, and such interference tolerance comes at a cost. (In the case of most commercial wireless systems like cellular, however, there is fortunately a trend to reduce the transmitted signal power by decreasing the distance from the receiver to the transmitter.) As regulators strive for more intensive use, they also no longer have the luxury of always being able to place like next to like, i.e. a collection of only low field strength services in one frequency range and high intensity ones in another; they increasingly need to place new services in bands not previously allocated for higher intensity use and that may become opportunistically available.

Receiving systems that cannot reject interfering signals transmitted outside their licensed frequencies can preclude or constrain new allocations in adjacent bands. A system view that facilitates trade-offs between receiver and transmitter characteristics is required. However, radio operation has traditionally been regulated using limits on transmitters, with few if any explicit constraints on receivers.

There have been many cases where receiver performance was a significant issue limiting the regulator's ability to allocate spectrum for new services that deliver higher undesired signal levels in adjacent bands than current systems can accommodate. The NTIA's comment on the Receiver NOI (NTIA 2003) enumerated "a number of instances of reported interference that could have been avoided if appropriate receiver standards had been applied," and the FCC

[1] It is worth noting that there are two distinct uses of the term "interference." Engineers typically use the term to connote a signal level, whereas in regulatory use it refers to the impact of a signal level on a system's performance. The regulatory meaning derives from the definitions in Article 1 of the ITU radio regulations. In this paper, we will follow the engineering usage; thus, the term "interference limit" refers to a signal level, not the response of a system to the presence of interference at that level. The ITU definitions are incorporated in 47 CFR § 2.1(c):

- *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.
- *Harmful Interference*. Interference which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with [the ITU] Radio Regulations.

Technological Advisory Council's white paper on Spectrum Efficiency Metrics provides additional examples (FCC TAC 2011, Appendix C); see the Appendix, Section 9.39.2 below for more information.

Receiver performance needs to be considered along with transmitters in determining the value that society can obtain from radio operation. A change of regulatory approach that defines the circumstances under which receivers can claim harmful interference is a necessary complement to existing transmitter regulation, and will encourage operators to apply the latest technology to improve receiver selectivity and decrease harmful interference. This paper proposes an approach based on specifying the level of third party interference that must be exceeded before services can make claims of harmful interference.

While the responsibility for interference ("unwanted effects") is shared between transmitters and receivers, and the existence of interference does not determine who is responsible for its mitigation, radio regulation has traditionally placed the onus on a new transmitter to fix any problems that may arise. The guiding principle in U.S. regulation is that new allocations, and particularly newly entering transmitters, should not cause harmful interference.[2]

Although regulation to minimize interference has traditionally focused only on transmitters, receivers have received some attention, such as the RF Monolithics contract to design and fabricate a TV receiver for the FCC "to demonstrate the feasibility of a cost-effective, high performance system that would permit greater utilization of spectrum currently allocated to UHF television broadcasting" (Ash 1984), and the recommendation of the Spectrum Policy Task Force (SPTFR, see Kolodzy et al. 2002) that "the Commission shift its current paradigm for assessing interference – based on transmitter operations – toward operations using real-time adaptation based on the actual RF environment through interactions between transmitters and receivers." However, to date regulators have focused on specifications of receiver performance rather than the characteristics of the radio signal environment.[3] The SPTFR recommended that "The Commission should consider applying receiver performance requirements for some bands and services" ("SPTFR", Kolodzy et al. 2002), and the 2003 Notice of Inquiry regarding receiver performance recognized that the "incorporation of receiver performance specifications could serve to promote more efficient utilization of the spectrum" (FCC 2003a). The NTIA stated in its 2003 comment on the Receiver NOI that it "believes that receiver designs that do not take into account their operational environment are often vulnerable to interference from non-cochannel signals because of inadequate selectivity or other unwanted signal suppression provisions" (NTIA 2003). The 2004 Report and Order in the 800 MHz proceeding set minimum receiver performance criteria that were required for non-cellular licensees to be entitled to full protection against "unacceptable interference," a concept introduced for the purposes of this proceeding only (FCC 2004b).

Receiver performance requirements set by the regulator, often known as receiver standards and referred to in this paper as receiver mandates, have been suggested over many decades as a way to manage receivers (e.g. Ash 1984, FCC 2003a). While they could in theory ensure that receivers can operate in a given interference environment, they have been controversial because of (1) the view that government should leave setting technology standards to technologists (e.g. CEA 2003); (2) the experience that standards, no matter how simple and generic at the outset, inevitably become complicated and technology-specific (Maior 2012, section 3.4.4); and (3) a concern that such standards increase the cost of receivers for consumers and reduce the opportunity to innovate (Maior 2012, section 3.4.3). However, there may be cases where the regulator can use receiver performance requirements proposed by

[2] 47 USC § 303(y) (2) (C): The Commission has the authority to allocate electromagnetic spectrum provided, among other things, that "such use would not result in harmful interference among users." 47 CFR § 2.102 (f): "The stations of a service shall use frequencies so separated from the limits of a band allocated to that service as not to cause harmful interference to allocated services in immediately adjoining frequency bands."

[3] The DTV transition represents a somewhat unique case where changing the RF environment also led to improved receiver performance. Improved receiver performance was a major consideration in the transition to DTV. Planning the DTV system went well beyond the RF Monolithics project of improving taboo channel performance and eliminated entirely the consideration of taboo interference for DTV receivers.

industry as a pre-condition for interference protection, as occurred in the 800 MHz band (see Section 7.2.1, and Appendix Section 9.6). In this case, receiver specifications were not mandated, and receiver protection rights were explicitly conditioned on their ability to cope with interference.

The Working Group believes that the FCC can increase service density, reduce regulatory risk and encourage investment with simple rules that make clear in which situations receivers and/or transmitters will bear the cost of mitigating any harmful interference, and doing so up-front rather than after lengthy post-dispute proceedings. More directly, rules that state explicitly when receivers may and may not claim harmful interference are a necessary complement to existing transmitter regulation. They can facilitate the transition to more intensive frequency use by providing service providers more clarity about the baseline regulatory and radio interference context going forward.

This paper focuses on explaining how *harm claim thresholds*, i.e. ceilings on the interfering signals that must be exceeded before a receiving system can claim harm, would improve coexistence without necessarily requiring the regulator to specify receiver standards that constrain technical and commercial innovation.

3. Interference Limits Policy

A guiding principle of this paper is that the number of interference disputes that require FCC resolution can be reduced if the responsibility to mitigate harms from interference is more clearly assigned, that is, if lines are more clearly drawn between the rights of transmitters and receivers.[4] In particular, clearer signal strength thresholds above which receivers may claim protection from harmful interference can obviate FCC-mandated receiver performance specifications. Harm claim thresholds provide incentives for operators to improve receiver performance on a voluntary basis, whereas receiver mandates require improvement.

As described in the NTIA report TR-03-404, Section 7.1.1 (Joiner 2003), the two main regulatory tools for influencing receiver performance are “describ[ing] the ‘standard’ environment(s) in which the receiver must be designed to operate” and “specif[ying] minimal performance requirements for various receiver parameters.” The NTIA report uses the term “receiver standard” to refer to both approaches, and sometimes only to the specification of receiver performance.[5]

The preferred use of the term standard is to refer to voluntary documents developed with appropriate due process on a consensus basis by groups of materially affected parties. The American National Standards Institute has established requirements for the due process associated with American National Standards. Unfortunately, the term standard is sometimes used to refer to government mandated performance, as in required “energy efficiency standards.” The same is true in the historical discussion of the relationship of receivers to spectrum efficiency when there have been calls for receiver standards with the intent being to mandate specific receiver performance metrics. Because voluntary standards are an important tool in documenting transmitter/ receiver systems and improving spectrum efficiency, this document uses the term standard in the traditional sense and mandate where direct regulation is intended.

In this paper we will therefore use the term *receiver standards* to refer to receiver performance requirements developed by standards organizations, and the term *receiver mandates* to refer to receiver performance requirements

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[4] Some scholars disagree that this is the most effective remedy. Hazlett & Oh (2012) argue that poorly assigned use rights, not poor rights definitions, are not the root cause of interference problems, and Tenhula (2012) argues that enforcement, not rights definition, is the most important tool in addressing interference problems.

[5] The term “receiver standards” is sometimes applied to managing receivers generally including through specifying the radio interference environment, and sometimes only to receiver performance requirements. Second, the term “standard” sometimes denotes a performance requirement, and sometimes to an established norm or requirement about technical systems that has been developed privately by a company or collectively by an industry or group of stakeholders.

(which may or may not have been developed by standards organizations) that are required by rule or statute. We use the term *receiver specification* to describe receiver performance requirements in general, whether developed by an individual manufacturer, standards organization (i.e. receiver standards), or the regulator (i.e. receiver mandates).

Each approach has strengths and weaknesses. In short, conformance of a device to receiver specifications is easily tested, but specifying them entails understanding and specification of service assumptions; whereas defining the environment in which receivers operate (such as the interference limits policy approach described below) necessitates a short list of parameters that does not entail a specific service, and that delegates system design trade-offs to operators, but enforcement of claims requires that resulting signal strengths be measured or modeled in the geographical area of the dispute. The two are linked, as explained in Section 3.5: for example, receiver specifications derived from interference thresholds by multi-stakeholder groups can ensure that devices function adequately up to the harm claim threshold. Receiver specifications can and arguably should be developed and managed by industry (e.g., standards bodies and ad hoc multi-stakeholder groups); regulatory receiver mandates will be rare.

Until now, expectations of receiver performance have almost always been implicit and often based solely on the ability of the receiver to perform its desired function in the context of the existing spectral environment. This has often led to downstream conflict due to a change in the environment and / or a differing understanding of requirements. For example, various parties drew different conclusions about the implied performance requirements for GPS receivers. This situation led to a conflict between GPS users and LightSquared, Inc. over potential harmful interference between services and became a public debate after LightSquared was given preliminary authority to operate terrestrial cellular transmitters in the mobile satellite service band just below the radionavigation satellite service band that includes GPS.

Receiver performance requirements mandated by the regulator, often loosely referred to as receiver standards, have frequently been put forward by advocates as a way to clarify the interference tolerance expected of receivers. While such mandates might ensure that receivers operate satisfactorily in a given interference environment, and have indeed been used occasionally, they have been controversial because they are very detailed and embed many assumptions about service models and system design into regulation, because of concerns that they increase costs and constrain innovation and because of a belief that regulators should minimize directly influencing design decisions. Interference limits do not mandate receiver performance and would leave design decisions in the hands of engineers and manufacturers. The implications of those decisions should be in the hands of those who procure and use the resulting wireless systems. In addition, regulatory approaches that require very detailed and/or codified assumptions about various modulation types, receiver performance specifications, and the exact services that are interfering with each other quickly become onerous when many different services and devices are established in nearby bands.

The harm claim threshold approach is based on stating a received signal strength profile that, if exceeded at a specific percentage of locations and times within a measurement area, allows a claim for harmful interference to be made; or conversely, the interference below which an assignee has no enforcement recourse at the FCC.[6] We use the term harm claim threshold to describe this set of parameters.[7] The threshold would be part of the operating entitlement of a wireless operator, e.g. a licensee or license-exempt system element, just as an assignment today has limits on the maximum allowed transmit power.

[6] This probabilistic approach resembles the regulatory framework for evaluating TV service coverage and interference, as described for example in OET Bulletin No. 69 (FCC 2004a). For digital television stations, for example, service is evaluated inside contours determined by DTV planning factors in combination with field strength curves derived for 50% of locations and 90% of the time. Service and interference data are calculated for cells 1 or 2 kilometers on a side.

[7] Since harm claim thresholds are the essence of the interference limits policy approach, we will use the terms “harm claim threshold” and “interference limit” interchangeably.

Interference limit policies are ways to describe the environment in which a receiver must operate without necessarily specifying receiver performance. Harm claim thresholds, the focus of this report, are a particular interference limit policy approach. Other examples of interference limits policy include the minimum receiver performance requirements in the 800 MHz public safety proceeding that amount to an interference limit (FCC 2004b, ¶ 109); the ground power limits on signals from WCS systems (FCC 2012b, ¶ 4); and the proposal of Kwerel & Williams (2011, 2012) that future allocations should "self-protect" against projected adjacent band interference by assuming a cellular service in the adjacent block. The Spectrum Policy Task Force Report's interference temperature concept (Kolodzy et al. 2002) is also arguably an interference limit policy, although it focused on creating additional co-channel operating rights rather than managing non-cochannel interference.

The interference limits approach does not directly attempt to distinguish between "good" or "bad" receiver performance. Operators, manufacturers and industry groups develop specifications for receiver performance given expectations about interfering signal levels (which may include harm claim thresholds), and these specifications and standards will then constitute a way to distinguish between receivers. More generally, the interference limits approach gives an operator the flexibility to decide how to best deal with the levels of interference it needs to tolerate, whether by improving receiver selectivity, increasing the strength of the desired signal at the receiver by deploying more base stations, moving a service away from the frequency boundary where necessary, or accepting the risk that their service will suffer occasional degradation given their choice of receiver design.

3.1. Harm Claim Thresholds

A harm claim threshold is a profile, called E, of field strength, or equivalently power flux density[8] (in customary logarithmic units dB(μV/m) per MHz or dB(W/m^2) per MHz, respectively)[9] that a service must be able to tolerate without recourse to a harmful interference claim, defined over frequency, both in-block and out-of-block, not exceeded at more than p_{loc} locations in any verification area in the licensed operating area, at more than p_{time} percentage of times in a specified verification window (Figure 1).

Since field strength varies with height, the measurement altitude should be given. A harm claim threshold will specify a reference antenna type and height(s); typical measurement heights are 1.5 m above ground level (e.g. for interference into hand held or fixed user equipment) and 10 m (e.g. for fixed station antennas); a 0 dBi omni-directional antenna is often used as a reference.[10]

Since the field strength varies from place to place and time to time over a region, depending on factors like terrain, obstacles, foliage and moving objects, harm claim thresholds are specified probabilistically, e.g. a not-to-exceed value at 95% of the locations within a license area.[11]

The probability can be imagined as comprising the minimum percentage of times (p_{time}) and locations (p_{loc}) where the harm claim threshold should be observed. It is calculated by distributing N measurement points evenly over a verification area, and counting the percentage of measurements when signal strength exceeds E.[12] For example, it

[8] Power flux density is defined thus in 47 CFR § 25.20: "The amount of power flow through a unit area within a unit bandwidth. The units of power flux density are those of power spectral density per unit area, namely watts per hertz per square meter. These units are generally expressed in decibel form as dB(W/Hz/m^2), dB(W/m^2) in a 4 kHz band, or dB(W/m^2) in a 1 MHz band." Power spectral density is defined as the amount of an emission's transmitted carrier power falling within the stated reference bandwidth, in units of watts per hertz.
[9] The conversion between them is dB(μV/m) = dB(W/m^2) + 145.76 (Sanders 2010, equation 28)
[10] As noted, receiver performance may be excellent, but reception is ultimately governed by the both the receiver and the expected antenna system.
[11] Note that the Part 15 out of band emission limits for unlicensed devices at UHF (200μV/m or 46 dB(μV/m) in 100 kHz) is higher than the protected noise limited contour level for DTV reception of 41 dB(μV/m) in 6 MHz.
[12] For decent statistics N should probably at least be order(1000), though order(100) may be OK in some cases.

might be an area 5 km x 5 km with measurement points every 250 m (N=400),[13] and the temporal window a period of 1 minute with measurements every 100 ms (N=600) (Figure 3). The 2004 Report and Order in the 800 MHz case describes a protocol for the measurement of the signal power to be used in a determination of unacceptable interference (FCC 2004b, paragraph 108), and delegates authority to the Office of Engineering and Technology (OET) to make changes to this protocol as needed. We recommend that OET be given that same authority to implement the parameters of harm claim thresholds. Establishing the measurement grid and timing has important implications for system design. For example, a smaller verification area with a finer grid spacing may be chosen for life-safety and mission critical services. A certain level of failure has to be taken into account in system design and operation: there may be nothing that a receiver designer can do to mitigate performance degradation in the p_{loc}% of locations where the interfering signal level exceeds the threshold, particularly with consumer-owned receivers.

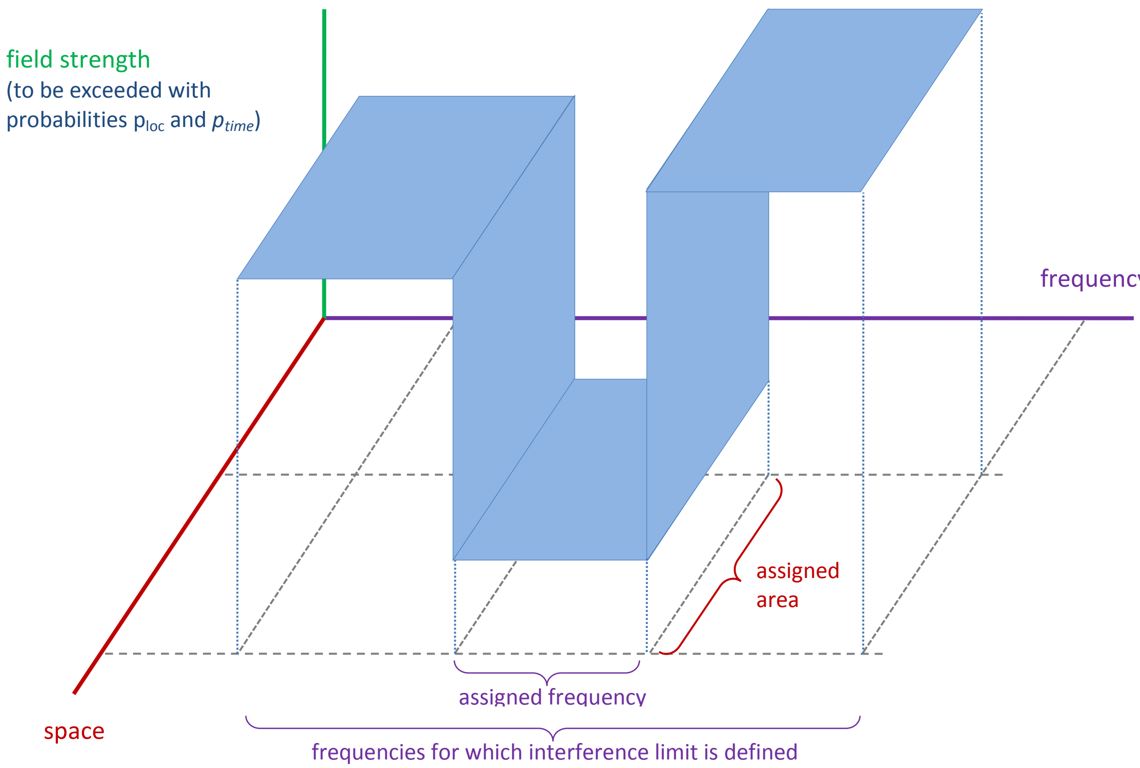

Figure 1: A simple harm claim threshold profile. Note that it extends over space (only one dimension of an assignment area is shown), and a limited frequency range beyond the assignment boundary.

Similarly, field strength measurement timing has implications for transmitter duty cycle and therefore receiver interference characteristics.

Continuing, harm claim thresholds are specified as follows:

> A service cannot claim harm unless the aggregate field strength at height {h_1, h_2, …} above ground level exceeds {E_1, E_2, …} dB(μV/m) per MHz at more than p_{loc}% of locations for p_{time}% of time, where the E_i is a profile of field strength values defined over frequency.

[13] In the most general case, it could also be a spatial volume.

A receiver operator could only make a claim for harmful interference if the aggregate signal strengths from neighbors exceeded the harm claim threshold. In a sharing scenario, a device wishing to operate on a secondary or unlicensed basis would be given a harm claim threshold profile that was as high as or greater than the interference generated by primary users; it would then have to determine whether it could operate satisfactorily given this interference.

Any service deployment results in a distribution of resulting signal strengths, from high near transmitters to low at the edge of coverage, typically captured as a cumulative distribution function as in e.g. Figure 16 in Transfinite (2008). For example, in Figure 2, the field strength is 80 dB(µV/m) per MHz or less for 50% of observations, that is, the median field strength is 80 dB(µV/m) per MHz. As the field strength threshold increases, there are fewer and fewer locations where the signal exceeds that level; for example, the resulting field strength exceeds 100 dB(µV/m)/MHz in 10% of cases, and 120 dB(µV/m)/MHz in 2% of cases. A harm claim threshold represents one point, i.e. a {field strength, probability} pair, on the distribution chosen by the FCC to represent the interference a receiving system needs to tolerate before claiming harm. Any of the pairs would represent the same distribution of interference. In other words, given the distribution of field strength depicted in Figure 2, the harm claim thresholds "field strength exceeding 100 dB(µV/m)/MHz in 10% of cases" and "field strength exceeding 120 dB(µV/m)/MHz in 2% of cases" would be equivalent. The choice of that point, and thus the probability of a field strength to be exceeded, is a political judgment, informed by the technical and operational system consequences of that point. Various services may have higher or lower expectations of the probability of interference.

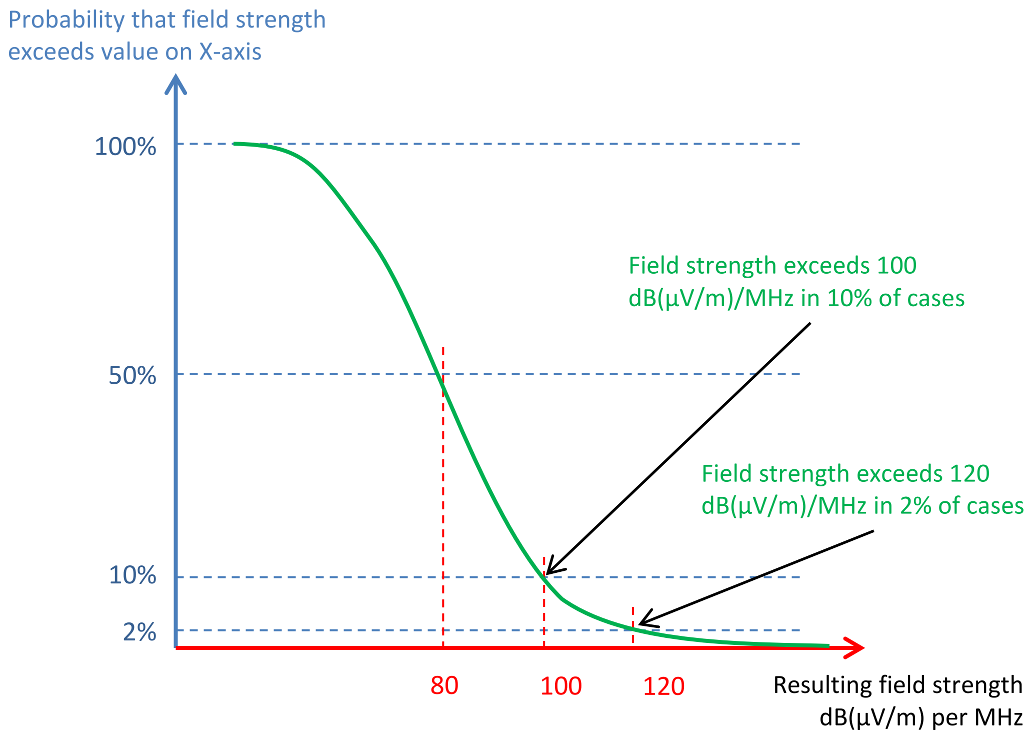

Figure 2. Cumulative distribution of resulting field strength for a hypothetical deployment of transmitters

For example, consumer services, such as broadband mobile data services, are generally able to tolerate short-term, limited duration or location specific-interference events. Thus, the probability levels for the harm claim thresholds may typically be examined at the 90% level for these types of services (meaning that 10% of the time, or at 10% of locations, the specified interference limits may be exceeded). However, harm claim thresholds may be stated at 99% or higher probability levels for mission-critical services (such as life-safety or public safety communications). Regulators would need to make judgments, based on industry and citizen input, on the appropriate levels for various service types (e.g., consumer, commercial/industrial, or mission-critical grade).

This approach focuses on stating the rights and responsibilities for accepting and dealing with harmful interference. It does not directly address the details of receiver interference modes discussed in Section 9.2, e.g. intermodulation (see e.g. Rhodes 2010, 2012a, 2012b). The private sector will play a key role in developing receiver specifications and standards that ensure adequate performance given the harm claim thresholds of a particular allocation (see Section 3.5).

The increased allowed interference starts at the edge of an assignment, i.e. there are no guard bands. This is intentional. Guard bands allow operators to externalize their costs, i.e. allow them to have filters that stretch into the guard bands, thus "using" frequencies they have not had to obtain. In the absence of guard bands, operators will have to bear these costs themselves by such techniques as improving their receiver filters or using part of their frequency assignment as an "internal guard band." Similarly, the harm claim thresholds proposed here do not slope up beyond the band edge, but are flat; this reduces the number of parameters the regulator has to choose, i.e. a constant harm claim threshold value over a given range, rather than two values at either edge of the range and a shape of the connecting curve.

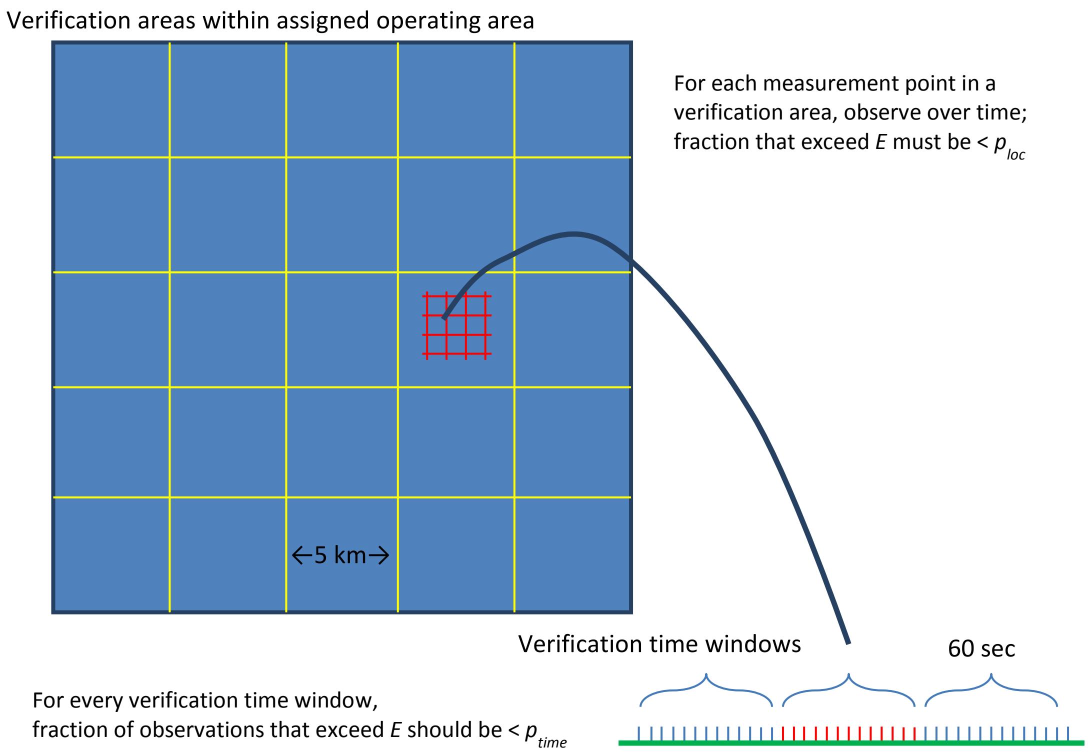

Figure 3: Determining received interfering signal strength. A harm claim can be brought provided the field strength exceeds the threshold within any verification area (here 5x5 km) or time window (here 60 seconds).

The baseline, generic harm claim thresholds described here are isotropic, average signal strength levels that would be sufficient for many common spectrum scenarios where transmitter and receivers are relatively widely distributed over a service area, the signal is noise-like and has a low peak to average ratio, and the duty cycle is high; for example, cellular systems. If the receiver location is fixed and high gain antennas are used, e.g. with satellite earth stations, it may be worth incurring the additional informational cost of defining harm claim threshold profiles at specific locations that vary by elevation and azimuth.[14] If the likely interfering signal varies significantly in time, e.g. some radar signatures, both a high and a low harm claim threshold can be defined, along with a duty cycle. The regulator may also opt to define the harm claim threshold both as spectral density (e.g. not to exceed 100 dBμV/m per MHz anywhere in the 30 MHz above the assigned block) and an aggregate value (e.g. not to exceed 110 dBμV/m over the whole 30 MHz block).

Harm claim thresholds can be specified by the FCC for licensed and unlicensed operation, and frequency assignment to government users by the NTIA. We will use the term "assignment" as a catch-all to encompass all these possibilities. They can be retroactively applied to legacy allocations in a way that captures the status quo and does not require modification of any existing receivers, and can also be implemented piecemeal, i.e. band by band.

Each allocation is likely to have a different harm claim threshold. Once a limit has been set, FCC rules should allow it to be adjusted by negotiation among affected neighbors through a multi-stakeholder forum that includes representation from all affected and / or interested parties, or through bilateral negotiation.

In new allocations, harm claim thresholds would most likely represent an upper bound on the signal levels generated by existing operations; thus, transmissions by incumbent neighbors would not exceed the chosen harm claim threshold, and may not trigger harmful interference claims. Likewise, new transmission permissions would be chosen so that the resulting signals did not exceed the harm claim thresholds of incumbent neighbors. If the band(s) next to a new allocation are currently unused or have low resulting field strength levels, the FCC could set harm claim thresholds that will allow more intensive use in the future. For example, by stipulating to a multi-stakeholder group that it should expect as a starting point that the adjacent band will be re-allocated for use as a cellular downlink, new licensees will be put on notice that they should not depend on quiet neighbors when designing their systems. The harm claim thresholds may be different on either side of the block to be allocated.

Interference limits could be added to existing rules in already-allocated bands, with values chosen to grandfather in existing devices and operations, i.e. to ensure that interfering signals from other operations would not be deemed to cause harmful interference to incumbent services. Again, multi-stakeholder groups could modify these harm claim thresholds over time as mutually agreeable alternative limits could be established including appropriate financial considerations to positively enhance the effectiveness of the limits values.

The preceding discussion, while applying to all assignments, has been framed in terms of licensed authorizations. Interference limits policy can also be applied in unlicensed service bands although some development and implementation details may vary.

Let's say that system R has a harm claim threshold specified in their service rules. The transmit permissions of a system T in an adjacent block can be chosen by the FCC to ensure that T's resulting transmissions do not exceed R's harm claim threshold. Since unlicensed transmitters operate independently of each other, the FCC will need to ensure that the aggregate unlicensed signal strength does not exceed the harm claim threshold of a licensed neighbor. In such cases it would analyze likely deployment scenarios of unlicensed devices, use that to calculate the probability distribution of resulting aggregate signal strength, and then set the transmission power for individual devices in a way that this result remains below the adjacent licensee's harm claim threshold. This is essentially the way transmit permissions for unlicensed devices have always been determined, without, perhaps, the benefit of an explicit ceiling expressed in terms of aggregate signal strength not to be exceeded at more than a specified percentage of locations and times. Even though multiple transmitters (unlicensed or otherwise) may be able to transmit in a particular band simultaneously, aggregate interference levels are often self-limited at a particular time and place because those transmitters share the channel amongst themselves by using time, frequency or code division, or carrier sensing, multiple access protocols.

[14] This corresponds to Matheson's angle-of-arrival electrospace dimension.

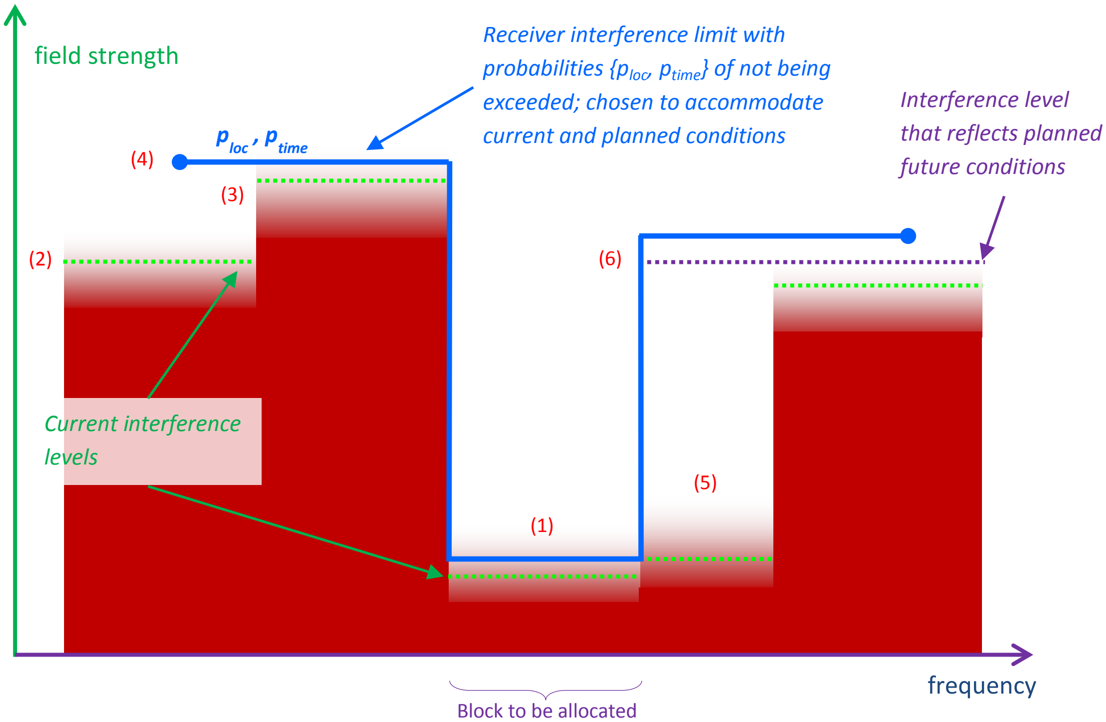

Figure 4: Choosing Harm Claim Thresholds. The numbers correspond to steps in the decision process described in the text.

If deployment densities of unlicensed devices turn out to be much lower than anticipated in the analysis, a rule change could increase their allowed transmit power; if the densities are higher, or evidence of interference problems emerges, it could be decreased. This would not change the requirement that unlicensed devices must not cause interference, but would be a way to reflect experience in practice with the potential of unlicensed devices to cause harm under a given rule. Analysis of aggregate interference from many unlicensed devices, such as that performed in the UWB proceeding (FCC 2004c), may be required when choosing unlicensed transmit power levels to meet harm claim thresholds of adjacent services.

Dynamic spectrum access can be facilitated by the use of harm claim thresholds. In order to facilitate more intensive and efficient sharing, the regulator would set and publish harm claim thresholds for all primary operations. Automated assignment tools (e.g. Stine 2007, Stine & Schmitz 2011) will be able to infer allowed transmit permissions from these limits and identify secondary operations that can safely operate alongside the primaries. Where operators with priority access require additional protection, specifying their harm claim thresholds will allow the regulator to determine how much other users have to back off their transmissions; this could occur in real time if a central coordinating database is in use. Such a database could pack in more operation by matching transmission permissions with receiver protections, something not possible if only transmission parameters are specified.

3.2. Choosing parameter values

Figure 4 illustrates the process of choosing harm claim thresholds for a new allocation, indicated by numeral (1).[15] In order not to change the rights of neighboring incumbents, harm claim thresholds would be no lower than the interference caused by existing operations; thus, transmissions by incumbent neighbors would not exceed the harm claim threshold and could not trigger a harmful interference claim. Conversely, if an incumbent neighbor's assignment includes harm claim thresholds, the transmission permissions assigned to a new operator in block (1) would be chosen so that the resulting signals will not exceed those thresholds.

If harm claim thresholds are in place for bands adjoining a new allocation, they enable the regulator to derive allowable transmission permissions rapidly and formulaically. The regulator can choose out-of-block levels that are above extant signal levels in adjacent bands, indicated by the dotted green lines (2), so that legacy operation in neighboring bands isn't newly categorized as interference. The harm claim threshold is greater than the current generated signal level, with a margin to allow for uncertainty and cases where signals from two operators in the adjacent band combine (3). This yields the protection level (4). The dot on the end of the protection limit line indicates that the block (1) will be given no protection against interfering signals beyond this point.

In new allocations where a currently quiet adjacent band (5) has the potential for transition to more intensive use, i.e. there is likely to be an increase in the aggregate signal level in the future due to new services, the regulator should define harm claim thresholds that reflect the anticipated future interference environment (6). This is a way to implement the proposal of Kwerel & Williams (2011) that future allocations should self-protect against projected adjacent band interference, and puts the new licensees on notice that they could not depend on the absence of adjacent channel interference to continue into the future.

The regulator can provide differential protection for different services in a technology neutral way by stipulating non-overlapping sets of parameter values. For example, let us assume that the regulator determines that a harm claim threshold of 100 dB(μV/m) per MHz in 1525-1540 MHz and 90 dB(μV/m) per MHz in 1540-1559 MHz, to be exceeded at more than 10% of locations and times, is appropriate for terrestrial GPS receivers. If the regulator sets these values for a 1.5 m measurement height, a terrestrial cellular operator that had a viable business model with these limits might go ahead with a deployment, and terrestrial GPS operators would have to bear the cost of improving their receivers, if necessary, to operate under these conditions. However, the regulator could set the harm claim thresholds 10 dB lower at heights above 30 meters (90 dB(μV/m) and 80 dB(μV/m) per MHz in 1525-1540 and 1540-1559 MHz respectively), and/or reduce the probability threshold to 1% of locations and times, in order to provide additional protection for aviation navigation systems. The cellular operator would then have to bear the cost of retrofitting aviation systems with improved filters if it wanted to deploy a system that did not meet these limits.

Protections for reception in a new allocation can be derived from the transmit permissions of pre-existing neighbors. This is straightforward if those permissions are expressed in terms of resulting aggregate field strengths as advocated by Matheson (2003, 2005, 2012) and Ofcom (2008a), since they match receiver interference protections expressed in the same way. If transmission rules are expressed as transmit power limits at the antenna, additional work will be required to match expected antenna heights and densities, and propagation path losses, to the harm claim thresholds.

Interference limits could be added to existing operating rights in already-allocated bands, with values chosen to grandfather in existing devices and operations, i.e. to ensure that interfering signals from other operations would not cause harmful interference to incumbent equipment. The regulator could either update the rights at license or allocation renewal time to include harm claim thresholds, or it could use "shadow harm claim thresholds," in the form of guidelines that use the declared harm claim thresholds would be the basis of a harmful interference analysis.

[15] The hard edges in the field strength distributions between one frequency range and another are an artifact of the illustration; the distributions are much fuzzier in reality.

These thresholds would be determined in cooperation with industry and defined by measurements of actual equipment in use at the time.

There may be cases where the initially assigned harm claim threshold is not economically efficient. For example, there might be net social gain if the threshold were increased, allowing increased transmit power and thus greater data bandwidth in the adjacent band.[16] The FCC rules should allow the limits to be adjusted by negotiation among affected neighbors. If the Commission deems that there is no prospect of such negotiations being concluded successfully, it could put assignees on notice that the harm claim thresholds will be increased over time in a series of steps, e.g. increasing the interference tolerance level by (say) 5 dB every five years. The time interval would take into account the current and anticipated reasonable product life-cycles in the allocation being considered.

3.3. Development and roll-out

The roll-out of interference limit policy-related rules and regulations might follow a three step process. The FCC could: (1) identify boundaries where defining harm claim thresholds would add significant value; (2) encourage a multi-stakeholder process to work out implementation details; and (3) engage in rulemaking as required.

First, the FCC would identify frequency allocation boundaries where harm claim thresholds would bring immediate value. Adjacent allocations with a prospect of intensified use are good candidates for early implementations of interference limits policy. Examples among the case studies examined by the Working Group include cellular and DTV in the UHF band, the 2.4 GHz unlicensed boundary with the 2.5 GHz BRS/EBS and terrestrial MSS bands, and the 3550-3650 MHz band.

Adjacent allocations where services have broadly similar technical characteristics are good candidates for early implementation of interference limits policy. Services that use modulation techniques with low peak to average power ratios (PAPRs) and have high duty cycles, such as FM broadcast radio and spread spectrum applications like Wi-Fi, can have their interference limits based on average power. For services that have high PAPRs or low duty cycles, such as CDMA and OFDM 4G cellular uplinks, narrowband radio, and most forms of radar, the equivalent average power must be calculated to arrive at a harm claim threshold. It may be necessary to err on the side of having conservative interference limits in these cases, since some radio receivers may be susceptible to bursty interference (cf. Parker & Munday 2011,).

Cases where systems use very different waveforms are more challenging, and may require the specification of harm claim threshold parameters in more detail. For example, the degradation of cellular data communications by radar depends on the cellular symbol length as well as the radar duty cycle (pulse width / pulse repetition cycle) and pulse repetition frequency. The high PAPR of the radar waveform may require both peak and average harm claim thresholds to be specified, and the size of the time verification window(s) will need to be matched to the characteristics of the radar neighbor(s).

A second step would be to initiate a consultation process where multi-stakeholder groups work out boundary issues and implementation choices, such as the parameters required (e.g. should one define limits as a field strength per MHz, and/or a field strength across an entire band), methods for determining harm claim thresholds (e.g. to what extent would the actual interference environment need to be measured and/or modeled), baseline receiver performance characteristics such as reference sensitivity and selectivity, and enforcement mechanisms in cases of dispute (e.g. would interfering field strengths be measured or modeled). A multi-stakeholder group would likely also develop guidelines and perhaps standards for receiver performance parameters such as receiver sensitivity, selectivity, and dynamic range, that, together with the transmitter power and deployment assumptions applicable to a

[16] A net gain would be realized if the value of greater data bandwidth arising from increased transmit power was greater than the cost of improving the adjacent block selectivity of the receiving service subject to the harm claim threshold. Some parties would gain and some would lose, but the net would be positive.

particular service, would ensure that conformant receivers would operate satisfactorily given interference up to the harm claim threshold. The Commission may choose to provide a starting point, e.g. with a broadly stated default assumption that a harm claim threshold should be compatible with a cellular downlink deployment. In the best case, the participants of the multi-stakeholder process for a group of neighboring allocations would agree on both parameters and their values that the FCC could then endorse. If this is not achieved, the group is likely to at least agree on relevant parameters and methods, if not the parameter values that establish a particular balance of costs and benefits between neighboring assignments. Finally, even if there was no agreement on the trade-off between transmitter and receiver interests, the multi-stakeholder process would assist the FCC in identifying critical issues and mapping out points of consensus vs. areas where the Commission itself would need to make the public interest trade-off. (See the appendix section 9.7 for more background on multi-stakeholder organizations.)

Thirdly, FCC would monitor the progress of the multi-stakeholder process. It would represent the interests of future licensees and other absent stakeholders, and ensure that the record developed provides a thorough basis for a Notice of Inquiry and/or Notice of Proposed Rulemaking, should that be required. If necessary, it would add interference protection entitlements to the rules for a new assignment.

3.4. Benefits of interference limits policy

Harm claim thresholds as described in this paper provide benefits both to radio system operators and to regulators 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 device types. This approach also delegates decisions about system design, including receiver performance, to manufacturers and operators.

Interference limits allow regulators to set, and if desired ratchet up, technology- and service-neutral expectations about receiver performance. They allow regulators to put new licensees on notice in an explicit, quantitative way that quiet adjacent bands may not always be so quiet. For example, if public safety had been given harm claim thresholds in 800 MHz, the Nextel case would not have arisen in the way it did, since the resulting OOB field strength from their proposed cellular deployment would have exceeded the harm claim thresholds that would (presumably) have been set on the basis of the pre-existing high power high tower deployment (De Vries 2009, section 4.1). In the event, the resolution of this case included non-mandated receiver performance requirements and a minimum threshold of desired signal strength before a claim of public safety system could claim unacceptable interference – in other words, an approach resembling an interference limits policy as outlined in this paper (see Section 7.2.1).

The FCC also benefits by not having to referee so many disputes after the fact. Interference negotiations between parties in the same service (e.g. cellular) are common, and the FCC is rarely if ever called upon. The interference limit approach seeks to broaden such inter-party dispute resolution to interference between different services. However, since incumbents are loath to accept any degradation, care will need to be taken to set initial threshold levels in legacy environments, as described in section 3.1above.

Operators benefit because business decisions such as the trade-off between receiver and transmitter performance can be delegated by the regulators. Interference limits reduce business risk:[17] for receivers, they provide a predictable future RF environment to design against; for transmitters, they preclude unexpected harmful interference claims from insufficiently selective receivers; and for both, they allow better estimates of deployment costs because interference risks are better known. For example, if the FCC had defined harm claim thresholds for the AWS-1 F block, it would have been absolutely clear at the time of the auction whether or not TDD operation would have been permitted in the AWS-3 block, sparing both the new entrant M2Z and AWS-1 licensees like T-Mobile considerable

[17] Business certainty provides greater benefits to those exposed to greater risk, e.g. new entrants may benefit more than incumbents.

uncertainty, wasted investment, and lobbying costs. Similarly, promulgating harm claim thresholds in the early stages of the LightSquared ATC proceeding would have made the interference management responsibilities of all parties explicit at the beginning of the process.

Last but not least, consumers and society at large benefit because increased clarity about the rights and responsibilities of parties at service boundaries means that more services can be deployed in limited spectrum. More clarity about rights will attract entrepreneurs to invest in innovation, and fewer protracted escalations to the FCC mean that valuable new services can be deployed more rapidly. Finally, incentivizing better receiver performance while leaving design decisions in the hands of industry will allow manufacturers to continue to create better products.

3.5. How harm claim thresholds lead to better receiver performance

Figure 5 shows how harm claim thresholds can lead to better receiver performance by sketching the steps between a regulatory harm claim threshold and a receiver performance specification. (For more details on receiver specifications, see Appendix, Section 9.3.) It indicates some of the ways in which trade-offs between receiver and transmitter performance can be made, including how receiver performance decisions made by industry can be shaped by the harm claim threshold incentives set by the FCC.

The schematic shows a few of the key artifacts, i.e. documents that represent inputs into, and outputs of, the system design process. The diagram does not deal with the processes that lead to input documents, such as the rulemaking process that leads to the setting of harm claim thresholds, and does not show the iterations or most of the feedback loops that comprise system design, changing both requirements and specifications. Not all connections are shown; for example, while the business case directly affects the quality of service requirement, as shown, it also influences interference tolerance requirements. As indicated by the bi-directional arrows, the requirements and specification interact through the design process which is a process of finding the optimal trade-off among all of them.

Figure 5 highlights some elements of the process. Before a system can be devised, the designer has to collect requirements. One of them is the RF interference that must be tolerated by the combination of transmitters, receivers and communications technologies used (1). Assumptions about likely interference are often implied by industry receiver standards; for example, the out-of-band blocking performance of an E-UTRA handset is given in Table 7.6.2.1-2 of the 3GPP TS 36.101 standard as three power levels in three frequency ranges, 15 MHz or more above or below the licensed band, which may not degrade maximum required throughput by more than 5% (3GPP 2012).[18]

This estimate of the actual expected interference environment is combined with the regulatory harm claim threshold (2) to set the RF interference design requirement. It is quite likely that the harm claim threshold was set to take account of the current or expected interference environment, as shown by the dotted line from (1) to (2) although it doesn't attempt to characterize it. If the expected actual environment is considerably quieter than the harm claim threshold, the design requirement may be set lower than the harm claim threshold. This is a business decision, since a lower interference requirement leads to lower system costs; however, if the interference at some point exceeds the design limit, but is still less than the regulatory limit, the system operator will not be able to force the neighbor to reduce their transmit power by making a harmful interference complaint.

Another high-level factor that shapes the design requirements is the business case: the operator or industry's assumptions about their business model (3). The business case has a direct impact on the quality of service requirements (4), e.g. the level of reliability that will be acceptable to customers expressed as the maximum bit error rate in the presence of the minimum desired signal level and the maximum interference. It also determines the cost constraints that determine, for example, how good the interference rejection capability of receivers will be. Other

[18] 3GPP represents a best case; in a multiservice environment, suitable receiver standards may not be available.

requirements include the expected levels of the desired signal (5), which determines the receiver sensitivity and dynamic range, and the minimum quality of service.

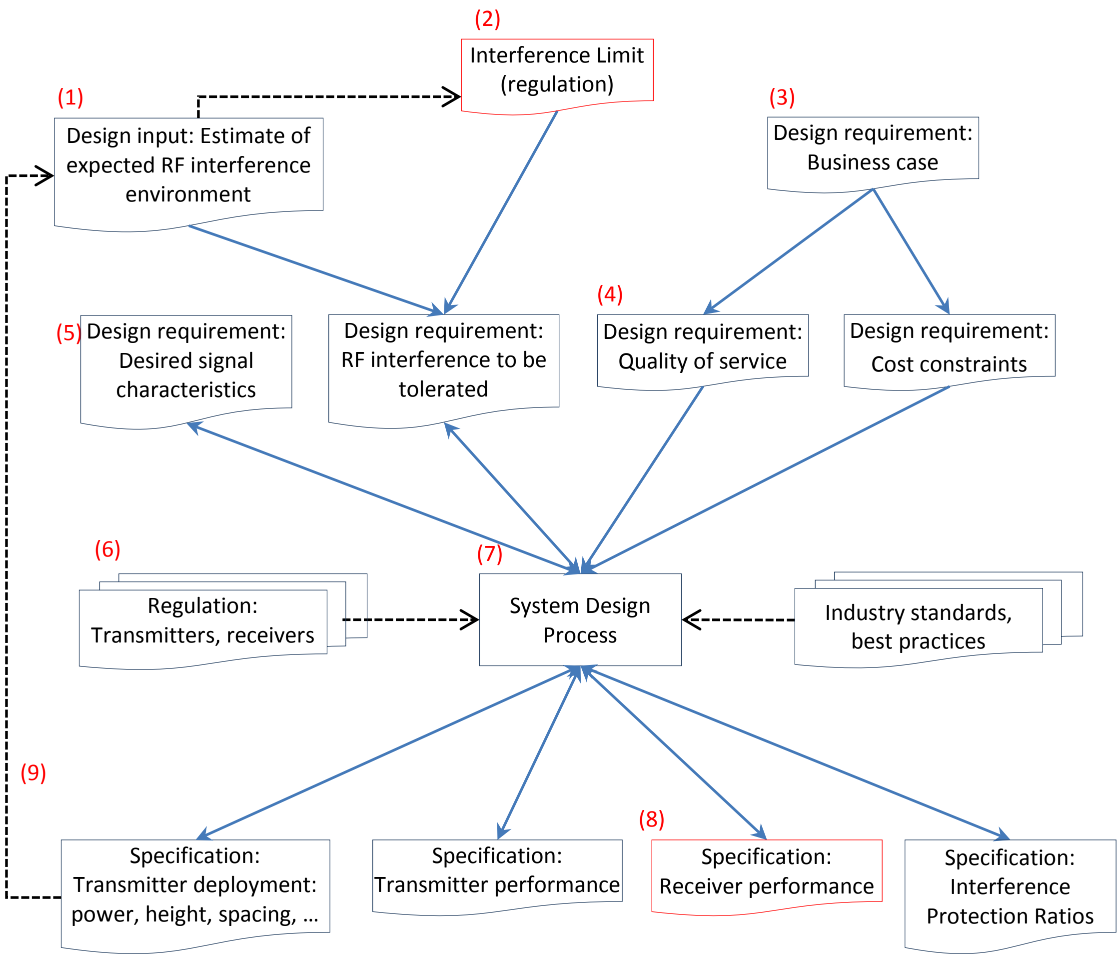

Figure 5: Relationship between harm claim thresholds, actual interference environment and receiver standards. Interference limits are one of many inputs to a system design process; receiver performance specifications are an output.

There are also requirements that are imposed from outside (6), including regulatory requirements on transmitter power ceilings and minimum receiver performance, and industry standards and best practices.

All these factors are then incorporated in the system design (7) that yields various system specifications including receiver performance requirements (8). Receiver performance specifications can include a multitude of parameters, including the minimal received signal power that would yield a minimally acceptable quality of service in the presence of specified co-channel and adjacent band and channel interference, out-of-block interference rejection capability, intermodulation resistance, and so on. All these factors, but particularly transmitter deployment, then feed back (9) to the RF environment, both self-interference between elements of an operator's system, and interference from one system to a neighbor.

3.6. Limitations of interference limits policy

A harm claim thresholds approach also has its limitations. One of the most striking, particularly in comparison with mandating receiver performance specifications, is that validating compliance is not just a matter of bench testing a device: it requires field measurements or the modeling of field strengths that result from a given transmitter deployment in a particular place. Both field measurements or modeling (or a combination of the two, see e.g. Riihijarvi et al. 2008 and Phillips et al. 2012) require assumptions about the statistical accuracy that is required. Modeling will require specification of terrain and propagation models, and field testing will require a significant investment of time and equipment. We believe that this limitation is acceptable, however, since testing whether a harm claim threshold is being met will only be required in cases where there is an interference dispute; it is not required before the fact.

A more general objection to interference limits policy is its novelty. This approach has not been used in the form proposed here, although there are similarities with the approach taken in the 800 MHz proceeding (see Section 7.2.1). Concerns about unintended consequences and the cost of uncertainty need to be put in the balance. For this reason, we have recommended that the FCC adopt the approach incrementally, starting with cases where the benefits will obviously outweigh the costs.

Since a harm claim threshold represents the aggregate resulting field strength that a system has to tolerate, it may be difficult to assign responsibility if energy from multiple transmitters combines to exceed the harm claim threshold. Given the exponential decay of field strength with distance from a transmitter, this is unlikely to be problematic with out-of-band harm claim thresholds since they are high. Difficulties with aggregate interference are most likely to arise in-band, due to a rise in the noise floor. Aggregate interference merits further investigation as a general matter; it is not limited to the interference limits approach.

The interference limits approach strives to encapsulate harm claim thresholds in a small number of parameters that are not system-specific, e.g. as noise-like aggregate signal strengths with low peak-to-average ratios, measured isotropically. As such, it cannot capture the nuances of harmful interference mechanisms, e.g. differential impact of various waveforms (e.g. modulations, duty cycles) on different target systems. We believe that the perfect should not be the enemy of good; the ease of use of a short, generic parameter list will usually outweigh the cost of adding more detail. However, the FCC may choose to add parameters where it judges that the generic list omits a key parameter that is vital to the effective management of a particular case.

Finally, harm claim thresholds attached to a transmitter license may be ineffective as a means of encouraging optimum receiver performance when receivers are not controlled by licensee. This case of “decoupled receivers” is addressed in detail in Section 7.1.

4. Examples

Harm claim thresholds apply to operations in a given assignment, and refer to the signal levels that result from the transmissions in neighboring assignments. Let us refer to the assignment being given thresholds as “R” the receiving system, and the neighboring system(s) as “T” since harm claim thresholds focus on the result of transmissions in T on the receiving system in R. Of course, there will also be receivers in block T, and transmitters used by R will play a role in R’s non-cochannel interference tolerance; however, we choose this mnemonic since the first order effect is from transmitters in T upon receivers in R.

Harm claim thresholds will be shaped either by the operations already in place in block R, in which case the limits will reflect the interference tolerance of deployed receivers, and/or by the services in the adjacent block T, in which case the limits will be a ceiling on the received signal strength delivered by that service T such that normal operation by that service doesn’t constitute harmful interference as determined by the harm claim threshold.

This section provides an outline of how harm claim thresholds could be derived in a sample of cases; these are illustrations of how the concepts might be applied, and not recommended methods, let alone rules. (More technical details on orders of magnitude and possible ways to derive harm claim thresholds are given in Appendix 9.4.)

After sketching possible values for in-block thresholds in Section 4.1, the rest of this section outlines ways in which one might approach the calculation of harm claim thresholds in three paradigm cases: protecting receivers where the location, height and transmit power of their transmitters are fixed in the license, e.g. television reception; setting harm claim thresholds that reflect an adjacent band where transmitters can be located anywhere, e.g. cellular base stations; and protecting receivers at known fixed locations, e.g. satellite earth stations.

In the first example (Section 4.2) there is, or is planned to be, a cellular downlink deployment in T. The section outlines how one might determine R's harm claim threshold levels over T's frequencies. This is the case where one wants to ensure that R cannot bring a claim for harmful interference against the authorized cellular operation in T.

In the second example (Section 4.3), television receivers are already deployed in R. The question here is: what threshold levels over adjacent (T) frequencies are needed to ensure that the R receivers continue to receive the protection they are already afforded in the rules? The third example (Section 4.4) is a variation of the second. Here we look at fixed satellite receivers, and ask how thresholds might be formulated to protect them.

Section 7.2.1 discusses the use of an interference limits-like policy in the resolution of the 800 MHz public safety/cellular case.

4.1. In-block harm claim thresholds

While the out-of-block values of a harm claim threshold are most germane to managing cross-allocation interference, the in-block (i.e. in-band or co-channel) value should also be defined as a way to guide the restrictions on the allowed spillover into an assignment from adjacent blocks.

The levels of allowed spillover chosen by regulators such as the FCC vary greatly, from over to 80 dB(μV/m) per MHz per the so-called 43+10logP attenuation rule for emissions outside a licensee's frequency band(s),[19] down to 41 dB(μV/m) per 6 MHz at the noise-limited signal contour for a DTV station.[20]

The 47 CFR § 15.209 limit on out-of-band emissions seems to be a reasonable starting point that could be adjusted on a case-by-case basis. For example, it is 200 μV/m per 100 kHz (i.e. 56.0 dB(μV/m) per MHz) in 216-960 MHz, and 500 μV/m per MHz (54.0 dB(μV/m) per MHz) above 960 MHz, at a measurement distance of 3 meters.[21]

4.2. Harm claim thresholds representing adjacent cellular service

One can also use harm claim thresholds that reflect the operation of current or planned service in the adjacent block. For example, a cellular downlink's in-block and out-of-block resulting signal strength distributions can be used as the lower bound for the out-of-block and in-block harm claim thresholds assigned to a new service next door. (The downlink's in-block signal is the out-of-block interferer for the new service, and vice versa.) This offers a

[19] This is the field strength at 3 meters from a transmitter radiating -13 dBm per MHz into a 0 dBi antenna; see e.g. 47 CFR § 27.53 (g)
[20] At 615 MHz; see e.g. OET Bulletin No. 64 (FCC 2004a), Table 2
[21] This limit may need to be re-examined as it has not been changed or studied in many years. The general shift from analog to digital services may make this limit somewhat problematic. Previously, an analog device might generate a few narrowband spurs on distinct frequencies that approach the limit. Modern digital devices tend to create broadband noise over large bands close to the limit.

way to operationalize the proposal by Kwerel & Williams (2011) that future allocations should "self-protect" against projected adjacent band interference by assuming a cellular service in the adjacent block.

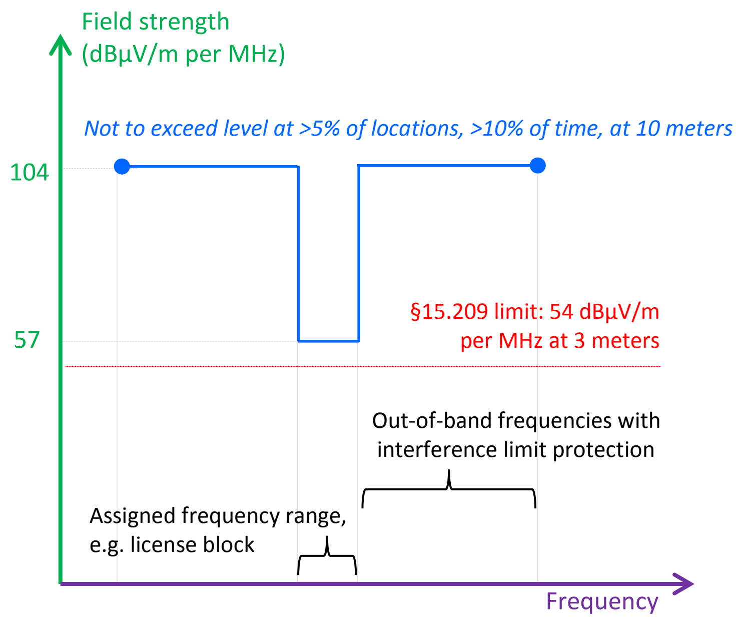

Figure 6. Notional harm claim threshold based on a cellular downlink neighbors

Appendix Section 9.4.2 (based on De Vries 2012) outlines how the modeling of the field strength that results from a generic base station power, height and spatial distribution by Transfinite Systems (2008) could be used to derive the following harm claim thresholds based on the transmissions of a cellular downlink:

> In-block: A service cannot claim harm unless the aggregate field strength at heights {1.5m, 10m} above ground level exceeds {40, 57} dB(μV/m) per MHz at more than 5% of locations in the 10 MHz assignment.
>
> Out-of-block: A service cannot claim harm unless the aggregate field strength at heights {1.5m, 10m} above ground level exceeds {86, 104} dB(μV/m) per MHz at more than 5% of locations in the first 30 MHz beyond the band, and no limit beyond that.

Figure 6 illustrates the harm claim threshold 10 meter altitude for an allocation flanked by cellular downlinks.

4.3. Protecting television receivers using harm claim thresholds

The general approach used here is to take adjacent channel protection ratio(s) D/U specified in 47 CFR § 73.616, and then calculate the harm claim threshold as equal to or above the maximum undesired signal strength U, using a desired signal strength D and the definition of D/U ratios that require that $U \leq D - D/U$. We use the DTV-to-DTV ratios as an approximation for the impact of a generic noise-like, digital signal on DTV reception.

For example, one can define harm claim thresholds at the edge of coverage, since a common worst case condition for five channels above and below, and including a receiver is a near-far effect at its edge of coverage, with a nearby adjacent transmitter. By definition, the licensed channel field strength at the noise limited signal contour is 41 - 20 log [615/(channel mid-frequency in MHz)] dB(μV/m)/6MHz. Let's assume we're looking at 615 MHz, and just use

D = 41 dB(μV/m)/6MHz. Per 47 CFR § 73.616, the {-1, 0, +1} channel D/Us are {-28, +15, -26} dB, leading to a harm claim thresholds U = D – D/U = {69, 26, 67} dB(μV/m)/6MHz. The resulting harm claim threshold is thus:

> An end user cannot claim harmful interference unless their receiver can operate satisfactorily for U = {69, 26, 67} dB(μV/m)/6MHz given D = 41 dB(μV/m)/6MHz.

Alternatively, one could define harm claim thresholds for every 2x2 km "grid cell" by using the interference thresholds defined in 47 CFR § 73.616 (e)(1). The harm claim threshold would be:

> A TV licensee may not claim harmful interference unless the interfering signal exceeds the thresholds set in Part 73.616 (e) (1).

Rather than a single value across the entire coverage area, every grid cell would have a different value calculated on the basis of the statutory D/U ratio (which provides more protection to TV receivers than A/74) and the desired signal strength in the cell calculated according to OET Bulletin No. 69 (FCC 2004a); following the statutory F(50,10) interference criterion, this value would need to be exceeded at more than 50% of locations, more than 10% of the time before the TV licensee could claim harmful interference. The details of this calculation can be found in Appendix Section 9.4.2.

Since the statute only prescribes D/U values for the co- and upper & lower first-adjacent channels, these harm claim thresholds would only cover those three channels. Extending the scope of these limits will require balancing cellular transmitter and TV receiver interests, and thus represents a starting point for negotiation. For example, it only protects the first-adjacent channels (adding more protected channels would be desirable for receivers) and applies a flat adjacent channel D/U for all desired field strengths (reflecting more negative D/U for larger values of D, as ATSC A/74 (Advanced Television Systems Committee 2010) does, would be desirable for adjacent transmitters operating near the TV tower).

The signal levels for D and U in the rules assume a DTV transmission with its characteristic emission mask, and thus the U signal includes both energy in the adjacent band and spill-over into the desired adjacent channel. This is a reasonable first approximation for the purposes of this illustration, since the amount of spill-over is small: -47 dB or more below the total average power outside the channel to meet ATSC A/64 (Advanced Television Systems Committee 2000, Figure 4.1). The approach used here also averages over the diverse situations found in consumer homes, where many different types of antennas may be used in different receive environments; for example, in high signal environments a small indoor antenna can be used, and is in fact preferable to avoid overload. Harm claim thresholds are stated as field strengths or (equivalently) power flux density, whereas a television set's performance depends on the signal levels at the set's input; the consumer's choice of antenna bridges between them.

4.4. Satellite earth stations

For satellite systems with mobile receivers (e.g. GPS) the harm claim threshold would resemble that for a cellular system: a profile of aggregate field strength over a spatial region, for the licensed block and a range of frequencies above and below it, observed at some height(s) above ground level, the threshold that must be exceeded at more than a given percentage of locations and times for a claim of harmful interference to go forward. Since the desired signal level from the satellite is known and relatively constant, the harm claim thresholds would be informed by the in-block and out-of-block protection ratios required by the receiver.

If the location of the transmitter is known, as in the case of geostationary satellites, the harm claim thresholds could vary in azimuth, with more interfering energy allowed from (say) a northerly direction if the satellite is in the southern sky; cf. the Northpoint case.[22]

Some earth stations in the fixed-satellite service have fixed locations specified in their license. In such cases, the harm claim threshold needs to be defined only at the location of the earth station, and not over a spatial region.

Satellite earth stations with low elevation angles have a significant difference in gain in azimuth that can exceed 10 dB. The harm claim thresholds would therefore vary with azimuth. In some cases, the pointing direction is fixed in the license; if that azimuth is α, then there would be one harm claim threshold for azimuth direction [α-10, α+10] degrees, and another for the remaining directions. However, many earth stations change their pointing direction because they are intended to operate with different satellites at different times; on the assumption of a location in the northern hemisphere using geostationary satellites, the azimuth ranges would be [45, 270] degrees looking south, and (270, 45) degrees looking north.

Since satellite antennas are highly directional, their off-axis gain is minimal more than 10 degrees off-axis (Morgan & Gordon 1989, Figure 3.74). Most earth stations operate with a minimum elevation angle of 5 degrees. The harm claim thresholds could therefore be specified for a partition of incoming elevation angles between 5 and 20. [23]

5. Implementation

The addition of harm claim thresholds to the other parameters in operating assignments can be rolled out in stages, starting with bands where intensive sharing is most likely and/or in bands where all the operations are under the control of a single agency or department, thus simplifying administration. Initially the limits can be set so that existing systems in each band comply with the requirement without any change, thus imposing no cost on existing users. Regulators may raise these limits over time in order to drive more intensive spectrum use.

The determination of harm claim threshold rules and regulations might follow a three step process. First, the regulator would identify band boundaries where harm claim thresholds would bring immediate value. This should take into account all plans and studies that may have a bearing on future uses. Adjacent allocations where the boundary separates distinct services that have similar characteristics (e.g. wireless data services and broadcast television) with a prospect of intensified use are good candidates for early implementations of harm claim thresholds policy. U.S. examples include cellular and DTV in the UHF band, and the 2.4 GHz unlicensed boundary with the 2.5 GHz BRS/EBS and terrestrial MSS bands.

A second step would be to consult with stakeholders about the technical issues associated with defining harm claim thresholds. The initial part of the consultation could be carried out by a multi-stakeholder group comprised of technically qualified experts that are representative of the stakeholders on both sides of the selected band boundary. Because of the success that they have had in the governance of the Internet, multi-stakeholder groups have become accepted as an efficient and effective means of addressing issues that are essential to the development of policies, rules and best practices in highly technical fields (Waz & Weiser 2011). This appears especially true in fields where the technology is changing rapidly and where the policy-maker or regulator may not have the specialized expertise and have available the range of processes necessary to expeditiously produce the desired results. In the context of

[22] The Commission issued the technical parameters for MVDDS operations in a Memorandum Opinion and Order and Second Report and Order, 17 F.C.C. Rcd. 9614 (2002), ¶67. The power flux density of an MVDDS transmitting system must not exceed -135 dB(W/m2) per in any 4 kHz band (34.8 dB(μV/m) per MHz) at a reference point at the surface of the earth at a distance greater than 3 kilometers from the MVDDS transmitting antenna. This is a partial formulation of an in-block harm claim threshold protecting a Direct Broadcast Satellite system.

[23] For example: 0-10, 10-20, greater than 20 degrees; or 0-5, 5-10, 10-15, 15-20, greater than 20 degrees

spectrum management in the U.S., in addition to the use of multi-stakeholder groups, other options for determining harm claim thresholds include the use of (a) the traditional Notice and Comment rulemaking process, (b) a Federal Advisory Committee, (c) the Negotiated Rulemaking process, (d) reliance upon outside technical bodies such as the National Academies or, more likely, combinations thereof. There are advantages and disadvantages to each of these options but here the focus will be on the use of multi-stakeholder groups (Brake 2012).

For example, the multi-stakeholder group associated with the selected band boundary could advise the Commission (and NTIA if applicable) on the technical issues associated with defining harm claim thresholds such as the parameters required (e.g. should one define limits as a field strength per MHz, and/or a field strength across an entire band), methods for determining harm claim thresholds (e.g. to what extent would the actual interference environment need to be measured and/or modeled), and enforcement mechanisms in cases of dispute (e.g. would interfering field strengths be measured and/or modeled). An advantage of the multi-stakeholder process (as well as the Federal Advisory Committee process) is that it could be used to not only develop recommendations for harm claim thresholds that would be formally incorporated into the FCC's rules through the traditional Notice and Comment process, but also to develop best practices that would be advisory in nature for the parties involved. While such consensus-based best practices would not have the force of law, they could be easily modified by the affected parties participating in the multi-stakeholder group without having to go through the more time consuming Notice and Comment cycle. An example of such a best practice could be a recommended measurement technique based upon the current state-of-the-art. While not having the force of law, the Commission could take it into account the use of such practices in resolving particular disputes.

Note that in initiating the multi-stakeholder process, the regulator may choose to provide a starting point for their deliberations. For example, the regulator could specify that the harm claim threshold would be based upon a continuation of the existing services on either side of the boundary or it could specify a broadly stated default assumption that a harm claim threshold should be compatible with a cellular downlink deployment.

The third step in the process would be for the FCC to (i) adopt the harm claim thresholds for the spectrum boundary at issue using the normal Notice and Comment process and (ii) take cognizance of the associated recommended best practices. Because many if not most of the technical issues would have been resolved satisfactorily during by the multi-stakeholder group process, it should be possible to carry out the rulemaking proceeding in an expedited fashion. At the conclusion of the process, the resulting harm claim thresholds would become part of the operating entitlements of existing allocations or part of the operating entitlements of a new allocation.

Even before the first formal inclusion of harm claim thresholds in a rule making, regulators broaden rule makings for new or changed allocations to address not just the impact of transmissions in a new allocation on adjacent bands, but also the susceptibility of services in the new allocation to interference from current or possible future transmissions in adjacent bands.

If the regulator needs to adjust operating rights as technology evolves, the use of both transmission and reception parameters provide a basis for calculating the new social welfare maximizing optimum using all the variables necessary for estimating the cost curves. In most if not all cases, the regulator has the authority to change the harm claim thresholds whenever it wishes; however good practice would suggest that it only does so at license renewal time in order to provide stability and predictability for business models that depend on parameter levels (De Vries & Sieh 2011).

6. Enforcement

Interference between adjacent services is unavoidable since real-world systems allow energy to leak into an operating channel from an adjacent assignment or into an adjacent assignment from an operating transmission. The goal of regulation should be to maximize the value of concurrent adjacent operations by finding the optimal combination of maximum transmitted energy, receiver design, and operating frequency choices. Since the providers of adjoining services are best placed to negotiate to a solution, the operating entitlements they hold should be clear enough, and transaction costs low enough, that they can resolve difficulties bilaterally.

However, successful negotiations are based on the ability to assert operating rights and enforce prohibitions against their violation. A service provider can make a claim for adjacent band interference if the aggregate signal strengths from adjacent services exceed the ceiling specified in the harm claim threshold.[24] The regulator should specify the acceptable mechanism(s) by which this can be demonstrated; they include RF environment modeling using stipulated propagation models, field measurements, or building on recent developments (Riihijarvi et al. 2008; Phillips et al. 2012), a combination of the two.

Once it has been demonstrated that the harm claim threshold has been exceeded, the complaining party also still has to satisfy the traditional tests of harmful interference, i.e. that the interference "endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service" (ITU Radio Regulations 1.169, U.S. 47 CFR § 2.1 and similarly for other regulators). The process by which enforcement actions would be taken in the FCC context is illustrated in more detail in the following two subsections.

6.1. Enforcement action – base case

In order to provide more clarity and detail, the process by which adjacent band interference situations would be resolved under a regime of receiver limits (based upon the concept of a harms claim threshold) is illustrated in the flow diagram in Figure 7 below. The flow diagram and associated description of the steps involved is based upon a set of conditions that reflect a comparatively straightforward adjacent band interference situation. This base case was chosen for its relative simplicity and is intended to provide the basis for (a) consideration of more complex situations (e.g., where decoupled rather than coupled receivers are involved) and (b) developing a logical framework for more detailed descriptions of each individual step.

The set of conditions or assumptions used in constructing the flow diagram include the following:

First, it is assumed that the services on either side of the frequency boundary separating the two bands are licensed services and that the associated providers of these services are commercial licensees with adequate resources to participate in the process. More complexity would be involved if, for example, the service on one side was a non-commercial service under the jurisdiction of the NTIA rather than the FCC.

Second, it is assumed that coupled receivers are associated with the licensed systems on both sides of the boundary. That is, it assumed the licensees have control over the technical performance characteristics of the associated receivers (and transmitters) and control the conditions and timing of their upgrading or replacement. More complexity would be involved if the receivers are not controlled by the licensees (e.g., as in the case of television broadcasting) and/or unlicensed services were involved.

Third, and importantly, it is assumed that the receiver interference limits/harm claim thresholds for services on both sides of the boundary have already been adopted by the FCC using the process described in Section 3.3. Likewise, it is assumed that transmitting system signal power limits have also been adopted for both sides of the frequency boundary.

Fourth, it is assumed for this base case that the interference being experienced is widely distributed both geographically and temporally. This would be the case when, for example, widely deployed consumer devices like television sets or handheld wireless devices receiving signals "over the air" are interfered with by, say,

[24] A large deployment in contravention of rules may implicitly set a de facto harm threshold by virtue of construed harm (the "squatters rights" or "adverse possession" problem).

geographically dispersed private land mobile radio, amateur radio transmitters or other wireless devices operating in an adjacent band. Thus the base case would exclude resolution of interference that arises when multiple radio systems (i.e., transmitters and receivers) are co-located at a single antenna site, or on a single tower, or even share a single antenna on a tower.[25] It would also exclude situations where the interference is very transient and does not occur with any degree of regularity.

Fifth, it assumed that the interference is being generated by intentional radiators, i.e., "a device that intentionally generates or emits radio frequency by radiation or inductions," as opposed to unintentional radiators that do not deliberately generate radio frequency emissions. Examples of unintended radiators include personal computers (whose internal clocks can generate such emissions) and switching power supplies. Furthermore it is assumed that the interference is not being generated by a limited number of malfunctioning devices or by intentional jammers.

Sixth, it is further assumed that the interference being experienced does not produce an immediate threat to public safety services. Interference that threaten the safety of life and property on an urgent basis is treated by the FCC and the NTIA and affected government agencies as a non-routine matter that differs from the more routine interference resolution processes of the type described herein.

The individual steps in the flow diagram below are color coded to indicate who is responsible for each of the steps. The steps involving actions to be taken by the operator of the system being interfered with are outlined in green. In some contexts the system receiving interference is referred to as the victim receiver or system but that term is avoided here in favor of a more neutral term, namely "target system." The steps involving actions taken by the FCC are outlined in red and steps taken by the FCC working in conjunction with a multi-stakeholder group are outlined in blue. Optional or voluntary steps are indicated by dashed rather than solid lines.

Each step in the flow diagram contains an abbreviated description and is identified by a letter running from A to Z. Following the flow diagram itself, more complete descriptions and explanations for each of the lettered steps is provided.

[25] When transmitters and receivers operate in very close proximity at a shared antenna site, severe forms of interference can result – including transmitter and receiver intermodulation, receiver overload, and receiver desensitization. Because each site is different in terms of, for example, the transmitter/receiver bands and frequencies employed, the physical spacing between antennas utilized by different systems, and the types of signals involved, the solutions for resolving interference issues tend to be site specific and they may include the deployment of special filters (e.g., high performance cavity filters) and other devices to allow the different systems to successfully coexist. Interference issues at shared antenna sites are typically resolved on a voluntary basis among the different parties, often with the help of the site owner, consulting engineers with specialized technical expertise, the frequency coordinators for the services/bands involved, or, potentially, in extreme cases involving public safety services, the FCC.

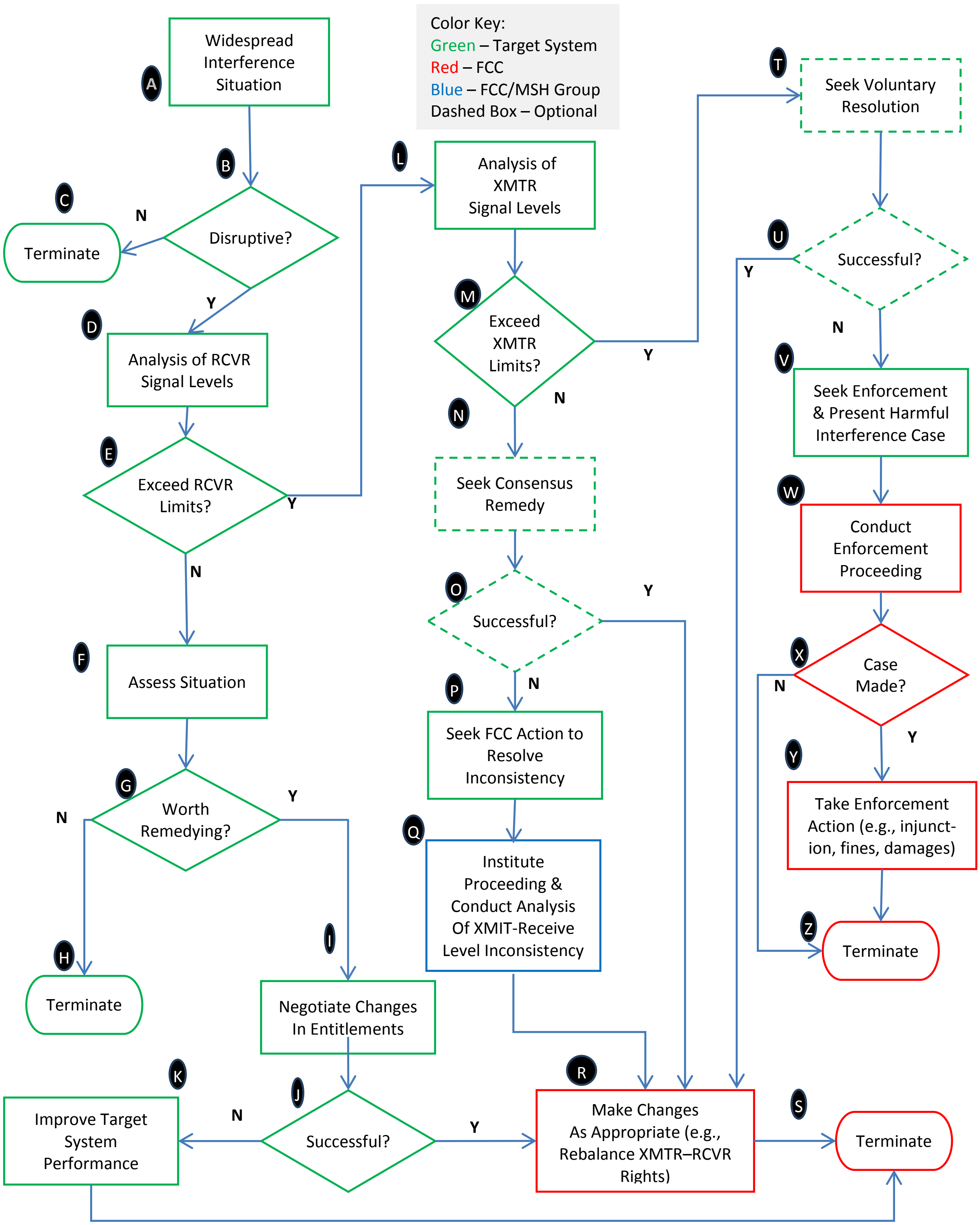

Figure 7. Enforcement Process. A decision tree for making enforcement decisions under the base case described in the text.

6.2. Description of steps

A . Step: Widespread Interference Situation — Actor(s): Target System Operator

The target system operator becomes aware of geographically and temporally widespread interference based upon consumer complaints, routine measurements or by other means.

B . Step: Disruptive? — Actor(s): Target System Operator

The target system operator makes an initial determination as to whether the interference is widespread and severe enough to warrant further action, i.e., it is at a level that "seriously degrades, obstructs, or repeatedly interrupts" its service [47 CFR § 2.1(c)].

C . Step: Terminate — Actor(s): Target System Operator

If the target system operator determines that the interference is neither widespread nor severe enough to warrant action, the process is terminated.

D . Step: Analyze RCVR Signal Levels — Actor(s): Target System Operator

If the target system operator determines that the interference is widespread and severe enough to warrant further action, the operator is responsible for conducting or having conducted an engineering study to determine whether or not established receiver interference levels are being exceeded over a specified geographic region; the study could be carried out through actual field measurements or engineering calculations using accepted radio signal propagation models or a combination of measurements and modeling.

E . Step: Exceed RCVR Limits? — Actor(s): Target System Operator

Based upon the results of the analysis conducted in Step D, the target system operator decides whether or not the established interference levels needed to establish a case of harmful interference are being exceeded (i.e., whether or not the harm claim threshold is exceeded).

F . Step: Assess Situation — Actor(s): Target System Operator

If in Step E the target system operator finds that the interference levels needed to establish a case of harmful interference are not being exceeded, then the operator needs to assess the situation to determine whether or not the problem is worth remedying.

G . Step: Worth Remedying? — Actor(s): Target System Operator

Having assessed the situation, the target system operator must decide whether to seek a voluntarily solution with the system operator whose transmitters are associated with the interference.

H . Step: Terminate — Actor(s): Target System Operator

If the target system operator determines that trying to remedy the interference situation is not justified, then the process is terminated.

I . Step: Negotiate Changes in Entitlements — Actor(s): Target System Operator

If the target system operator determines that trying to remedy the situation is justified, then the operator can attempt to negotiate voluntary changes with the operator of the transmitters in the adjacent band to reduce the interference being received; for example, the target system operator could pay the operator in the adjacent band (the source of the interference) to reduce power, to employ additional transmitter filtering, change antenna orientation, or provide additional guard band space.

J . Step: Successful? Actor(s): Target System Operator

In this step, the target system operator determines whether the negotiations described in Step I have been successful; i.e., that they will reduce the interference to tolerable levels.

K . Step: Improve Target System Performance Actor(s): Target System Operator

If on the other hand, the negotiations carried out in Step J are not successful, then the target system operator can still improve the performance of his or her system in the face of interference by, for example, improving receiver system performance or increasing internal guard bands. After making such improvements, the target system operator terminates the effort in Step S.[26]

L. Step: Analysis of XMTR Signal Levels Actor(s): Target System Operator

If in Step E, the target system operator determines that the harm claim thresholds are being exceeded, the next step is to determine whether or not this is being caused by the operator in the adjacent band operating his or her system at power levels that exceed the allowed levels as specified by the relevant transmitter rights regime. In some services, this may require the cooperation of the FCC.

M . Step: Exceed XMTR Limits? Actor(s): Target System Operator

Based upon the analysis described in Step M, the target system operator determines whether the allowed XMTR signal levels are being exceeded.

N. Step: Seek Consensus Remedy Actor(s): Target System Operator

If it is determined in Step M that the operator in an adjacent band is producing power levels exceeding the transmitter limits, the target system operator could seek to achieve a consensus remedy between or among the affected parties in order to avoid a potentially costly and lengthy FCC process. (Note that this step and the one following are optional.)

O. Step: Successful? Actor(s): Target System Operator

Based upon the attempt at consensus described in Step O, the target system operator determines whether consensus has been reached. If consensus has been reached, then the FCC makes appropriate changes to its rules in Step R (if required) and the process is terminated in Step S.

P. Step: Seek FCC Action Actor(s): Target System Operator

If in Step M it is determined that the operator in the adjacent band is not producing power levels exceeding the transmitter limits and, optionally, the target system operator is not able to obtain a consensus remedy in Steps N and O, then the target system operator can seek action by the FCC.

Q. Step: Institute Proceeding/Conduct Analysis Actor(s): FCC/MSH Group(s)

If in Step P, the target system operator determines that the operator in the adjacent band is not producing power levels that exceed the transmitter limits, then the FCC, perhaps in cooperation with one or more MSH groups, will undertake a more in-depth analysis as to what is causing the situation in which the harm claim thresholds are being exceeded even though the operator in the adjacent band is not exceeding his or her transmitter rights. Such a discrepancy could arise because of problems with the process used to establish the initial harm claim thresholds or with the data used in the process. For example, in the case of the former, the propagation model used to establish the receiver interference could be inadequate thus leading to a situation where the actual received signal levels are greater than that predicted by the model.

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[26] Rather than improve his or her own system, the target system operator could still try to get the FCC to intervene based upon a claim of harmful interference even though the transmitter power limits are not being exceeded.

The latter case could arise in the situation where, for example, the number of interfering emitters operated by the operator in the adjacent band exceed the number and/or geographic distribution assumptions used to establish the original harm claim thresholds. Based upon the analysis, the FCC then makes appropriate changes to its rules in Step R and the process is terminated in Step S.

R . Step: Make Changes as Appropriate — Actor(s): FCC

If the target system operator determines that the voluntary negotiations have been successful, then the FCC makes appropriate changes to its rules in Step R (if required) and the process is terminated in Step S.

T. Step: Seek Voluntary Resolution — Actor(s): Target System Operator

If in Step M, the target system operator determines that the operator in the adjacent band is producing power levels that exceed the transmitter limits, the target system operator can seek voluntary resolution of the matter with that operator i.e., the system operator whose transmitters are associated with the interference.

U. Step: Successful? — Actor(s): Target System Operator

Based upon the attempt at a voluntary resolution, the target system operator determines whether the issue has been resolved satisfactorily. If consensus has been reached, then the FCC makes appropriate changes to its rules in Step R (if required) and the process is then terminated in Step S.

V. Step: Seek Enforcement/Present Case — Actor(s): Target System Operator

If in Step M, the target system operator determines that the operator in the adjacent band is producing power levels that exceed the transmitter limits and, optionally, the attempt at voluntary resolution is not successful in Step U, then the target system operator can seek enforcement action by the FCC. In seeking the enforcement action by the FCC, the target system operator presents the results of his or her analysis of the XMTR signal levels.

W. Step: Conduct Enforcement Proceeding — Actor(s): FCC

If the evidence that the target system operator gathers on the XMTR signal levels is persuasive as determined by the FCC, then the target system operator still must demonstrate that the excessive signals actually cause harmful interference.

X. Step: Case Made? — Actor(s): FCC

If the target system operator successfully demonstrates that the harm claim thresholds are being exceeded and, as a result of Step W, immediately above, the FCC determines that the resulting interference is harmful using the traditional definition of that term, then the target system operator will have made his or her case.

Y. Step: Take Enforcement Action — Actor(s): FCC

If the answer in Step X is affirmative, then the FCC will take enforcement action such as issuing an injunction, levying fines, or (if authorized) awarding damage payments and then terminate the proceeding (Step Z).

Z. Step: Termination — Actor(s): FCC

If the answer in Step X is negative (the case of harmful interference is not made), then the proceeding is also terminated in Step Z.

7. Alternatives to harm claim thresholds

7.1. Four ways to manage interference tolerance

This paper recommends that interference limits policy be targeted to cases where cross-allocation interference problems can be foreseen, for example when a currently quiet band will be re-allocated to a higher power service at a later date. Setting harm claim thresholds will allow the regulator and band users to head off problems by drawing lines early, i.e. clarifying where responsibilities for interference harm mitigation will lie.

Interference limit policy may not be necessary at all. On the other hand, harm claim thresholds may not be sufficient in other cases. There are at least two alternative approaches for such cases: self-certification and receiver mandates. In the first, a manufacturer would *self-certify* that a device is fit for the purpose of its envisaged use, e.g. that it will operate successfully (i.e. suffer no harmful interference in accordance with 47 C.F.R. § 2.1) given the prescribed harm claim thresholds. If it was a "cheap and cheerful" product that is only intended for use where signal levels are high, or that can tolerate interruption due to adjacent channel overload, for example, its marketing would need to make it clear that high performance should not be expected.

A self-certification could be a retail warranty, enforced by false advertising regulation, or it could be part of a process where the FCC requires the manufacturer to submit a testing protocol that includes quality of service criteria (determined by the manufacturer, and keyed to the intended use) that allows validation of the claim to be fit for purpose as part of equipment authorization (http://transition.fcc.gov/oet/ea/). While a manufacturer may develop its own service quality metrics and performance parameters to use in self-certification, the manufacturer may opt to self-certify to an industry standard using an industry certification process, e.g. a "Good Housekeeping Seal of Approval" arrangement, rather than an in-house specification if an industry standard-setting organization has developed applicable receiver performance standards.

A more onerous regulatory path is for the regulator to *mandate specific receiver performance requirements*. This step may be required if an assignment is to be made to unlicensed devices and a neighboring band is currently quiet but is planned for more intensive use later, or if the neighboring band is used sporadically, especially by government services (see below for a discussion of the applicability of various regulatory approaches to use contexts).

An introduction to the specification of receiver performance requirements is given the Appendix, section 9.3. The regulator may choose to incorporate industry standards in rules, as is done by the FAA for aviation receiver standards, or the FCC's use of the ASTM DSRC standard in the Dedicated Short Range Communications service (47 C.F.R. § 90.379). In other cases, the FCC may base performance values on industry standards, manufacturers' technical filings and specification sheets, and standard reference works, as it did in formulating the minimum receiver requirements for 800 MHz voice radios in 47 C.F.R. § 22.970 (b).[27]

Developing its own receiver performance mandates is the most challenging option since the FCC would have to first determine what harmful interference means (e.g. quality of service criteria like acceptable bit error rate), and then define receiver performance parameters (e.g. adjacent channel selectivity, EMC tolerance, image rejection, intermodulation rejection, and spurious rejection). Care must be taken not to preclude market development, e.g., due to implementation costs or other burdens on product development. Minimal receiver performance criteria such as a requirement that receivers implement a front-end filter with specified out-of-block attenuation may be sufficient in some cases. All participants are likely to hold out the hope that only minimal performance criteria will be required; however, this is difficult to achieve in practice since standard-setting almost inevitably leads to more complexity as all the use cases are explored (Maior 2012, section 3.4.4).

Thus, there are four ways to manage interference tolerance:

[27] Paragraph 110 in FCC 04-168, Report & Order in WT Docket 02-55 released August 6, 2004.

1. Do nothing beyond customary transmitter rules
2. Interference limits
3. Self-certification
4. Receiver mandates

In order to structure the application of these approaches, we divide services into three categories:

- Licensed operations
- Decoupled receivers (defined below)
- Unlicensed devices

Where licensees are established organizations that control both the transmission and reception components of their systems, the regulator can reasonably expect they will have the expertise to take harm claim thresholds into account in the design of their systems, and to recognize that they will not be able to fall back on harmful interference claims if their systems suffer performance degradation in the presence of interfering signals below the harm claim threshold.

Adding harm claim thresholds to existing rules is unlikely to add significant value at block boundaries where licensees on either side have similar business models and technology, interact with each other repeatedly, and control both transmitters and receivers. For example, cellular systems tend to use common industry standards that manage cross-service interference, and carriers frequently conclude negotiations to vary their regulator-assigned rights to improve their operating efficiency. When both the service technology (e.g., OFDMA/CDMA/TDMA and FDD/TDD methods) and deployment scenarios (e.g., deployment densities, antenna heights, transmit power levels) are similar, it is generally much easier to enable beneficial system coexistence.

In cases where a licensee is operating next to a busy band with a different service but where the generated signals match the harm claim thresholds, such thresholds should be sufficient. Explicit harm claim thresholds may be useful here, though, because services on either side of the boundary do not have the benefit of identical technology and business models to facilitate the resolution of disputes; harm claim thresholds thus provide a framework for negotiation.

There are a few cases of licensed services where the regulator may wish to ensure the interference tolerance not just of licensed systems of a whole, but of individual receivers as well; the paradigm case is aviation where life safety is paramount. In such cases, receiver mandates may be imposed, such as the mandatory technical standards orders published by the Federal Aviation Administration that requires HF radio receiving equipment to meet RTCA standards (see e.g. Joiner 2003, section 3.4 and 5.2). In many cases, industry standards already exist for receivers. Even where life safety is not involved, the trust gap between government (particularly military) and civilian users as a result of previous interference problems such as the garage-door case (GAO 2005) may lead the FCC to require that civilian devices sharing bands with government users should demonstrate adequate operation given the specified harm claim threshold. At a minimum, device self-certification could be required of all devices, including those operated by licensees. If the civilian devices are unlicensed, mandated performance criteria may be required for certification. For a detailed discussion of interference limits policy in the context of sharing between federal and non-federal services, see PCAST (2102), Appendix D.

In summary, approaches listed above may (but need not) be mapped to licensed services as follows:

- *Same service across boundary*: nothing beyond customary transmitter rules
- *Different service across boundary, but occupancy matches harm claim thresholds*: perhaps harm claim thresholds
- *Low intensity use across boundary*: harm claim thresholds

- *Performance critical services*: self-certification, perhaps receiver mandates

In cases where licensees do not control the design, sale or operation of receivers used with their system, i.e. where receivers are *decoupled*, the cross-allocation interference problem can be particularly acute. Examples of decoupled receivers include television, GPS, FM radio and satellite weather receivers.

There is a risk that decoupled receiver manufacturers could sell devices that fail even for signals below the harm claim threshold; the risk increases with unsophisticated purchasers that do not understand that they are obliged to accept the resulting performance degradation. The situation can be exacerbated when there are many small manufacturers serving a large retail market. When consumers suffer harmful interference, they may seek a remedy through the political process, rather than with the regulator or the manufacturer (as occurred in the garage door case, see GAO 2005).

For the purposes of receiver performance, unlicensed devices are similar to decoupled receivers: there is no licensee taking a system view of receiver/transmitter interaction in the presence of adjacent band interference, and there is often a diverse manufacturing industry serving a large retail market. We therefore treat these two cases together.

In these cases it may be desirable to augment harm claim thresholds with explicit receiver performance specifications that commit the manufacturer, either voluntarily or by FCC mandate, to acceptable performance levels for individual devices. Quality of service parameters depend on the usage; some users or operators will be more tolerant of service degradation than others, and some scenarios will require higher performance than others. Both "cheap and cheerful" low-performance offerings and premium performance products may meet a market need, and so one should expect quality levels. For example, purchasers may be willing to suffer occasional interference as the price of a cheap product – but they need to be properly informed that they will not be able to claim harm if the interference falls below the harm claim threshold. However, particularly in mass markets with unsophisticated buyers it may be necessary to require a minimum performance level, keeping in mind that industry must be able to produce devices that meet this performance level at a cost consumers will pay; for example, NTIA required conformance with interference immunity metrics in digital to analog converter boxes in order for them to qualify for the coupon program during the DTV transition.

Self-certification is likely to be sufficient when the band next to the affected decoupled receivers and unlicensed devices is already occupied, and interference from the neighboring service matches their harm claim thresholds, since problems with interference tolerance are likely to be apparent immediately.

However, when the block across the boundary from decoupled receivers or an unlicensed service is now quiet but foreseen to increase its energy levels, at least self-certification is necessary. If there is a concern that manufacturers will not design their products to adequate performance levels, the FCC may need to impose receiver mandates.

Finally, if the neighboring band contains performance-critical services, e.g. life safety or government applications, there is a strong *prima facie* case for receiver mandates. Industry standards for life-safety or government equipment already specify receiver performance levels in many cases.

In summary, the regulatory approaches listed above may (but need not) be mapped to decoupled receivers and unlicensed allocations as follows:

- *Occupancy of service across boundary matches harm claim thresholds*: self-certification
- *Low intensity use across boundary*: self-certification, perhaps receiver mandates
- *Performance critical services*: self-certification, perhaps receiver mandates

The mapping of regulatory approaches to allocation regimes is summarized in Table 1:

Table 1: A possible mapping of regulatory approaches to allocation regimes

Service on other side of block boundary	Licensed	Decoupled receivers in licensed service; unlicensed devices
Similar service type, no change envisaged	Nothing beyond customary transmitter rules	Harm claim thresholds
Different service across boundary, but occupancy matches harm claim thresholds	Either "do nothing" or harm claim thresholds	Harm claim thresholds, perhaps self-certification
Currently low intensity use across boundary, but change to more intensive service planned	Harm claim thresholds	Self-certification, perhaps receiver mandates
Performance-critical services	Self-certification, perhaps receiver mandates	Perhaps self-certification, probably receiver mandates

7.2. Other interference limit policy approaches

The interference limit policy approach seeks to enable the deployment of systems that can function optimally in the presence of potentially interfering signals in adjacent frequencies. This paper has focused on implementing interference limit policy using harm claim thresholds. However, there are also other policy tools that seek the same end. We discuss two here: the use of non-mandated receiver performance criteria for public safety systems in the 800 MHz band, and the proposal of Kwerel & Williams (2011, 2012) that users in bands next to bands targeted for flexible use must eventually self protect against interference from such operations.

7.2.1. The 800 MHz Approach

The minimum performance criteria for non-cellular 800 MHz licensees to be entitled to full protection against unacceptable interference developed in the 2004 Report and Order in WT Docket 02-55 (FCC 2004b) seem to be an example of some desired attributes of an interference limits policy approach. (See the Appendices, Section 9.6, for a summary of SMR interference to public safety in the 800 MHz band.) The rules (47 CFR § 22.970) implicitly stated the non-cochannel interference level by specifying a minimum desired signal level, a Carrier to Noise plus interference (C/(I+N)) ratio of the receiver, and requirements for intermodulation rejection and adjacent channel rejection ratio that had to be met to qualify for full protection. However, the performance criteria were optional, not mandated. Many of the performance limits generally corresponded to the industry-specified levels in the P25 public safety radio specification (the TIA-102 series), with the exception of the minimum desired signal level. The coverage area within which receivers had protection rights was clearly stated in terms of receiver performance with respect to minimum desired signal strength, without requiring receivers to meet certain specifications. However, receivers that met certain performance criteria would receive full protection, whereas entitlement to protection is reduced for lesser performing receivers (e.g., poorer selectivity that leads to a lower SINR than a receiver that meets the baseline criteria).

The contrast with the harm claim threshold method can be seen in that the interference level was implicit (to be derived from C/(I+N) and the receiver performance requirements) rather than explicit, and the receiver performance requirement was only explicitly given for voice units; requirements for digital units were less explicit: "In the case of data radios, unacceptable interference occurs when the received signal power criteria, above [the -104 and -101 dBm levels], are met and the bit error rate of the radio exceeds the value specified by the radio's manufacturer for reliable operations" (FCC 2004b, paragraph 19; no minimum receiver requirements are specified for data radios in 47 CFR § 22.970 (b)).

7.2.2. The Kwerel & Williams Proposal

Kwerel & Williams propose to use standard and well accepted transmitter-side technical rules as the basis for defining and evolving interference protection rights more generally to help pave the way for the future repurposing of spectrum for flexible use.

Kwerel & Williams (2011) recommend that future allocations should "self-protect" against projected adjacent band interference by assuming that they will receive only the "protections provided between flexible use bands" i.e. assuming a cellular service in the adjacent block. Kwerel & Williams (2012) explain that when a new allocation is being established next to a band likely to be repurposed for flexible use, the new allocation must (1) protect existing systems and future flexible use systems in that adjacent band, and (2) self-protect against interference from those systems, where flexible use systems is defined as "a dense deployment of base, mobile and fixed transmitters operating at fully functional power levels typical of a modern wireless cellular architecture." Incumbents in bands transitioning to this new interference regime would be given a generous amount of time to replace and upgrade their equipment if they wanted to do so, but could also just accept the additional interference.

A major advantage of this approach compared to harm claim thresholds is that it does not require that field strength threshold levels for harmful interference claims be developed. It uses well-established transmitter-side technical rules to quantify the interference that systems need to self-protect against. Since flexible use cellular deployments are currently seen as a paradigmatic high value use of spectrum, this approach provides a pragmatic solution for likely adjacent band coexistence scenarios. De Vries (2012, Section 4.5) argues that operationalizing the Kwerel & Williams approach results in harm claim thresholds such as those described here in Sections 4.2 and 9.4.2.

8. Recommendations

Since bringing receivers into the regulatory picture by using harm claim thresholds is a new approach, the regime should be introduced gradually, allowing time for the concept to mature and bugs to be worked out. The first step would be for a regulator to develop an interference limit policy framework through consultation on a variety of topics, including:

- allocations where the approach can be tested;
- how parameters should be set, e.g. the attributes of signal strength profiles such as average and/or peak values, altitudes where they should be defined, and the required granularity in spatial, temporal and frequency parameters;
- how parameter values should be determined, e.g. the degree to which they need to reflect the current or future signal environment;
- criteria and methods for supplementing harm claim thresholds with receiver performance requirements like receiver self-certification and standards, enforcement mechanisms, e.g. the use of measurement vs. modeling to resolve disputes;
- and the need to add enabling provisions to communications rules and statutes.

The next step would be to update the statutory instruments if necessary, and then define harm claim thresholds for selected new assignments. Once confidence in the approach and its value has been established, existing assignments would be progressively updated to include harm claim thresholds.

We suggest that the FCC begin to evaluate the harm claim thresholds policy approach. The following recommended actions can be implemented in parallel.

1. *The FCC should encourage the formation of one or more multi-stakeholder groups to investigate interference limits policy at suitable high-value inter-service boundaries*. A multi-stakeholder group could work to develop the appropriate parameters, methods to determine parameter values, and detailed enforcement mechanisms that would be appropriate to the particular stakeholder interests in each case. Candidate service boundaries include television/cellular systems in the 600/700 MHz band, the interface with radar systems in 2700-2900 MHz, federal/commercial coexistence in 3550-3650 away from coastal areas, 2.4/2.5 GHz.
2. *The FCC should issue an appropriate request for input on the implementation of the interference limits policy*. In contrast to a multi-stakeholder process, an invitation to comment would not need to be limited to a particular band, and it could solicit both general and specific feedback on implementation questions. For example, the FCC could issue a Public Notice or Notice of Inquiry (NOI) that invites all interested parties to comment on, among other things: (1) the use of interference limits policy at service boundaries in general, or at particular boundaries; (2) inter-service boundaries where this approach would be valuable, or inappropriate; (3) institutional approaches for implementing harm claim thresholds, including the use of multi-stakeholder processes and rulemaking; (4) suitable parameter sets for harm claim thresholds, and technical methods to determine their values. If desired or simply convenient, an alternative mechanism might be a Notice of Proposed Rule Making (NPRM) connected to a band of interest where the request might be both focused on the matter under consideration and on the general concept.
3. *The FCC should, where necessary, develop the expertise and gather the relevant data to facilitate the establishment of harm claim thresholds at high-value inter-service boundaries*. The Commission would be able to direct attention to a particular case of current regulatory interest, which it could not do in the multi-stakeholder case where it would have to depend on the voluntary ad hoc formation of a group. It could focus work on areas where competing pleadings by competing stakeholders have not, or will likely not,

provide an adequate record for decision making. For example, the FCC could characterize receiver performance, gather data on the geographical distribution of transmitters and receivers in specific bands to support the determination of suitable harm claim thresholds, and/or commission technical consultants to develop pro forma thresholds, or ways to evaluate competing proposals for thresholds, for specific inter-service boundaries.

References

3GPP. (2012). Evolved universal terrestrial radio access (E-UTRA); user equipment (UE) radio transmission and reception. *Technical Specification* TS 36.101. Retrieved from http://www.3gpp.org/ftp/Specs/html-info/36101.htm

APCO, CTIA, Motorola, Nextel, and PSWN (2000): Avoiding Interference between Public Safety Wireless Communications Systems and Commercial Wireless Communications Systems at 800 MHz - A Best Practices Guide. *Technical Report*. Retrieved from http://www.safecomprogram.gov/library/Lists/Library/Attachments/210/A_Best_Practices_Guide.pdf

Advanced Television Systems Committee (2000). ATSC Standard: Transmission Measurement and Compliance for Digital Television, Document A/64, Revision A, 30 May 2000.

Advanced Television Systems Committee (2010). ATSC Recommended Practice: Receiver Performance Guidelines, Document A/74:2010, 7 April 2010.

Ash, D. L. (1984). Improved high performance television receiver. *Technical report* by RF Monolithics, FCC.

Brake, D. (2012). Policy development options. In *Receivers, Interference and Regulatory Options: A Silicon Flatirons Roundtable*. Silicon Flatirons Center. Retrieved from http://www.siliconflatirons.com/documents/conferences/2012.11.13%20Spectrum/PolicyDevelopmentOptions.pdf

CEA (2003). Comments to the Interference Immunity Specifications for Radio Receivers, *Notice of Inquiry*, ET Docket No. 03-65 and MM Docket No. 0-39, 18 FCC Rcd 6039.

Coase, R. H. (1959). The Federal Communications Commission. *Journal of Law and Economics*, 2:1-40.

Code of Federal Regulations, Title 47, Part 90. Private Land Mobile Radio Services, Subpart I: General Technical Standards and Subpart S: Regulations Governing Licensing and Use of Frequencies in the 806–824, 851–869, 896–901, and 935–940 MHz Bands.

Davies, L., & Winter, P. (2010). Study of current and future receiver performance: Final report to Ofcom by TTP. *Technical report*. Ofcom. Retrieved from http://www.ofcom.org.uk/research/technology/research/.

De Vries, J. P. (2009). Radio regulation summit: Defining inter-channel operating rules. *Technical report*, Silicon Flatirons Center. Retrieved from http://www.silicon-flatirons.org/documents/misc/OOBSummit/Inter-channelSummitReportv1.0.1.pdf.

De Vries, J. P. (2010). How I learned to stop worrying and love interference: Using well-defined radio rights to boost concurrent operation. In *International Symposium on Advanced Radio Technologies (ISART) 2010*. National Telecommunications and Information Administration.

De Vries, J. P. (2011). Receiver protection limits: a better way to manage interference than receiver standards [Blog post]. Retrieved from http://deepfreeze9.blogspot.com/2011/06/receiver-protection-limits-better-way.html

De Vries, J. P. (2012). Optimizing receiver performance using interference limits. *40th Research Conference on Communication, Information and Internet Policy, TPRC 2012*. Retrieved from http://ssrn.com/abstract=2018080.

De Vries, J. P. & Sieh, K. A. (2011). The Three Ps: Increasing concurrent operation by unambiguously defining and delegating radio rights. In *New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on*, pages 56-70. IEEE.

De Vries, J. P. & Sieh, K. A. (2012). Reception-oriented radio rights: Increasing the value of wireless by explicitly defining and delegating radio operating rights. *Telecommunications Policy*, 36(7):522-530.

Elektrobit (2011). Legacy UE RX blocking with band 23 LTE UE as interferer – measurement results. *Technical Report R4-112261*, 3GPP TSG-RAN WG4.

FCC TAC, Spectrum Working Group. (2011). Spectrum efficiency metrics, version 1.0 (20 December 2011). *Tech. rep.*, FCC Technology Advisory Council. Retrieved from http://transition.fcc.gov/bureaus/oet/tac/tacdocs/SpectrumEfficiencyMetricsV1-12-20-11.docx

FCC. (2003a). Interference Immunity Specifications for Radio Receivers, *Notice of Inquiry.* ET docket no. 03-65 and MM docket no. 0-39. 18 FCC Rcd 6039. Adopted March 13, 2003. Retrieved from http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-03-54A6.pdf.

FCC. (2003b). Establishment of an Interference Temperature Metric to Quantify and Manage Interference and to Expand Available Unlicensed Operation in Certain Fixed, Mobile and Satellite Frequency Bands. *Notice of Inquiry and Notice of Proposed Rulemaking*. ET Docket no. 03-237. FCC 03-289, adopted November 13, 2003. 18 FCC Rcd 25309. Retrieved from http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-03-289A1.pdf.

FCC. (2004a). Longley-Rice methodology for evaluating TV coverage and interference. *Technical Report*. OET Bulletin No. 69.

FCC. (2004b). Improving Public Safety Communications in the 800 MHz Band, *Report and Order, Fifth Report and Order, Fourth Memorandum Opinion and Order, and Order*. WT Docket 02-55, adopted July 8, 2004.

FCC. (2004c). Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems. *Second Report and Order and Second Memorandum Opinion and Order*. ET Docket No. 98-153. FCC 04-285, released December 16, 2004. Retrieved from http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-04-285A1.pdf

FCC. (2007a). Interference Immunity Specifications for Radio Receivers, *Order.* ET Docket 03-65, adopted May 2, 2007. 22 FCC Rcd 8941. Retrieved from http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-07-79A1.pdf.

FCC. (2007b). Establishment of an Interference Temperature Metric to Quantify and Manage Interference and to Expand Available Unlicensed Operation in Certain Fixed, Mobile and Satellite Frequency Bands. *Order*. ET Docket no. 03-237. FCC 07-78, adopted May 2, 2007. Retrieved from http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-07-78A1.pdf.

FCC. (2012a). Workshop on Spectrum Efficiency and Receivers. Federal Communications Commission. Retrieved from http://www.fcc.gov/events/workshop-spectrum-efficiency-and-receivers-day-1.

FCC, (2012b). Statement From FCC Chairman Julius Genachowski on U.S. Actions at the World Conference on International Telecommunications (WCIT). Retrieved from http://transition.fcc.gov/Daily_Releases/Daily_Business/2012/db1214/DOC-317950A1.pdf

GAO. (2005). Potential spectrum interference associated with military land mobile radios. *Technical Report*. Report GAO-06-172R. Retrieved from http://www.gao.gov/products/GAO-06-172R

Hazlett, T. W. and Oh, S. (2012). Exactitude in defining rights: Radio spectrum and the "harmful interference" conundrum. *George Mason University Law and Economics Research Paper Series* 12-55, George Mason University.

IEEE. (2008). IEEE recommended practice for the analysis of in-band and adjacent band interference and coexistence between radio systems. IEEE Std P1900.2-2008. Retrieved from http://dx.doi.org/10.1109/IEEESTD.2008.4584236.

Joiner, B. (2003). Receiver spectrum standards: Phase 1 – summary of research into existing standards. *Technical Report* TR-03-404, Institute for Telecommunication Sciences, NTIA. Retrieved from http://www.its.bldrdoc.gov/publications/2435.aspx.

Kwerel, E. & Williams, J. (2011). Forward-looking interference regulation. *Journal on Telecommunications and High Technology Law*, 9(2):516-518. Retrieved from http://jthtl.org/content/articles/V9I2/JTHTLv9i2_DeVries.PDF.

Kwerel, E. and Williams, J. (2012). Solving the receiver problem without receiver standards. Slide presentation. FCC Workshop on Spectrum Efficiency and Receivers (Day 2). Retrieved from http://transition.fcc.gov/bureaus/oet/receiver-workshop1/Session6/SESSION-6-1-Kwerel-Williams-FCC.pdf.

Kolodzy, P., et al. (2002). Spectrum policy task force report. *Technical report*, FCC. Retrieved from http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-228542A1.pdf.

Larson, K., et al. (2002). Spectrum policy task force: Report of the interference protection working group. *Tech. rep*., FCC. Retrieved from http://transition.fcc.gov/sptf/files/IPWGFinalReport.pdf

Maior, M. (2011). FCC's authority to regulate receivers. Conference brief, Silicon Flatirons Center, University of Colorado, Boulder. Retrieved from http://www.silicon-flatirons.org/documents/Roundtables/2011.10.18-1021/FCCAuthorityMemo.pdf.

Maior, M. (2012). Efficient interference management: Regulation, receivers, and right enforcement. A report on a Silicon Flatirons summit, held 18 October 2011. Silicon Flatirons Center, University of Colorado, Boulder. Retrieved from http://www.silicon-flatirons.org/documents/Roundtables/2011.10.18-1021/EfficientInterferenceManagement.pdf

Matheson, R. J. (2003). The Electrospace model as a frequency management tool. In *International Symposium on Advanced Radio Technologies (ISART) 2003*. National Telecommunications and Information Administration.

Matheson, R. J. (2005). Flexible spectrum use rights: Tutorial - ISART 2005. In *International Symposium on Advanced Radio Technologies (ISART) 2003*. National Telecommunications and Information Administration.

Matheson, R. and Morris, A. C. (2012). The technical basis for spectrum rights: Policies to enhance market efficiency. *Telecommunications Policy*, 36(9):783-792. Retrieved from http://www.sciencedirect.com/science/article/pii/S0308596112000821. For a pre-print, see http://www.brookings.edu/research/papers/2011/03/03-spectrum-rights-matheson-morris

Morgan, W. L. and Gordon, G. D. (1989). *Communications Satellite Handbook*.

NTIA. (2003). Comment. *Notice of Inquiry*, ET Docket No. 03-65 and MM Docket No. 0-39. November 12, 2003. Retrieved from http://www.ntia.doc.gov/federal-register-notice/2003/comments-standards-non-government-radio-receivers

Ofcom. (2008a). Spectrum usage rights - a guide. *Technical Report*. Retrieved from http://stakeholders.ofcom.org.uk/spectrum/spectrum-management/spectrum-usage-rights/.

Ofcom, (2008b). Initial assessments of when to adopt self- or co-regulation. *Report*. Retrieved from http://stakeholders.ofcom.org.uk/consultations/coregulation/

Parker, I. and Munday, S. (2011). Assessment of LTE 800 MHz base station interference into DTT receivers. ERA Technical Report 2011-0351, Ofcom. Retrieved from http://stakeholders.ofcom.org.uk/binaries/consultations/dtt/annexes/Ite-800-mhz.pdf

Paul, A., Hurt, G., Sullivan, T., Patrick, G., Sole, R., Brunson, L., Wang, C.-W., Joiner, B., & Drocella, E. (2005). Interference protection criteria: Phase 1 - compilation from existing sources, NTIA report 05-432. Tech. rep., NTIA. Retrieved from http://www.ntia.doc.gov/osmhome/reports/ntia05-432/IPC_Phase_1_Report.pdf

PCAST. (2012). Report to the President: Realizing the Full Potential of Government-held Spectrum to Spur Economic Growth. Retrieved from http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf.

Phillips, C., Ton, M., Sicker, D., and Grunwald, D. (2012). Practical radio environment mapping with Geostatistics. Preprint.

Rhodes, C. W. (2010). Interference to DTV reception from FM radio signals. IEEE Transactions on Consumer Electronics, 56(1):18-22.

Rhodes, C. W. (2012a). Future spectrum demands will impact DTV and GPS receiver designs. In 2012 IEEE International Conference on Consumer Electronics (ICCE), pages 281-282. .

Rhodes, C. W. (2012b). Interference to digital broadband communications and spread spectrum communications. In 2012 IEEE International Conference on Consumer Electronics (ICCE), pages 283-284. .

Rhodes, C. W. and Sgrignoli, G. J. (2005). Interference mitigation for improved DTV reception. IEEE Transactions on Consumer Electronics, 51(2):463-470.

Riihijarvi, J., Mahonen, P., Wellens, M., and Gordziel, M. (2008). Characterization and modelling of spectrum for dynamic spectrum access with spatial statistics and random fields. In *Indoor and Mobile Radio Communications* (PIMRC 2008), pages 1-6.

Sanders, F. H. (2010). Derivations of relationships among field strength, power in Transmitter-Receiver circuits and radiation hazard limits. *Technical Memorandum* TM-10-469, NTIA. Retrieved from http://www.its.bldrdoc.gov/pub/ntia-rpt/10-469/10-469.pdf

Stine, J. A. (2007). A location-based method for specifying RF spectrum rights. In *New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2007, 2nd IEEE Symposium on* (pp. 34-45). IEEE. doi:10.1109/DYSPAN.2007.13

Stine, J. A., & Schmitz, S. (2011). Model-based spectrum management—Part 1: Modeling and computation manual. *Technical Report*. The MITRE Corporation. Retrieved from http://www.mitre.org/work/tech_papers/2011/11_2071/.

Tenhula, P. A. (2012). Enforcement of spectrum usage rights: Fair and expedient resolution of 'interference' disputes. *40th Research Conference on Communication, Information and Internet Policy, TPRC 2012*. Retrieved from http://ssrn.com/abstract=2032312.

Transfinite Systems (2008). Derivation of power flux density spectrum usage rights. *Tech. rep*., Ofcom. Retrieved from http://stakeholders.ofcom.org.uk/binaries/consultations/clearedaward/transfinite.pdf

Waz, J. and Weiser, P. (2011). Internet governance: The role of multistakeholder organizations. In *Internet Governance: The Role of Multistakeholder Organizations*. Silicon Flatirons Center. Retrieved from http://siliconflatirons.com/documents/publications/report/InternetGovernanceRoleofMSHOrgs.pdf

Weiser, P. (2008). Exploring Self-Regulatory Strategies for Network Management, *Report*. Silicon Flatirons Center. Retrieved from http://members.bitag.org/kwspub/background_docs/WeiserNetworkManagement.pdf

White House. (2011). International Strategy for Cyberspace: Prosperity, Security and Openness in a Networked World. Retrieved from www.whitehouse.gov/sites/default/fils/rss_viewer/international_strategy_for_cyberspace.pdf.

9. Appendices

9.1. Prior work

The importance of receivers in maximizing the value of radio operation has been understood for a long time. As early as 1984, RF Monolithics performed an FCC contract that "designed and fabricated [a TV receiver] to demonstrate the feasibility of a cost-effective, high performance system that would permit greater utilization of spectrum currently allocated to UHF television broadcasting" (Ash 1984).

After a long hiatus when only a few lone voices like Dale Hatfield kept reminding the community of the importance of receiver performance, the issue resurfaced in 2002 in the report of the FCC's Spectrum Policy Task Force ("SPTFR", Kolodzy et al. 2002). The SPTF's Interference Protection Working Group recommended that the FCC pay attention to receiver characteristics. The report of the Interference Protection Working Group of the SPTF documents extensive comments on minimum receiver performance characteristics, a term used interchangeably with "receiver standards" (Larson et al. 2002, section VII. B.).

The SPTFR introduced the concept of *interference temperature*, a metric that would establish maximum permissible levels of interference, thus characterizing the "worst case" environment in which a receiver would be expected to operate.[28] Overall, the interference temperature focused on allowing additional operations within a band, with an emphasis on using real-time adaptation based on the actual RF environment through interactions between transmitters and receivers and the opportunities for new spectrum access that this would create (SPTFR, Figure 3, section VI. B.). There were suggestions that interference temperature could be used to maintain both in-block and out-of-block (non-cochannel) emissions within permissible limits, and could serve as an alternative to out-of-block emissions limitations, but the use of out-of-block harm claim thresholds to characterize receiver protections was not addressed explicitly.

In 2003, Margie (2003) provided a detailed discussion of the regulatory definitions of "interference" and "harmful interference" and demonstrated that the FCC has not articulated a workable legal standard for permissible interference, even if it were to use interference temperature as the technical criterion. He proposed, following Coase (1959), that the Commission state that the purpose of the permissible interference standard is to maximize total utility in each band rather than to minimize interference to any individual spectrum user, an approach we follow in this paper.

In 2003, the FCC began a Notice of Inquiry regarding receiver performance, building on the work of the Spectrum Policy Task Force (FCC 2003a). However, even while (following the lead of the Spectrum Policy Task Force) it flagged the importance of shifting the assessment of interference towards a focus on the actual RF environment, and interactions between transmitters and receivers, it limited itself to interference immunity performance specifications and did not consider descriptions of the radio interference environment as a regulatory tool. Still, it clearly recognized the role of receivers in maximizing the capacity of spectrum resources: "We believe that incorporation of receiver performance specifications could serve to promote more efficient utilization of the spectrum and create opportunities for new and additional use of radio communications by the American public."

The Notice of Inquiry was met with opposition from many parties, however, who questioned the FCC's authority to impose receiver standards and claimed that the setting of receiver standards should be left to industry. The Commission also opened a Notice of Inquiry and Notice of Proposed Rulemaking on "Interference Temperature" in 2003, responding to the SPTF Report (FCC 2003b). This proceeding also met with opposition from industry, and both proceedings were terminated four years later (FCC 2007a, 2007b).

[28] Interference temperature is compared to interference limits in Section 9.4.

Also in 2003, an NTIA report on receiver spectrum standards (Joiner 2003) undertook a broad review of existing standards, both mandatory and voluntary, government and commercial, and US and international. A planned second phase, intended to assess trade-offs among potential regulatory approaches and develop appropriate recommendations, was never begun. Another NTIA report (Report 05-432, Paul et al. 2005) reviewed publications of national, international, public and private organizations to compile established interference criteria for various radio services operating between 30 MHz and 30 GHz; this compilation contributes material that could inform the calculation of harm claim thresholds in some cases.

The work of Matheson and Ofcom in the mid-2000s emphasized the importance of defining rights in terms of signal strength rather than transmit power. Matheson (2003, 2005), citing W. R. Hinchman's "Use and management of electrospace: a new concept of the radio resource," (*Proc. IEEE ICC'69*, 1969), defined electrospace as a multi-dimensional space (frequency, time, location, and angle-of-arrival) over which the radio signal environment is defined in terms of signal strength (power flux density) rather than as power radiated from the transmitter.[29] In an apparently independent development, Ofcom (2008a) introduced Spectrum Usage Rights (SURs) defined as the maximum level of interference that a licensee is allowed to cause, rather than the power that can be transmitted, on the basis that this directly controls the interference problem. The key advance of Ofcom's work on SURs on Matheson was the explicit introduction of probabilistic metrics into the definition of operating rights.

De Vries (2010) built on this foundation by taking an explicitly probabilistic approach to rights definition and defined operating rights not only in terms of statistical transmission permissions expressed as resulting signal strengths, but also of the reception protections an operator could expect, defined as probabilistic resulting signal strength, leading to the "Three Ps" approach (<u>P</u>robabilistic transmission <u>P</u>ermissions and reception <u>P</u>rotections) of De Vries & Sieh (2011, 2012). This led to the use of harm claim thresholds, called "reception protections" initially and then "interference limits", as an alternative to receiver performance requirements (De Vries 2011). The interference limits approach is described in detail in De Vries (2012).

An unpublished 2009 Ofcom consultation on "Shadow SURs," a right that would sit alongside a traditional radiated-power entitlement, prefigures the Three P's reception protections and the interference limits policy approach advanced in this paper. Shadow SURs were intended to be a form of agreement between neighboring license holders and the regulator as to the level of emissions that the regulator will allow in neighboring bands.

Stine's Model-Based Spectrum Management approach proposed using spectrum consumption models that included a characterization of receivers (Stine 2011). He proposed a set of spectrum modeling constructs, including an intermodulation mask, that are combined to form models of transmitter, receiver and system consumption. Transmitter models capture RF emissions, and receiver models convey the conditions necessary for reception of transmissions.

Kwerel & Williams (2011, 2012) highlighted the difficulty that arises when a new allocation is made while there are no incumbents in an adjacent band or the band is lightly used: there is no incentive on the new licensee to deploy systems that could tolerate such interference, thus precluding some future re-allocation options. They recommended that the FCC should require that licensees self protect against interference exposure from adjacent band(s) by assuming that those bands would be licensed under a flexible use, i.e. cellular, model. The assumption of a cellular neighbor is similar to a harm claim threshold derived from a cellular deployment (Section 4.2).

The role of receivers in harmful interference has been highlighted by U.S. regulators and the executive branch. On March 12, 2012, the FCC held a two-day workshop on spectrum efficiency and receivers (FCC 2012a); the video and slide materials on the conference web site provide an up-to-date survey of US perspectives on receiver management. While there was no agreement on the most appropriate regulatory tool, there seemed to be a consensus among both academics and industry that action was required. In a July 2012 report of the President's Council of

[29] For Matheson's current thinking, see Matheson & Morris (2012)

Advisors on Science and Technology about realizing the potential for government-held spectrum (PCAST 2012), the Council included a recommendation that harm claim thresholds should be used to manage spectrum sharing between federal and non-federal services.

9.2. Receivers and interference

There have been many cases where receiver performance was a significant issue limiting the regulator's ability to allocate spectrum for new services. For example, the NTIA's comment on the Receiver NOI (NTIA 2003) enumerated "a number of instances of reported interference that could have been avoided if appropriate receiver standards had been applied", including "commercial fixed-satellite service receiving earth stations that use low noise amplifiers at the antenna and have little or no filtering prior to active components, commercial digital radio relay receivers which use low noise amplifiers with little or no filtering prior to active components, consumer unlicensed Part 15 receivers such as garage door openers which use very wide bandwidths, analog television and other consumer receivers with generally very poor Radio Frequency selectivity, commercial Very High Frequency (VHF) Maritime receivers with insufficient selectivity resulting in interference from National Oceanic and Atmospheric Administration (NOAA) weather broadcasts and land mobile transmitters" and "wireless cable system receivers with insufficient selectivity resulting in interference from Air Traffic Control radars in the 2700 to 2900 MHz band."

More recently, the FCC Technological Advisory Council's white paper on Spectrum Efficiency Metrics summarized nine of them (FCC TAC 2011, Appendix C), including:

- The prospect of overload interference to legacy Satellite Digital Audio Radio Service (SDARS, aka SiriusXM) receivers from mobile devices in the Wireless Communications Service (WCS) required application of strict technical rules and effectively created 5 MHz guard bands on each side of the SDARS allocation
- Many C-band satellite earth station receivers operating at 3700–4200 MHz are susceptible to signals from well inside the 3650–3700 MHz band that was transferred from federal to commercial use, risking the possibility that much of the federal transferred spectrum would be useless.
- The use of the 20 MHz AWS-3 band (2155–2175 MHz) for time-division duplex operation was blocked because cellular handsets in the lower adjacent AWS-1 F-block (2145–2155 MHz) were designed to operate across the AWS-3 spectrum consistent with international (but not U.S.) allocations,[30] and thus were unable to reject interference from nearby AWS-3 handset transmissions.
- The AWS-1 downlink spectrum at 2110–2155 MHz is upper adjacent to the broadcast auxiliary service (BAS) at 2025–2110 MHz. AWS-1 licensees were required as the newcomers to correct any harmful interference to the BAS operations. Since BAS equipment had not been designed with sharp filters, AWS-1 operations were found to cause harmful interference to BAS, requiring the AWS-1 licensees to pay to design, purchase and install new filters for BAS equipment.
- TV Receiver performance was a significant issue for the access of unlicensed devices in unused portions of the TV bands (i.e., the TV White Spaces). The roll-off of the TV filters is the dominant factor limiting the amount of energy that a TV White Space device may emit on allowed TV channels and therefore the potential applications for the devices.
- Receiver performance relative to adjacent channel and intermodulation characteristics was a major element in the issue of rebanding the 800 MHz spectrum to avoid interference between Nextel and Public Safety operations on interleaved channels

[30] The ITU IMT-2000 and European UMTS downlink band is 2110–2170 MHz, whereas the US AWS-1 downlink band is 2110–2155 MHz.

- LightSquared's proposed deployment of ancillary terrestrial component (ATC) base stations as part of a hybrid terrestrial–satellite service has raised significant concerns about potential harmful interference to the GPS service operating in the upper adjacent spectrum due to the potential for receiver overload, i.e. power transmitted in LightSquared's licensed frequencies causing degradation of GPS devices that did not filter out this energy sufficiently well.

The effect a transmitter has on a receiver, whether desired or undesired, decreases with separation between them in frequency and space. Interference therefore comes in two flavors: between operations using the same frequency range but in adjacent geographical areas, and operations using adjacent frequencies in the same geographical area. The first is managed by controlling the distance between systems using the same frequencies; the second depends on the distribution of transmitted energy over frequency, and performance of the receiver. The first type is referred to as co-channel interference. We focus on the second case, non-cochannel interference, which can be sub-divided into adjacent channel, nonadjacent channel, band edge and far out-of-band interference (see Figure 8; for an alternative classification, see Figure 6 in IEEE 2008).

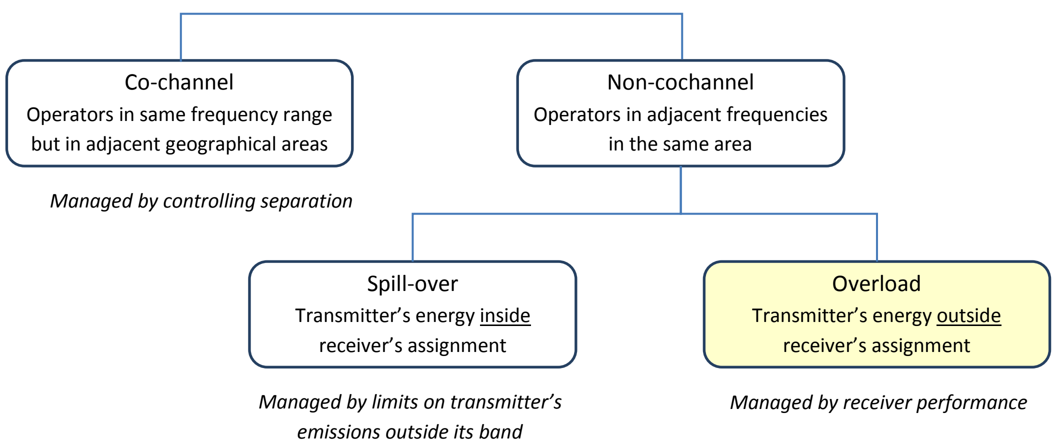

Figure 8: Classification of Interference

There do not seem to be regulatory definitions for the terms "channel" and "band." We will thus use the term "block" when referring to a generic operating frequency assignment, whether channel or band.[31, 32]

Broadly speaking, interference across frequency boundaries can be due to one of two causes (Figure 9):

[31] Cf. http://www.its.bldrdoc.gov/fs-1037/dir-024/_3495.htm or http://life.itu.int/radioclub/rr/art01.htm. Frequency bands are loosely defined by their propagation characteristics and allocated to radio service types by regulator(s); frequency blocks are assigned to licensees by regulator(s); licensees implement channels based on certain technologies.

[32] The terms allocation and assignment are defined in Article 1, Section II of the ITU Radio Regulations (see http://life.itu.int/radioclub/rr/frr.htm) and incorporated into national regulations (e.g. http://www.gpo.gov/fdsys/pkg/CFR-2010-title47-vol1/xml/CFR-2010-title47-vol1-part2.xml):

1.16 *allocation* (of a frequency band): Entry in the Table of Frequency Allocations of a given frequency band for the purpose of its use by one or more terrestrial or space radiocommunication services or the radio astronomy service under specified conditions. This term shall also be applied to the frequency band concerned.

1.18 *assignment* (of a radio frequency or radio frequency channel): Authorization given by an administration for a radio station to use a radio frequency or radio frequency channel under specified conditions

1. Spill-over: energy from a frequency neighbor falling in a receiver's assigned frequencies, due to imperfect filtering of the transmitter, unwanted transmitted energy falls into the receiving bandwidth of the receiver; usually regulated via limits on emissions outside the transmitter's authorized bandwidth.
2. Overload: energy outside the victim's assigned frequencies that its receiver cannot ignore, due to imperfect filtering in the receiver. This mode (also known as out-of-band interference,[33] blocking, or desensitization) involves several possible undesired responses of the receiver to the fundamental emissions in the transmitter's tuned channel; in other words, cases where signals outside of the nominal receiver bandwidth cause the victim receiver to experience an increased noise level or produce non-linear responses.

Transmitter spill-over needs to be controlled by filtering in the transmitter, since it coincides in frequency with the desired signal that the receiver wishes to decode. The impact of an overload signal can be reduced either by reducing its transmitted power, which is to the transmitter's detriment since this is the desired signal in its assigned frequency range, or by a receiver using filters that reject this signal that by definition falls outside its assignment.[34]

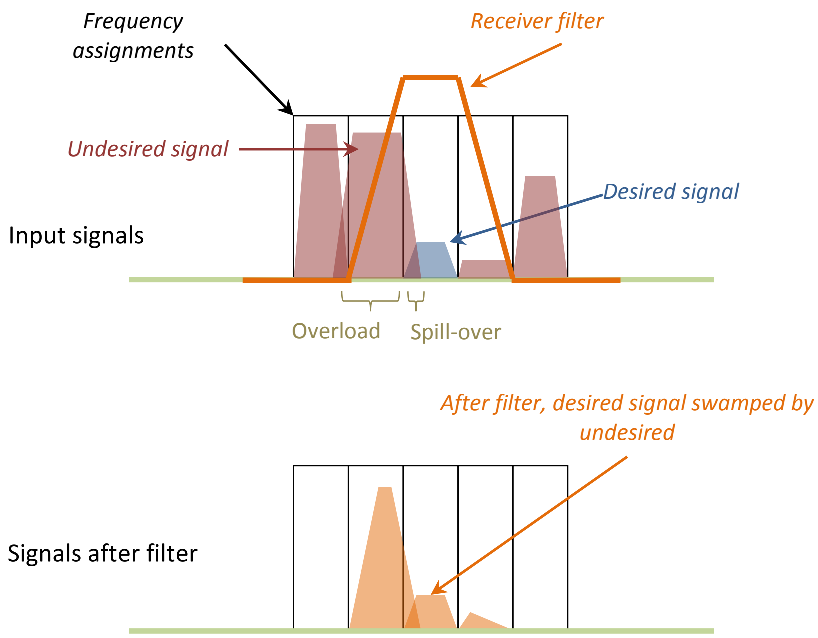

Figure 9: Schematic of spill-over and overload interference, showing importance of filter performance. An undesired signal can have both overload and spill-over components. Receiver filtering can reduce overload components, but not spill-over. If the overload component is strong enough, and the filter wide enough, it may swamp the desired signal after the filter stage. Additional spurious signals generated in the desired band by strong out-of-block signals are not shown.

[33] The term out-of-band is confusing, since its meaning depends on whether it's being described from the perspective of a receiver or a transmitter. From the receiver's perspective, what we define as overload is out-of-band interference. On the other hand, seen from a transmitter, out-of-band emissions falls within a receiver's assigned channel, and is called spill-over here.

[34] A "guard band" results when the allowed transmit power next to a receiver's assignment is set to a very low level. A receiver operator may implement an "internal guard band" by leaving a gap inside its assigned frequencies between the band edge and its desired signal.

Since dealing with overload problems is more or less under the receiver's control, this paper will focus on the overload scenario as indicated by the highlight in Figure 8, i.e. the extent to which a receiver has the responsibility of dealing with energy outside its assigned frequencies.

There are many mechanisms for this second mode of non-cochannel interference. For example, energy from outside a victim's operating frequencies may desensitize[35] a receiver, hiding desired signals, or it may generate signals within the operating frequency range by non-linear mixing in the receiver (known as intermodulation interference). The NTIA report on receiver standards gives the following list (Joiner 2003):

- feed through of non-cochannel signals to the demodulator due to inadequate selectivity (filtering) at RF and IF stages;
- blocking due to an undesired very strong signal saturating the first amplifier stages and causing severe distortion
- receiver desensitization resulting from erroneous automatic gain control responses to non-cochannel signals;
- gain compression due to inadequate RF selectivity and dynamic range;
- spurious responses (to non-cochannel signals that mix with locally generated signals and fall within the receiver pass band); and
- intermodulation of the desired and non-cochannel signals or two or more non-cochannel signals in non-linear stages of a receiver (e.g., in connection with gain compression).

These effects are outside the transmitter's control since they are caused by authorized signals generated within the transmitter's assigned frequencies. The regulatory management of receiver interference rejection therefore focuses on non-cochannel interference due to signal energy outside its assigned operating frequency range.

9.3. Receiver performance specifications

A receiver's ability to process the desired signal in a frequency channel without being affected by interfering signals present in adjacent and other channels is described as its selectivity, and is largely determined by the following factors (Davies & Winter 2010, section 1.2; see also Joiner 2003, section 2):

- *Receiver channel filter performance*. The ability to receive large and small signals simultaneously. In modern digital receivers, this is divided into analog filtering prior to analog-to-digital conversion (ADC) of the received signal, and digital filtering following the ADC. The quality of digital filtering is dictated by the dynamic range of the ADC.
- *Reciprocal mixing*. When the received RF signal is mixed with a local oscillator to convert it to typically a much lower frequency for channel filtering and demodulation, noise is added by the local oscillator that can swamp small wanted received signals.
- *Receiver linearity*. Nonlinearities in analog receiver elements such as amplifiers, mixers, and active filters introduce distortion to both the wanted and any unwanted signals that can lead to the creation of interfering signals at new frequencies. If these occur at critical frequencies within the receiver, they will affect the receiver's ability to receive a small wanted signal.
- *Spurious responses*. Unwanted signals at certain receiver-dependent frequencies could block the wanted signal.

[35] Desensitization refers to a reduction in receiver sensitivity due to the presence of a high-level off-channel signal overloading the radio-frequency amplifier or mixer stages.

A receiver's behavior in the presence of such effects is characterized by a variety of parameters, including (Joiner 2003, section 2):

1. *Adjacent channel rejection (attenuation)*. The ability of a receiver to reject signals in the adjacent channel.
2. *Adjacent channel selectivity*. The ability of a receiver to discriminate between a desired (in-channel) signal and an undesired signal in an adjacent channel.
3. *Image frequency rejection*. The ability of a receiver to reject signals at the image frequency.
4. *Intermodulation rejection (aka cross modulation rejection)*. The ability of a receiver to reject intermodulation products produced by the mixing of two or more signals at the input to the receiver.
5. *Selectivity*. Rejection (attenuation) of an undesired signal at frequencies close to the desired signal frequency. It is often specified as the amount of frequency difference between desired and undesired signals needed to produce a specified attenuation of the undesired signal.
6. *Sensitivity depression or desensitization*. The level of a non-cochannel signal that increases a receiver signal power threshold or decreases receiver gain by a defined amount.
7. *Spurious response (aka spurious rejection)*. Undesired receiver response resulting from mixing of the local oscillator and undesired signals. This includes the response to undesired signals at the image frequency.

Specifying receiver performance parameters to prevent non-cochannel interference is therefore complicated, since there are so variables, and different types of receivers are characterized in different ways. The complexity of standards for receiver performance is well illustrated in the NTIA Report 03-404 (Joiner 2003). This document summarizes US federal agency, US industry association, and international standards. The parameters used to specify receiver standards in the NTIA Manual vary from service to service, and include adjacent channel rejection (different values for analog and digital), EMC tolerance, frequency stability, image rejection, intermodulation rejection, receiver interference suppression circuitry, selectivity, and spurious rejection (Joiner 2003, Table 1). For example, the Department of Agriculture's specification for VHF High-Band receivers is a 12 row by 6 column table of parameter values (Joiner 2003, Table 5).

The FCC has mandated receiver specifications in a very few cases. 47 C.F.R. § 15.117 set requirements on TV broadcast receivers for tuning controls, attached antennas, "peak picture sensitivity," noise figure, DTV reception (a tuner mandate), antenna/cable selector switch isolation, and the now-obsolete consumer alert for analog-only receivers. The 47 CFR § 15.118 rules for cable TV receivers provides very detailed requirements and measurement methods for adjacent channel interference, image channel interference, direct pickup interference, tuner overload and cable input conducted emissions.

In the 800 MHz public safety proceeding (800 MHz 5th R&O 4th MO&O docket 02-55 (2004) at paragraph 109 ff., promulgated as 47 CFR § 22.970 (b)) the FCC specified minimum requirements that a receiver should meet before it could claim entitlement to full protection against unacceptable interference. 47 CFR § 90.672 goes into further detail, resulting in an inventory of 14 parameters that are required to specify the receiver performance requirements:

- median desired signal strength: -104 dBm or -88 dBm, depending on band (2 parameters)
- voice transceiver C/(I+N): 20 dB or 17 dB, depending on band (2 parameters)
- non-voice transceivers: target BER "reasonably designated by the manufacturer" (1 very elastic parameter)
- voice units intended for mobile use: 75 dB intermodulation rejection ratio; 75 dB adjacent channel rejection ratio; -116 dBm reference sensitivity (3 parameters)
- voice units intended for portable use: 70 dB intermodulation rejection ratio; 70 dB adjacent channel rejection ratio; -116 dBm reference sensitivity. (3 parameters)

- voice units intended for mobile or portable use in the 900 MHz Business/Industrial Land Transportation Pool: 60 dB intermodulation rejection ratio; 60 dB adjacent channel rejection ratio; -116 dBm reference sensitivity. (3 parameters)

Note that intermodulation, adjacent channel rejection ratio and sensitivity aren't specified for non-voice units. The Commission states in the R&O (at 107) that "because the technical parameters necessary for acceptable performance by non-voice systems vary significantly by system, we will use the value(s) reasonably designated by the manufacturer of the equipment." This seems to leave the definition of acceptable performance entirely in the hands of individual manufacturers.

Mandated receiver performance requirements are a challenging option: they require the regulator to understand the performance of all the receivers in every allocation where they are used, they lock in particular service scenarios since they refer to particular receiver architectures, and they limit the freedom of receiver operators to respond to interference in ways that the regulator did not anticipate. Even so-called generic standards cover many parameters (and thus a raft of additional measurement protocols); see e.g. Table 2, and note that the input signal level and output minimum performance criterion that are required to establish these performance ratios are not given.

Attempts to develop minimal requirements usually fail as the many engineering options in designing receivers, and the dynamics of the rule-making process, generates a multitude of permutations that each has to be addressed in the specification. In the U.S., industry objections to date have typically stymied attempts by the FCC to develop such mandates. For example, no action was ever taken to mandate the TV receiver design developed by RF Monolithics (Ash 1984), and the receiver performance NOI (FCC 2003a) was terminated by the FCC in 2007 without any action being taken after extensive opposition from industry. Further, the FCC's authority to regulate is uncertain (see Maior 2011 and references therein).

Table 2: Example of a Generic Receiver Spectrum Standard

Requirement	High performance receivers designed to operate in areas of high RF interference	Standard receivers designed to operate in less demanding environments
Spurious response rejection	-70 dB	-50 dB
Adjacent channel rejection	-50 dB	-40 dB
Semi-adjacent channel rejection	-80 dB	-60 dB
60 dB selectivity BW_{60} [a]	< 3 times BW_3	< 5 times BW_3
Intermodulation rejection	-80 dB	-60 dB
Image frequency rejection	-70 dB	-50 dB
Blocking immunity	-70 dB	-50 dB
Source: Joiner 2003, Table 20		

[a] BW_{60} and BW_3 refer to the 60 dB and 3 dB bandwidths respectively.

9.4. Examples

9.4.1. In-block harm claim thresholds

While the out-of-block values of a harm claim threshold are most germane to managing cross-allocation interference, the in-block (i.e. in-band or co-channel) value should also be defined as a way to guide the restrictions on the allowed spillover into an assignment from adjacent blocks.

The levels of allowed spillover chosen by regulators such as the FCC vary greatly. As will be seen in the following discussion, they vary from over to 80 dB(μV/m) down to 41 dB(μV/m) per MHz. As context, the thermal noise power spectral density is generally taken to be -174 dBm per Hz, or -114 dBm per MHz; this power is induced into a 0 dBi antenna at 1 GHz by a field strength of 23.2 dB(μV/m) per MHz.

It has become conventional to limit the power of any emission outside a cellular licensee's frequency block to -13 dBm per MHz using the "43+10logP attenuation rule" (see e.g. 47 CFR § 27.53 (g)). Since the field strength in dB(μV/m) at 3 meters is the transmitted power in dBm plus 95.2,[36] this equates to a field strength limit of 82.2 dB(μV/m) per MHz at 3 meters from the transmitter. This is a very large figure that covers base stations as well as handsets, and is thus not a good guide to an in-block harm claim threshold.

The limits on the out-of-block emissions of intentional radiators in the FCC's Part 15 rules provide an indication of the lowest reasonable value of an in-block harm claim threshold, i.e. the energy delivered into an assignment by non-assigned operations. 47 CFR §15.209 stipulates that emissions from an intentional radiator above 960 MHz shall not exceed 500 μV/m per MHz, that is 54.0 dB(μV/m) per MHz , at a measurement distance of 3 meters. The probability of this value being exceeded depends on the likelihood of a test point being within 3 meters of transmitter that observes this constraint.

Another indicative value can be inferred from the ceiling on the median field strength at or beyond the geographical border of a cellular license area per 47 CFR § 27.55, i.e. 47 dB(μV/m) per MHz in the 2 GHz bands. This represents the maximum in-block field strength that a geographically adjacent licensee needs to tolerate.

Similarly, the service area of a US DTV station above channel 14 (i.e. above 470 MHz) is bounded by the locations where the predicted F(50,90) field strength (i.e. at 50% of locations, 90% of the time) of the station's signal drops below 41 dB(μV/m) per 47 CFR § 73.622.

9.4.2. Cellular

We now turn to the case where the service in the band adjacent to a new assignment is, or is expected to be, cellular communications. The goal is to derive harm claim thresholds that would allow cellular operation in a neighboring band, or if the band is currently unoccupied, to put the operators in the new assignment on notice of the interference they will have to tolerate without being able to make a claim for harmful interference.

The analysis is based on work that Ofcom commissioned from Transfinite Systems (2008). Transfinite computed the resulting signal strengths of a variety of services in the UHF band.[37] Since a transmitter's in-block signal is out-of-block for a receiver, one can use Transfinite's in-block results an estimate of an out-of-block harm claim threshold.

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[36] This can be calculated by assuming free space propagation from a 0 dBi radiator. It is cited, for example, by the FCC in "Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems" First Report and Order, ET Docket 98-153, released April 22, 2002, in footnote 325 to para 216.

[37] Note that the modeling assumed European TV channel widths of 8 MHz

The calculated in-channel field strength generated by an IMT-2000 downlink[38] at 826 MHz observed at 10 m altitude is 104 dBμV/m per MHz[39] or less at 95% of locations; we use this as the harm claim threshold out-of-block relative to the new assignment. The regulator needs to decide how far on either side of the assigned frequencies the harm claim threshold will stretch; I've arbitrarily chosen 3x the assigned bandwidth in this example. Transfinite also calculated the field strength at 1.5 meter altitude. That yields the following harm claim threshold:

> A service cannot claim harm unless the aggregate field strength at heights {1.5m, 10m} above ground level exceeds {86, 104} dB(μV/m) per MHz at more than 5% of locations in the first 30 MHz beyond the band, and no limit beyond that.

An IMT-2000 downlink produces a field strength in the immediately adjacent channel at 10 m altitude of 57 dBμV/m per MHz or less at 95% of locations; this value suggests the in-block interference the new assignee needs to tolerate. This suggests the in-block harm claim threshold:

> A service cannot claim harm unless the aggregate field strength at heights {1.5m, 10m} above ground level exceeds {40, 57} dB(μV/m) per MHz at more than 5% of locations in the 10 MHz assignment.

Assuming similar services on either side of the new assignment gives the harm claim threshold in Figure 10.

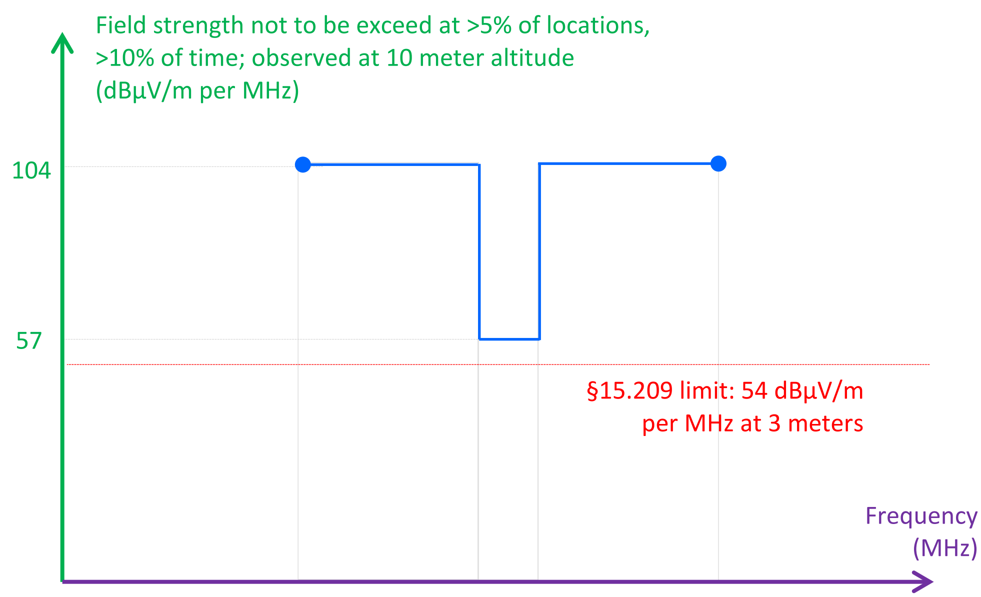

Figure 10: Cellular downlink-inspired harm claim threshold

With the assumptions used by the Transfinite study, the resulting out-of-block aggregate interference from handsets is considerably lower than that generated by a downlink, not exceeding 65 dB(μV/m) per MHz at more than 5% of locations at 1.5 meter height, and 83 dBμV/m per MHz at 10 meters. The downlink thus represents an upper bound on likely interference, and is chosen as guideline for the harm claim threshold.

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[38] The Transfinite model assume a bandwidth of 3.84 MHz within 5 MHz, with an EIRP of 22.7 dBW, antenna height of 30 m and transmitter separation distance of 1.86 km; see Transfinite (2008) Table 7

[39] Transfinite reports their results in units of dB(W/m^2) ; I convert to dB(μV/m) using the formula to dBμV/m = dB(W/m^2) +145.8, see Sanders (2010) Section 2.3, equation 28.

For those more accustomed to thinking in receiver power than signal strength, 104 dBμV/m results in a power of -31.5 dBm induced in a 0 dBi antenna at 826 MHz. Powers of this magnitude seem within the blocking capability of LTE handsets; for example, a study of seven legacy PCS LTE handsets shows that all can tolerate blocking power of -24 dBm or (much) better, even though the requirement is only -44 dBm (Elektrobit 2011, section 2.9.1)

9.4.3. Television receivers

This analysis computes harm claim thresholds for TV receivers based on 47 CFR § 73 and OET Bulletin 69 (FCC 2004a). That results in a quite limited view. Extending the scope will require balancing transmitter and receiver interests, and so the result below could be a starting point for negotiation. For example, it only protects the first-adjacent channels (adding more protected channels would be desirable for receivers) and applies a flat adjacent channel D/U for all desired field strengths (reflecting more negative D/U for larger values of D, as ATSC A/74 does, would be desirable for adjacent transmitters operating near the TV tower). There are three specific ways in which this analysis might be optimistic. First, one of the likely interferers into television service is LTE, which has a higher PAPR than U.S. DTV transmission. Second, the field strength specified in the rules in a 1 x 1 km area may not reflect actual interference from mobile handsets. Third, while interference for 10% of the time is the regulatory definition of the edge of coverage, it may be unacceptable to television viewers.

In summary, the approach applies the D/U ratios in Part 73.616 on an individual rectangular cell basis (e.g. 1 x 1 km) using the Longley-Rice value of D to calculate the U representing the harm claim threshold. It is tailored to a high tower/high power service where the antenna location, ERP and height are fixed as a condition of the license.

For the first-adjacent channels, use the D/U ratios in 47 CFR § 73.616 (e) (1) (ii) and (iii)

- lower first-adjacent {-1} channel: -28 dB
- upper first-adjacent {+1} channel: -26 dB

This section uses DTV-to-DTV D/U ratios as a good approximation for a flat, noise-like interferer into TV receivers.

Following OET 69, use the prescribed Longley-Rice method to calculate the predicted median field strength in a rectangular cell (e.g. 1 km x 1 km); call this D. The harm claim threshold becomes, using U = D - D/U:

> "Within each reference cell with calculated median desired signal strength D, a receiver may not claim harmful interference unless the interfering signal exceeds {D+28, D+26} dB(μV/m) per 6 MHz on the {-1, +1} channels at more than 50% of locations, more than 10% of the time."

While this may be reminiscent of a receiver specification, it isn't one because the rule doesn't specify the service level that must be met, e.g. the transport stream bit-error-rate must be below 3×10^{-6} as long as the interfering signal is below {D+28, D+26}.

The co-channel case is a bit more complicated because the D/U ratio in Part 73.616 (e) (1) (i) is a function of SNR. The harm claim threshold will therefore not be simple function of the desired threshold as above (e.g. D+28 for the lower adjacent channel), but a function of D.

The planning factors in Table 3 "Planning Factors for DTV Reception" of OET 69 combine in the following way (FCC 2004a, p. 4):

$$\text{Field} + K_d + K_a + G - L - N_t - N_s = C/N.$$

Taking the planning factors from OET Table 3 for UHF, one gets for 615 MHz:

$$\text{Field} = C/N -(-130.8) - K_a - 10 + 4 + (-106.2) + 7 = C/N - K_a + 25.6$$

At 615 MHz, the dipole factor adjustment Ka = 20 log [615/(channel mid-frequency in MHz)] = 0. The assumption of G = 10 dB antenna gain and downlead line loss L = 4 dB is reasonable where the received TV signal is weak, but less so where the field is strong since viewers usually don't use roof-mounted antennas when they're close to the transmit tower.

Part 73.616 uses the abbreviation SNR instead of C/N and D for the desired signal, so rewrite "Field = C/N - Ka + 25.6" as D = SNR - Ka +25.6, or SNR = D + Ka - 25.6

Now 47 CFR § 73.616 (e) (1) (i) gives the co-channel D/U as follows:

SNR in dB	**Co-channel D/U in dB**
SNR = 16	+23
16 <= SNR < 28	15 + 10 log10[1.0 / (1.0 -10^{-x/10})], where x = SNR-15.19
SNR >= 28 dB	+15

Using SNR = D + Ka - 25.6, we can get the D/U for various D given above in the harm claim threshold:

Desired signal in dB(µV/m) per 6 MHz	**Co-channel D/U in dB**
D = 41.6 - Ka	23
41.6 - Ka >= D < 53.6 - Ka	15+10 log10[1.0 / (1.0 -10^{-x/10})], where x = SNR-15.19 = D + Ka - 40.8
D >= 53.6 - Ka	15

Using U = D – D/U, we get the harm claim thresholds U for various D as follows:

Desired signal in dB(µV/m) per 6 MHz	**Harm claim threshold in dB(µV/m) per 6 MHz**
D = 41.6 – Ka	18.6 - Ka
41.6 - Ka >= D < 53.6 - Ka	D - Ka - 15+10log10[1.0/(1.0 -10^{-x/10})] where x = SNR-15.19 = D + Ka - 40.8
D >= 53.6 – Ka	38.6 - Ka

Since harm claim thresholds are usually expressed in a 1 MHz resolution bandwidth, using a 7.8 dB conversion from 6 MHz to 1 MHz this becomes

"Within each reference cell with a calculated median desired signal strength D, a receiver may not claim harmful interference unless the interfering signal exceeds the following values

Desired signal in dB(µV/m) per MHz	**Harm claim threshold in dB(µV/m) per MHz**
D = 33.8 - Ka	10.8 - Ka
33.8 - Ka >= D < 45.8 - Ka	D - Ka – 7.2 +10log10[1.0/(1.0 -10^{-x/10})] where x = SNR-15.19 = D + Ka – 33.0
D >= 45.8 - Ka	30.8 - Ka

at more than 50% of locations, more than 10% of the time. Ka is the dipole factor adjustment of 20 log [615/(channel mid-frequency in MHz)]."

The harm claim threshold at edge of the noise-limited service area, field strength is D = 41.6 dB(μV/m) per 6 MHz = 33.8 dB(μV/m) per MHz for center frequency 615 MHz is given by :

> “Within each reference cell at the noise-limited service contour, a receiver may not claim harmful interference unless the interfering signal exceeds {61.8, 10.8, 59.8} dB(μV/m) per MHz on the {-1, 0, +1} channels at more than 50% of locations, more than 10% of the time.”

9.5. Comparison with interference temperature

The harm claim threshold approach can be contrasted with an earlier effort in this general area, the “Interference Temperature” concept introduced by the Spectrum Policy Task force in 2002, which is also framed in terms of received signal strength. While harm claim thresholds and interference temperature use similar units,[40] they are used differently and have different goals in mind (Table 3).

Both focus on incorporating receiver considerations into spectrum regulation but they have very different goals in mind. Interference Temperature envisaged characterizing the actual interfering signal environment in a licensed band continuously in real time, with the stated benefit of allowing additional, ad hoc unlicensed operations in that band. On the other hand, harm claim thresholds focus attention on the signal strength outside an allocation, do not create additional operating rights in a band, and signal levels only have to be determined if and when there is a dispute about harmful interference. While harm claim thresholds will facilitate sharing by giving a clear indication of the interference receivers will have to tolerate, this is primarily in the context of neighboring assignments, not co-channel operation.

Interference Temperature is like saying anybody can come into your back yard as long as all the visitors together don’t make noise above a given level. Interference limits are rules that say how loud the noise in the next door neighbor’s yard can be before you can call the police.

Table 3: Comparison of Interference Temperature with Harm Claim Thresholds

Interference Temperature	Harm Claim Threshold
Focuses on in-block, co-channel operation	Focuses on solving out-of-block, cross-allocation interference
Designed to facilitate and encourage second party, co-channel operation	Does not grant second party rights in a primary licensee’s frequency block
Aims to create additional operating rights	Adjunct to existing definition of operating rights
Needs to be measured at all locations at all times	Only needs to be measured when concern that limit is being exceeded
Deterministic values	Probabilistic

[40] The units are not, in fact, identical. Interference temperature (footnote 38 to SPTF Report, Kolodzy et al. (2002), section VI. B) is the power flux density available at an antenna in watts per meter squared multiplied by the effective capture area of the receiving antenna in meters squared, divided by both the associated RF bandwidth in hertz and Boltzmann’s constant. A harm claim threshold is specified as field strength, or equivalently, a power flux density per unit RF bandwidth, in units of watts per meter squared per hertz; that is, they differ by an area measure, the effective aperture of the receiving antenna. Interference temperature is thus antenna dependent, whereas an interference limit is not.

9.6. SMR interference to public safety in the 800 MHz band

Specialized Mobile Radio (SMR) was initially allocated to frequencies in the 800 MHz band in 1974. Eventually the SMR allocation in that band grew to 80 channels with a Public Safety allocation of 70 channels, plus an additional 100 channels allocated to Business and Industrial licensees. The frequency channels were interleaved, placing each public safety channel between two channels of another type (SMR, Business or Industrial). One set of allocated channels was dedicated for radio uplink to repeaters and a second set of identical channels was used for repeater downlink.

As miniaturization of radio technology progressed over the years handheld mobile devices replaced higher power in-vehicle radios, resulting in the potential for closer physical proximity of radio devices operating on adjacent channels. Over time the density of devices grew to a point at which significant interference occurred between devices on adjacent channels. Usually, due to the different ways the systems were architected, portable public safety receivers were the recipients of interference from portable SMR transmitters and repeaters.

Several mechanisms of interference have been identified and most can be attributed to receivers that are susceptible to out-of-channel energy or spurious emissions from nearby channels. In particular, very strong received signals levels at ground level from the interleaved cellular-like services (e.g., Nextel) were determined to cause intermodulation distortion in LMR receivers. If the receivers had been designed to conform to well-defined Receiver Interference Limits, the interference problem in the 800 MHz band could have been eluded.

9.6.1. Introduction

A long history of communications in the 800 MHz band contains both public safety (PS) and specialized mobile radio (SMR) applications. As the two radio services have evolved conditions have become favorable for interference between them. This section examines the characteristics of each type of communication and what makes them incompatible for operation in close proximity. A case is presented that such incompatibility of communications systems would not exist if receiver interference limits were enacted.

As long ago as 1974 the FCC allocated frequency channels in the 800 MHz band for SMR and PS applications. Over time channels were assigned on an interleaved basis between the two services (see Figure 11). The band was divided into two segments for both services. The 806-824 MHz segment contained uplinked signals from radios to repeaters and the 851-869 MHz segment was for the downlink from repeaters to radios.

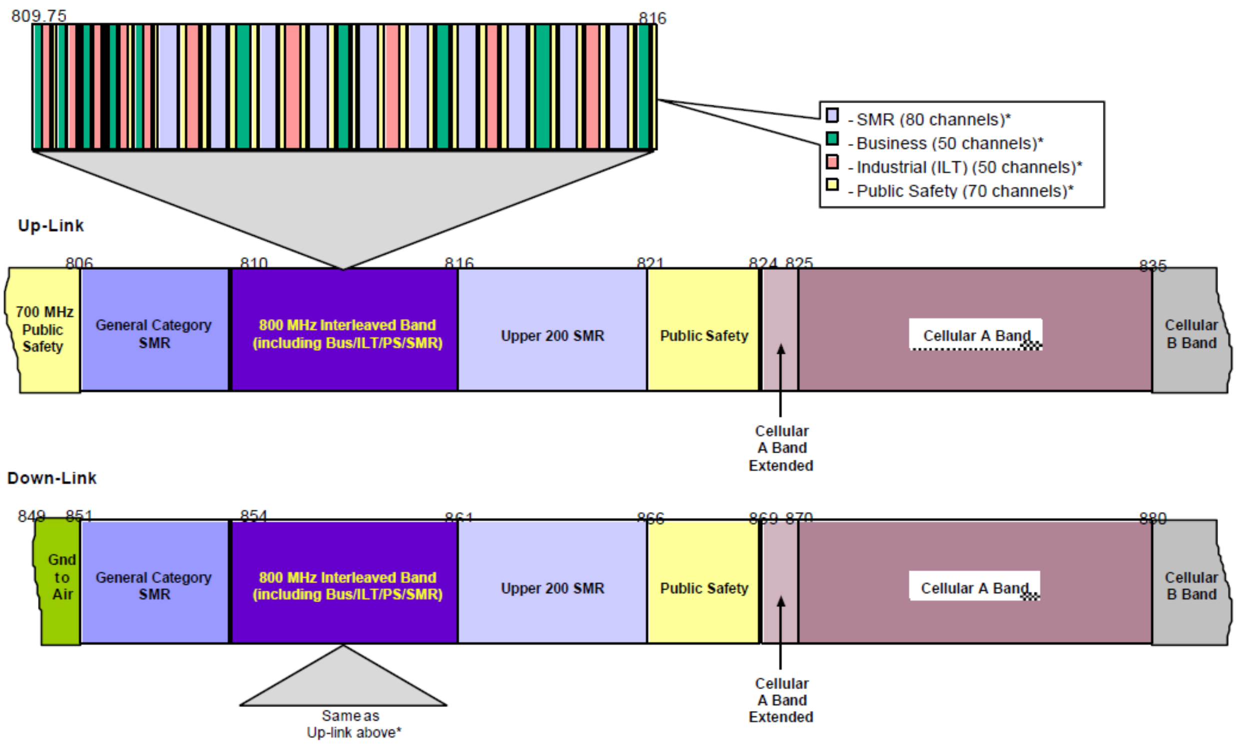

Figure 11. FCC Spectrum Allocation of the 800 MHz Band. Allocations are different along the Mexican and Canadian borders. From APCO, CTIA, et al. (2000).

Originally there were no complaints of interference from either service. Over time, as the use of the channels changed, instances of interference to public safety communications in the 810-816/854-864 MHz segments were reported. The source of the interference was mainly from communications by Nextel Corporation, which used a higher density architecture for their SMR communications system than had been used on those frequencies before. There have also been instances of regular cellular telephone operation causing interference to PS radio communication in the 800 MHz band.

9.6.1.1. Public Safety

Public Safety radio communication in the 800 MHz band has taken the form of trunked radio systems. A trunked radio is one that shares several frequency channels, which are allocated on demand to facilitate communications between a public safety officer's radio and a dispatch center. This type of system must be highly reliable as even a single missed transmission can have disastrous consequences.

The typical trunked radio system as utilized by public safety consists of one or more repeater/controllers that cover a relatively large geographical area, at least several miles square. When a trunked radio first transmits it is allocated a frequency channel for the exclusive use of communications with another radio on that system. The trunked system consists of several channels that are allocated as needed.

The front end of a radio receiver consists of filtering that rejects out-of-band signals and an amplifier that increases the strength of weak in-band signals. Because a trunked radio must be able to communicate on whichever channel it is assigned it must have a front end with relatively wide band coverage. Since the architecture of the system is based on few repeaters and many radios, the radios must have very sensitive front ends. For example, the P25 public safety radio receiver performance specification requires reliable signal reception down to at least the -

116 dBm level. Both of these front end characteristics make trunked radios more susceptible to adjacent channel interference.

Initially when the frequencies were first allocated public safety radios consisted mostly of car-based radios, which transmitted higher power (25-100 watts) and used car-mounted antennas to help strengthen signals. Radios in cars experience few obstacles to radio propagation since they are usually operated while the car is on the street.

Over time radios evolved to handheld varieties that are worn on the uniforms of public safety officers. The characteristics of these radios trend toward lower powers and poorer signal propagation. They transmit less power (4 watts or less) both because of concern for personal safety and limited battery life. They use small, inefficient antennas that require receivers to be more sensitive. Personal radios are often used in locations that attenuate radio signals such as inside cars and inside buildings. Thus the transition to personal radios for public safety personnel required front end designs with increased sensitivity.

Requirements for personal radios used by public safety include that they be small and light weight and that their batteries remain operations for at least 8-hours. These two requirements have a direct bearing on the type of battery that is supplied with the radio, which in turn affects RF receiver performance.

9.6.1.2. Specialized Mobile Radio

Early SMR applications had a similar architecture to that described for PS trunked systems. As such, the two services coexisted with little to no interference to each other. Over time SMR evolved to have a cellular architecture, with many “repeaters,” each covering a comparatively small area (similar to modern cellular systems). SMR systems with dense cellular architectures are identified as Enhanced SMR (ESMR) systems.

In a system with cellular architecture that have a higher geographical density of transmitted signals, particularly an ESMR system, expected signal strengths are higher in all locations than in a system with few transmitters. This means that the SMR receivers can be designed to be less sensitive, making them less likely to receive interference from adjacent channels.

9.6.2. Receiver Interference Modes

There are several mechanisms that result in interference to a receiver from an adjacent channel. Front end overload occurs when a strong signal that is in an adjacent channel exceeds the dynamic ranges of the first amplifier stage in the receiver. This causes the amplifier to act nonlinearly, compressing weaker signals so they cannot be heard at all. Some front end receiver amplifiers use a method called Automatic Gain Control (AGC) to vary the amplifier’s gain so that it does not enter its nonlinear region. In the presence of a strong signal the AGC decreases gain so very weak signals are not sufficiently amplified to be heard. These mechanisms are often referred to as “Front-End Overload” or “Receiver Desensing.”

The other mechanism of adjacent channel interference mentioned above is intermodulation distortion or noise. If the signal from the adjacent channel enters the receiver front end circuitry with sufficient amplitude to force the amplifier into its nonlinear region and mixes with other signals that also enter the front end, intermodulation causes the sums and differences of those signal frequencies to generate new frequency components that may be in the receiver channel, or it may cross-modulate the desired signal directly. The intermodulation products, if strong enough, can obscure the desired signals on that frequency.

9.6.2.1. Analysis of Adjacent Channel Interference

Regulations for the 800 MHz band specify that many SMR systems, particularly for the channels highlighted in Figure 11, operate in 25 kHz channels using 20 kHz of bandwidth, setting up 5 kHz guard bands between adjacent channels (47 CFR § 90.209). The amount of out-of-channel power that can be transmitted is specified by an emission mask that is defined by an equation based on the transmitter power. The emission mask for many SMR systems in the 800 MHz band is plotted in Figure 12 for a 1 watt transmitter, such as what is commonly transmitted by a handheld SMR radio (47 CFR § 90.691). The out of channel transmitted power for a 1 watt transmitter is a maximum of 0.2 mW at the channel edges, dropping to 0.01 mW through most of the adjacent channel. This should not be enough power to cause interference in the adjacent channel unless the adjacent channel receiver has a wider bandwidth than its own channel boundaries.

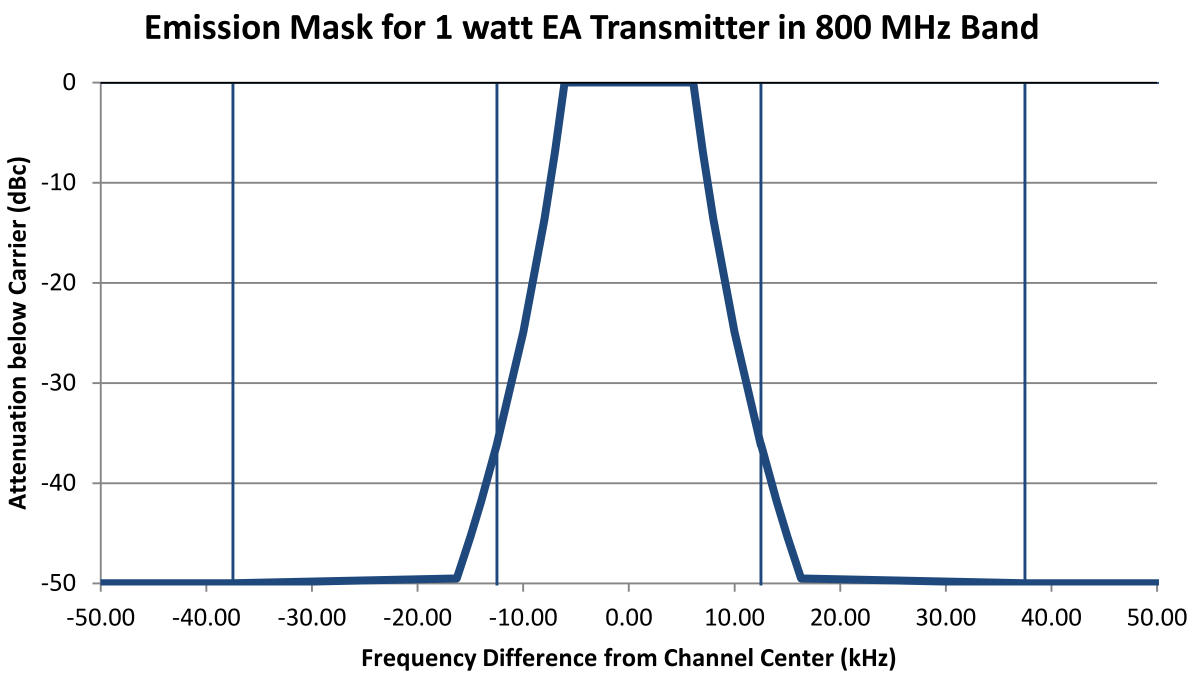

Figure 12. Emission mask for 1 watt transmitter in portions of the SMR region of the 800 MHz band (809–824 and 854–869 MHz). Vertical lines represent channels borders; co-channel and two adjacent channels are shown. Mask limit in the adjacent channel at -36 dBc. Calculated from 47 CFR § 90.691.

The plot in Figure 13 shows the same emission mask equation for a 100 watt transmitter, such as is used in a repeater (47 CFR § 90.691). With this type of transmitter the adjacent channel power levels are higher, with a maximum of 24 mW of transmitter power at the channel edges, dropping precipitously to 0.01 mW at the center of the adjacent channel. With an adjacent channel receiver that has a front end bandwidth greater than its channel boundaries it is possible that the receiver will undergo one or more of the interference mechanisms described above, depending on relative signal strengths of the repeaters in its own channel and what leaks across the channel boundary from the channels surrounding to it.

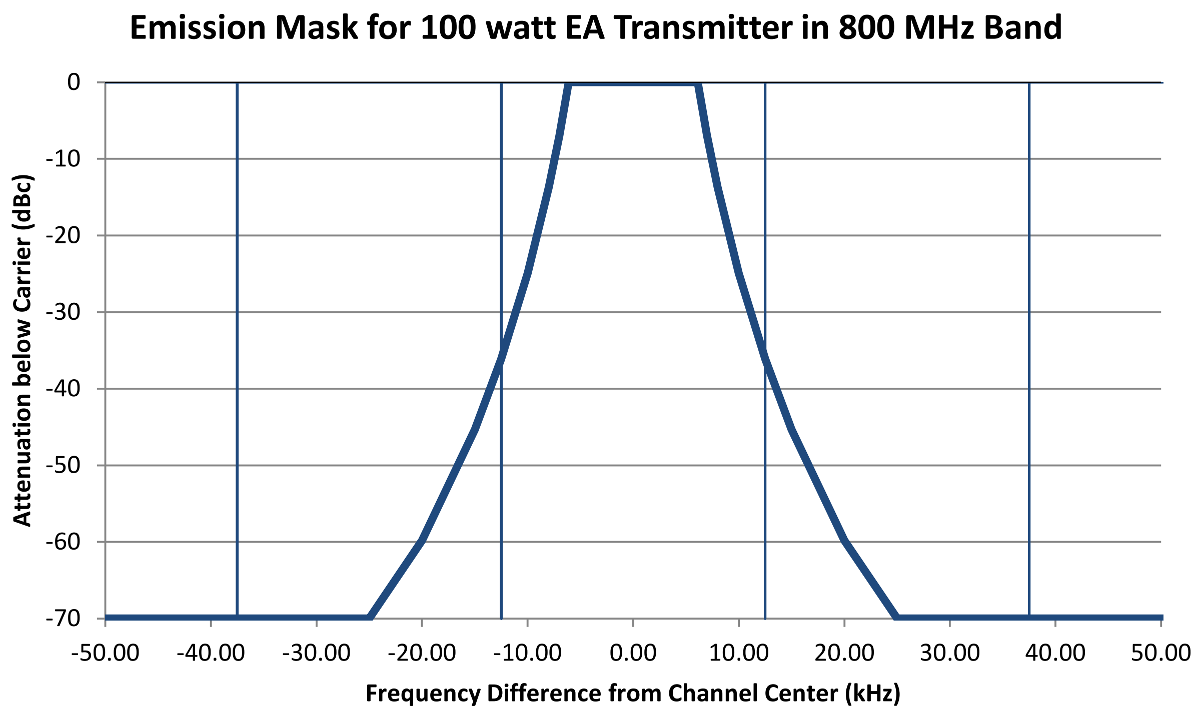

Figure 13. Emission mask for 100 watt transmitter in portions of the SMR region of the 800 MHz band (809–824 and 854–869 MHz). Vertical lines represent channels borders; co-channel and two adjacent channels are shown. Mask limit in the adjacent channel at -36 dBc. Calculated from 47 CFR § 90.691.

9.6.2.2. Techniques to Decrease Front End Interference

With modern design techniques it has become possible to avoid receiver interference even in the presence of a strong signal on an adjacent channel. Ultimately, the best way to avoid adjacent channel interference is to strongly filter out everything except what is in the received channel. In the past this was difficult to realize in receivers that had to change channels over a wide operating range, such as the public safety trunked radios. In recent years dynamically tunable filter techniques have evolved to make it possible to retune the front end for each channel that is received.[41]

Amplifier circuits have also evolved to make them more compatible with noisy RF environments. During receiver design there is a tradeoff between the IP3 specification of an amplifier and the amount of current that amplifier requires. This tradeoff has a direct effect on the requirements that personal radios used by public safety officers be small and light and have at least an 8-hour battery capacity. Two developments have improved public safety receiver performance in this respect: New battery technologies have made greater amounts of energy available in a smaller and lighter packages. The IP3 parameter of the amplifier specifications has become much larger with less current draw, making the amplifier less prone to entering its nonlinear region in the presence of large signals. This also makes AGC circuitry less of a factor, decreasing the likelihood of front end desense. An amplifier with increased IP3 is then less prone to interference from strong signals in an adjacent channel and is also less likely to produce intermodulation products

[41] The problem described in this section is in part due to older technology, including superheterodyne receivers, where tunable front-end filters can help with adjacent channel rejection.

The FCC has recognized the value of improving receiver performance in order to alleviate the interference problem that public safety officers were experiencing in the 800 MHz band (FCC 2004b, Report and Order in the matter of Improving Public Safety Communications in the 800 MHz Band). In the regulations that specify how an ESMR or cellular system should correct interference issues, one of the possibilities is (47 CFR § 90.674(c)(vii)):

> Supplying interference-resistant receivers to the affected public safety licensee(s). If this technique is used, in all circumstances, the ESMR and/or part 22 Cellular Radiotelephone licensees shall be responsible for all costs thereof.

It should also be noted that the P25 public safety radio standard (TIA 102.CAAB) already specifies very high performance levels on public safety receivers (e.g., 90 dB spurious response rejection levels, 80 dB intermodulation rejection levels, etc.).

9.6.3. Summary

Considering the history of the growth of SMR and PS communications in the 800 MHz band it is not reasonable to expect all receiver units to have been designed to avoid the types of interference described here. However, with modern receiver design techniques it would be possible to avoid interference in that band. With hindsight we can predict that the calculation of receiver interference limits for the 800 MHz band would have prevented any interference problems if the 800 MHz band allocation was made today.

9.7. Multi-stakeholder Organizations

This section describes the use of Multi-stakeholder Organizations ("MSH") in the development of interference thresholds that must be exceeded before receiving systems can claim harmful interference (i.e. harm claim thresholds).[42] This appendix briefly defines Multi-stakeholder Organizations and how they have been used in other contexts.

Multi-stakeholder Organizations are widely used as a tool in Internet governance. Organizations such as the Internet Corporation for Assigned Names and Numbers (ICANN),[43] the Internet Engineering Task Force (IETF),[44] and the Worldwide Web Consortium (W3C),[45] have played a role in ensuring a predictable process around coordinating and assigning IP addresses, developing Internet standards, and generating best practices for Internet governance (Brake, 2012). The Broadband Internet Technical Advisory Group (BITAG)[46] is an example of a more recently formed MSH that deals with network management issues associated with the Internet.

According to Joe Waz and Phil Weiser's article, *Internet Governance: The Role of Multistakeholder Organizations*, the term "multi-stakeholder" does not lend itself to simple definition, and its application varies from case to case. However, there are at least two components that typically make up an MSH: "(i) representation (or, at a minimum, openness to representation) from a diversity of economic and social interests (and not limited to a single economic perspective), and (ii) a representational role for civil society, generally defined as relevant stakeholders other than government and industry (Waz & Weiser 2011, p. 6)." Other variables to consider when organizing an MSH include the diversity of participants, the geographic reach of the body, the scope of the problem to be addressed, the processes and output of the body, and its relationship to sovereign government (Waz & Weiser 2011, p. 6). In a 2008 Ofcom report, *Initial assessments of when to adopt self- or co-regulation*, the British regulator put forth a list of criteria to consider when adopting a form of co- or self-regulation, e.g. an MSH. The criteria included:

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[42] *See* section 3.1for discussion on how an MSH could help in the process of setting harm claim thresholds.
[43] *See* http://www.icann.org.
[44] *See* http://www.ietf.org.
[45] *See* http://www.w3.org.
[46] *See* http://www.bitag.org.

public awareness and visibility; transparency; significant number of industry stakeholders are members; proportionate cost; enforcement measures; audit of members and scheme; system of redress in place; involvement of independent members; pro-active and planning in research and regulation; and non-collusive behavior (Ofcom 2008b, section 4). MSHs, generally, try to build trust, knowledge, and expertise among a diverse set of interests in order to bring greater flexibility, adaptability, speed, or efficiency to the governance process than is possible using traditional tools of government (Waz & Weiser 2011).

Some advantages that have been attributed to using MSH in the regulatory process are that MSHs tend to be more flexible than traditional rulemaking bodies, and "embod[y] the open and inclusive nature of the Internet itself by allowing nongovernment stakeholders to contribute to the discussion on equal footing with governments (White House 2011, p. 22)." Also, it has been claimed that getting a group of technically-minded, interested participants together to work on a specific issue often fosters a more collegial atmosphere conducive to collective problem solving, even if only to avoid having onerous regulations imposed by the regulator (Weiser, 2008, section IV. B). Finally, many MSHs use consensus-based decision making which gives the decisions "a powerful claim to legitimacy (Waz & Weiser 2011, p. 7)."

However, there are also some challenges that should be recognized. It is important that the scope and output of an MSH be well defined (and limited to a specific issue) up front to achieve the best outcome. It is also important to note that in some cases membership to an MSH may be prohibitively expensive for some stakeholders. Waz and Weiser explain, "'openness' is always relative, as participation in many of these organizations is frequently gated by resources—not every potential stakeholder has the financial wherewithal, the technical expertise, or the ability to commit time and talent to participate in the large and growing number of MSH organizations (Waz & Weiser, 2011, p. 6)." Another potential challenge with an MSH is that it doesn't have the same transparency requirements of a traditional rulemaking process. Many of these challenges can be addressed in the structure, organization, and guiding principles of the MSH.

Finally, an MSH must consider its relationship to a sovereign government. There are nearly as many models of how an MSH interacts with the government as there are MSHs. As Waz and Weiser explain,

> [i]n some cases, an MSH organization derives its power from sovereign governments; in many cases, its power derives solely from the consent of those who agree to be governed. In some cases, the MSH exercises its power on behalf of a sovereign government to further a government identified policy goal; in many cases, the MSH exercises its power through and on behalf of the aggregate body of participating stakeholders who agree to be bound to one another through the consensus guidelines and may also voluntarily adopt the resulting standards and practices (Waz & Weiser, 2011, p. 8).

Like other aspects of the organization of an MSH, the framework adopted to guide interaction with a sovereign government will affect the output. Some have suggested looking at various models of self-regulation in order to develop a framework for how an MSH should interact with a sovereign government. Several case studies on how self-regulation has been implemented may provide useful models for how MSHs could interact with sovereign governments. In his article, *Exploring Self Regulatory Strategies for Network Management*, Phil Weiser gives examples of two such case studies: frequency coordination and the interaction between the FCC and the American Radio Relay League (Weiser 2008, section IV.B). Both examples are given as successful models of MSH-like organizations' interactions with the government.

Multi-stakeholder Organizations can be a valuable tool in the regulatory process for developing technical standards. The success of MSH processes in Internet governance could provide a useful model for how MSHs may be used in other arenas, including spectrum management. As FCC Chairman Julius Genachowski recently said: "[t]he Internet has thrived over the past two decades thanks to the free flow of data and information, and the multi-stakeholder model of Internet governance (FCC 2012b)." It is important to keep the goals, guidelines, advantages, and disadvantages of MSHs and MSH processes in mind when developing a MSH to establish harm claim thresholds.