A Harmful Interference Model for Unlicensed Device Operation in Licensed Service Bands

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Abstract—**Recent FCC proceedings have considered the notion of unlicensed device operation in licensed bands. Licensed users are concerned about harmful interference while unlicensed device manufacturers are concerned that harmful interference is an imprecise design concept. This paper addresses two elements to these concerns. First, it develops an explicit model of harmful interference to be included in unlicensed device rules. Such a model provides explicit bounded protection to the licensed user while providing assurances and performance goals to the unlicensed device manufacturers. Second, it presents an analytic model for assessing harmful interference that not only provides quantitative analysis, but, also provides insight into how factors such as directional antennas, power control, and licensed channel avoidance strategies affect the aggregate interference. Further, it suggests that complex factors such as unlicensed device modulation schemes can be captured in a simple measurement. These ideas are applied to the notice of proposed rulemaking on Unlicensed Operation in the TV Broadcast Bands.**

Index Terms—**harmful interference, unlicensed devices, broadcast service, digital television**

I. Introduction

The FCC 04-186 proceedings discussing the notice of proposed rulemaking, Unlicensed Operation in the TV Broadcast Bands, the recent Ultra Wideband rules, and existing Part 15 rules open the possibility for unlicensed devices to coexist with licensed devices in licensed broadcast bands [5]. The traditional approach (UWB and Part 15) limits the unlicensed devices to low powers in order to minimize the potential for harmful interference. Today's technology enables more sophisticated radios that can use means other than simply limiting power to avoid harmful interference. This technology in turn enables more sophisticated operational rules. These rules should encourage investment in socially meaningful unlicensed devices while protecting the existing licensed users. We foresee two challenges to this goal which we denote the harmful interference process and interference parameter setting.

In the NPRM, the commenters question what criterion should be used to evaluate the impact of unlicensed devices operating in the TV broadcast bands. Many comments make worst-case assumptions to show that any unlicensed device could have a negative impact on licensed devices, while others argue that the impact will be minimal. This uncertainty has the effect of delaying or preventing the adoption of any rules. But, more fundamentally it points to a general lack of consensus on how the impact should be measured and codified in rules such as these. The FCC has a long-standing notion of "harmful interference", but this is not precisely defined and is mainly used in a context of evaluating existing interference in post facto proceedings. This ambiguity about what eventually will and will not be allowed can deter investment in technologies that would provide unlicensed access to these bands. Therefore, a clearer standard of what defines harmful and acceptable interference is needed to be articulated in policy and unlicensed device rules. Further a proactive process is needed that specifies how the harmful interference is measured and remedied over time.

Once a potential interference process is defined there will be parameters to be defined such as the maximum power levels or the required fidelity of a channel avoidance mechanism. Fielded deployments are expensive and time consuming. Laboratory tests can be artificial and deriving parameter relationships laborious. An analytic model can help expose these relationships clearly so that parameter tradeoffs can be made more intelligently and can provide insights into the harmful interference and channel avoidance processes.

Accordingly, this paper builds on an earlier paper [3] and provides two contributions. First, the paper decomposes the ongoing process of regulating and enforcing harmful interference requirements. It presents the choices available to regulators at each stage in the process and the relative merits of each. These ideas are applied to the NPRM to show their impact on the regulatory process. Second, it develops an analytic interference model that predicts the fraction of licensed devices affected as a function of parameters in an unlicensed device deployment.

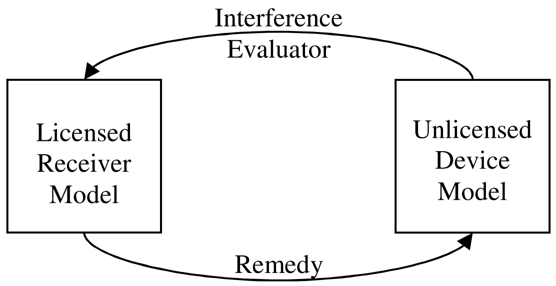

Figure 1. Elements of an Interference Measurement Scenario

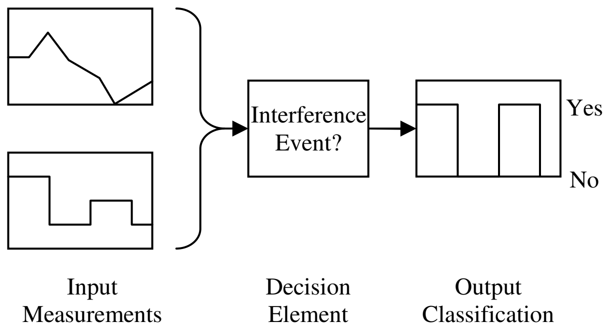

Figure 2. Measurement Event. One or more continuous or discrete measurements are assessed in each measurement event by a decision element as to whether there was an interference event or not.

II. Harmful Interference Process

This section presents the concept of an interference measurement scenario that is a framework for defining proactive harmful interference rules. The framework is a set of interference notions that policymakers can choose from when setting policy and defining unlicensed device rules. Who should evaluate if there is harmful interference and potential remedies are also considered. These ideas are developed in more detail in the following sections.

A. *Measurement Scenario*

We assume that unlicensed devices are built and deployed according to a set of unlicensed rules. These rules can not be assessed unless a clear measurement scenario is defined. The measurement scenario is shown in Fig. 1 and consists of four parts. It specifies (1) the interference evaluator who measures the level of interference; (2) a model for the licensed receivers and what constitutes harmful interference to them; (3) a model for the unlicensed devices and the conditions under which they can be considered to be causing harmful interference; and finally (4) the remedy path if unlicensed devices are found to be causing harmful interference.

As an example, harmful interference can be defined as a condition where a single licensed receiver suffers any service outage due to the operation of an unlicensed device in any setting as measured by the licensee. If this occurs, then the licensee can request the unlicensed device to turnoff. Each of these elements can have a much richer realization than this simple example. The remaining sections describe models for each of the four elements.

B. *Interference Evaluator*

Interference must be carefully defined. Interference is a receiver phenomenon. When a radio device receives both desired and undesired signals at the same time, the undesired signals at the receiver are interference. Signals that are present at the receiver when it is not receiving; that are on the path from the transmitter to receiver; or that are at the transmitter are not directly relevant.

In practice any radio device radiates electromagnetic energy across a wide swath of spectrum that extends beyond its nominal channel. The signal power propagates beyond where it can usefully be received. Many sources unintentionally emit power in the form of radio signals. Low-power unlicensed devices are already permitted in many bands. Thus a licensed device receives not only desired signals, but also unwanted signals from transmitters in nearby bands, distant transmitters in the same band, unintentional radiators, and unlicensed devices. All of these unwanted signals can not be prevented. An absolute interference ban in a band is impossible. Therefore wireless receivers are designed to accommodate a certain level of interference.

It is when the interference power becomes too large relative to the received signal that performance degradation occurs. Performance degradation can manifest itself as lower data throughput, lower voice quality, or video distortions, depending on the service. A definition of when this degradation is too much is required for each service. In principle it should only be considered too much if it is observable by the end user. For instance, a source of interference may cause more errors in a digital signal, but, if the end user can not differentiate the performance with and without the interferer, then it is negligible. A robust communication system may be able to compensate for many sources of interference. At the physical layer power control can increase power if necessary to overcome an interfering signal. At the link layer, error correcting codes can correct bit errors. At the network layer, communicating devices may route around areas of high interference. The transport layer can implement an end-to-end retry mechanism. Applications can adapt by, for instance, using lower rate audio or more buffering when data is being lost. These mechanisms may collectively provide an acceptable communication performance for the end user in the presence of interference. However performance degradation may still be present in the form of greater battery use or other non-communication degradations. This discussion points out that the notion of interference must be carefully defined as to what level in the protocol stack it is measured and what criteria are included.

We define a notion of a *measurement event* as shown in Fig. 2. A measurement event is defined according to the service that is being considered. For instance, it could consist of one or more measurements over a defined interval of time or over a single connection. A broadcast service might define a one minute measurement interval. While a mobile telephone service might measure over a single call attempt. During the event various parameters are measured such as signal to interference ratios or whether the call attempt was successful or not. These measurements are assessed as to whether there is a performance degradation using a decision element. If there is a performance degradation, the decision element classifies the measurement event as an *interference event*.

It is beyond the scope of this paper to define the rules that determine an interference event. We emphasize that this definition is the heart of any interference framework. It should define the rules for classification and additional context factors such as whether a receiver that is turned off can experience an interference event. Though we do not define it here, we assume an interference event can be and is defined by the unlicensed rules.

The definition of an interference event is in terms of measurements made by a licensed receiver. In practice, though, the measurements can be made by one of several parties involved in the unlicensed operation. These include the licensee, the unlicensed device manufacturer, the licensed receiver user, the unlicensed device user, and the regulator. With whom is the burden of showing harmful interference or not? And to whom is it necessary to show?

Embedded in these questions are several models and these should be explicit. The first is whether the burden of proof is on showing harmful interference or on showing no harmful interference. One might argue that existing licensed services have enjoyed operation without the additional interference permitted by a new set of unlicensed rules and therefore the burden is on the owners and manufacturers of the unlicensed devices to demonstrate no harmful interference. Alternatively, a licensed band may be viewed as under-utilized and the burden is on the licensee as part of their continued use of the band to monitor and demonstrate any harmful interference.

Historically the licensee has claimed harmful interference to the FCC or in courts of law. But, if unlicensed devices wish to use more aggressive measurement models that are more difficult to substantiate harmful interference or not then the burden may be on the unlicensed device users and manufacture to monitor the compliance. These efforts can be financed by, for instance, a fee on the sale of the unlicensed devices.

Beyond who makes the measurements, there is a question of how the measurements are made. As more computing and sensing capabilities are integrated into radio devices, there is the potential for certain levels of self monitoring by the licensed or unlicensed devices. A mobile telephone network contains sophisticated tools in the handsets and base stations for measuring performance per call, over time, and across users. In cases such as this, direct measurements and reporting are possible by the affected devices. Data on interference events can be collected and an assessment of harmful interference made.

For other services, none or only some licensed receivers may have the capability to make and report measurements. A sampling approach can be taken in this case. A set of monitoring stations can be set up that provide measurements. Sampling must address the issues of accuracy and precision. Accuracy means that the sampling measurements are unbiased and representative of the population. Precision means that the sample is large enough so that the sample mean is close to the mean of an infinite sample. To achieve a representative sample, the monitoring stations should be placed in typical locations and configurations in the region of interest.

The number of monitoring stations needed is a function of the licensed receiver model. A single monitoring station can make measurements over a long period and develop an accurate estimate of the fraction of interference events that it is experiencing. But, measurements from several such monitoring stations must be combined to be representative and perhaps many stations must be measured to be precise. To see the problem, let x_i be the fraction of interference events for monitoring station i, let $\hat{x}$ be the sample mean of N of these stations, and set the goal of monitoring to determine if the expected value for the entire population, $\mathrm{E}(x)$ is above a threshold $\bar{x}$. If the monitoring stations are representative $\hat{x}$ is a random variable with mean $\mathrm{E}(x)$. In this case we can set a goal of determining $\hat{x}$ to within some limit ε of $\mathrm{E}(x)$ with some confidence probability p:

$$\Pr\left\{ \left|\hat{x} - \mathrm{E}(x)\right| > \varepsilon \right\} < 1 - p$$

Using the central limit theorem, $\hat{x}$ is approximately Gaussian and $\Pr\left\{ \left|\hat{x} - \mathrm{E}(x)\right| > \varepsilon \right\} = 2Q(\frac{\varepsilon}{\sigma_N})$, where $Q(x)$ is the probability that a standard normal exceeds the value x and $\sigma_N = \frac{\sigma}{\sqrt{N}}$ is the standard deviation of the mean of a random variable with standard deviation σ. Together these imply, $N > \left(Q^{-1}\left(\frac{1-p}{2}\right)\frac{\sigma}{\varepsilon}\right)^2$. Given $\bar{x} < 0.5$, the largest σ possible that satisfies $\mathrm{E}(x) \le \bar{x}$ is $\sigma = \bar{x}$. A reasonable estimation limit is $\varepsilon = \frac{\bar{x}}{10}$. If we want a $p = 95\%$ confidence we derive $N > 196$.

Thus there are two problems with sampling, the sample may not be representative or the number of monitoring stations needed could be prohibitively large. In addition, when licensed devices are able to make direct measurements, not all devices may report and a non-representative subset may be all that reports. Finally, the measurements made in a measurement interval are subject to variability and error and thus measurement intervals may have false positives or false negatives. These problems can be minimized but never eliminated. Therefore, in addition to designating who evaluates for harmful interference, the unlicensed rules should also specify an *agreed measurement procedure* that specifies the method for making measurements in the measurement interval and the method for sampling. This then becomes the standard for defining harmful interference when combined with the unlicensed device model and the licensed receiver model.

C. *Licensed Receiver Model*

An interference event does not necessarily constitute harmful interference. We define the following licensed

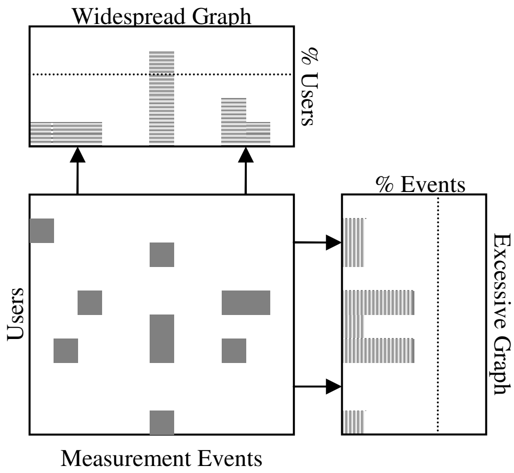

Figure 3. User Measurement Event Graph (UMEG). A dark square indicates that the measurement event is classified as an interference event. The Widespread Graph (WG) sums interference events across users. The Excessive Graph (EG) sums interference events across measurement events.

receiver models that define how interference events are classified as harmful relative to the licensed receiver.

a) Conceivable Interference Event: There exists some conceivable configuration of licensed and unlicensed device that can cause an interference event in the licensed receiver.

b) Observed Interference Event: An interference event occurs under typical usage of the licensed and unlicensed device.

c) Excessive Interference Events: A licensed receiver under typical usage has more than a specified fraction of the measurement events classified as interference events.

d) Widespread Interference Events: More than a specified fraction of licensed receivers experience an interference event at any time.

e) Widespread Excessive Interference Events: More than a specified fraction of licensed receivers suffer excessive interference events.

f) Excessive Widespread Interference Events: Widespread interference events occur more than a specified fraction of the time.

g) Expected Interference: More than a specified fraction of licensed devices experiencing an interference event, averaged over time.

These models can be explained in terms of the graphs in Fig. 3. The user measurement event graph (UMEG) in the lower left plots which measurement events are classified as interference events for different users. The excessive graph (EG) on the right is the percentage of measurement events that are classified as interference events for each user. The widespread graph (WG) on the top is the percentage of users in a measurement event that are classified as having an interference event. The widespread graph can be applied when the events by different users are synchronized.

Embedded in these models are a notion of a measurement sample and a licensed receiver population. The EG is defined for a given measurement sample defined by a number of measurement events. Too few events (e.g. a few minutes) will not properly capture long term unlicensed performance. More events will better capture this long term performance and can also capturing egregious violators quickly. As an example, if the measurement period covers one year and interference events covering up to one hour in that year are allowed, a poorly behaving unlicensed device could violate this limit and harmful interference claimed in the first day. Note that when harmful interference violations can be claimed before the end of the measurement period in this way, the threshold should be in terms of an absolute number.

The licensed receiver population could be defined by geographic area, type of usage, and type of device; for instance, television receivers in the Denver Major Trading Area [11]. As noted in the previous section, the population could be defined to be a set of monitoring stations. The receiver population is comprised of users. A user can consist of a single unlicensed receiver, such as a TV, or, a larger entity such as a wireless network or a mobile telephone base station and its subscribers. Clearly, what is measured and how it is measured depends on the user definition. A user definition based on a network of licensed devices has the advantage that higher level performance can be defined. A wireless data network could use end-to-end throughput. A base station could use user capacity.

The first three licensed receiver models are on a per user basis. Conceivable interference implies that an interference event could appear in the UMEG. In all the remaining models an actual interference event must appear in the UMEG. In observed interference, it is enough that at least one interference event appears anywhere in the graph across the measurement sample and the licensed receiver population to claim harmful interference.

Excessive interference is defined in terms of the EG. A threshold, x_e, is defined as the maximum percentage of measurement events that can be interference events for any one user. If any one user exceeds this threshold, then there is harmful interference.

The next four models are aggregate standards defined for some set of licensed receivers. Aggregate here refers to the total effect across many licensed receivers. It is not related to the issue that a receiver may suffer an interference event as a result of the sum of multiple unlicensed device signals. This concept is captured in the unlicensed device model. Individual licensed receivers may have many interference events as long as the set of licensed receivers meet the aggregate criteria. Widespread interference is defined in terms of the WG. A threshold, x_w, is defined as the maximum percentage of users that can simultaneously suffer an interference event. If at any measurement event this threshold is exceeded then there is harmful interference.

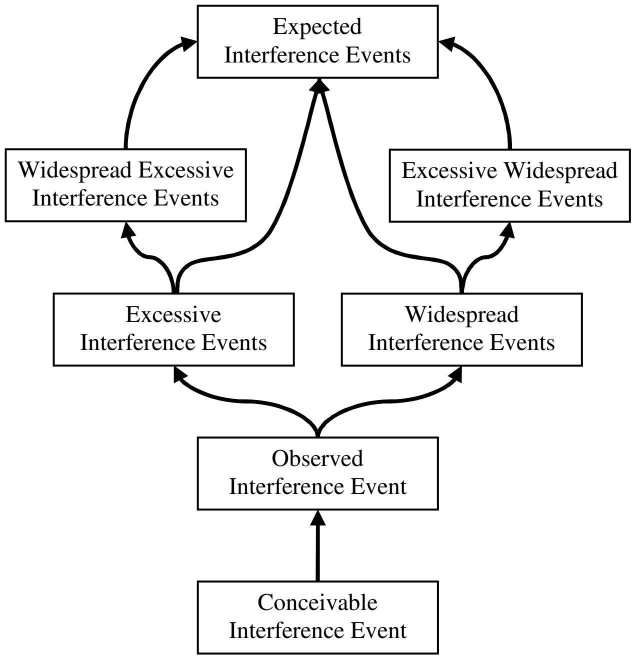

Figure 4. Licensed Receiver Model Relationships

The next two models combine the excessive and widespread concepts. Excessive widespread interference is when there is widespread interference for more than the fraction x_{ew} of the measurement events. Widespread excessive interference is when there is excessive interference for more than the fraction x_{we} of the users. These models are not the same. Excessive widespread interference is based on the fraction of measurements which are above threshold in the WG while widespread excessive is based on the fraction of users which are above the threshold in the EG. These fractions can be different. In Fig. 3 no user exceeds the threshold in the EG while at least one measurement exceeds the threshold in the WG.

As can be seen in Fig. 3, the excessive and widespread models may or may not deem a UMEG as harmful depending not only on the number of interference events but also on their distribution. The final model, expected interference considers the average fraction of interference events across users and measurement events. It sets a threshold $\bar{x}$ on the maximum fraction allowed.

The relationships between the models is shown graphically in Fig. 4. As indicated by the arrows, a licensed receiver model lower on the graph can be used to satisfy a model higher on the graph. For instance, if no interference events are ever observed than all of the higher models of harmful interference are automatically satisfied. Similarly, if no user experiences more than x_e interference events, then it is not widespread that users are experiencing x_e interference events. The relationship between parameters is shown in Tab. 1.

Once a model is chosen, the parameters for the model must be chosen. Wireless signals are highly variable. Interference events can occur even with a stringent limit on other devices on or near the licensed band. Users may be operating far from the licensed receiver outside the defined coverage area and therefore have signals too weak to be reliably received. Similarly the device may be located in an area where coverage was not intended such as in the basement. The defined coverage area may specifically allow that some licensed devices suffer interference events (TV bands allow for outages at the defined edge of coverage.).The signal may be susceptible to natural interference such as caused by lightning or solar flares or variations due to season and weather. The receiver device itself may suffer loss of service (e.g. when there is a power utility outage, or when a user misconfigures the device). The receiver may simply be turned off. Finally, the licensed transmitter might have planned or unplanned service outages for maintenance or due to equipment failure. Thus, when evaluating harmful interference caused by a new unlicensed device it must be within the context of these pre-existing interference events. In particular, a harmful interference standard can not be set more stringent than what is caused by these preexisting outages.

D. *Unlicensed Device Model*

An interference evaluator and licensed receiver model define harmful interference, but under what conditions for the unlicensed device? The conditions must define the following, the allowed usages and the allowed deployments. The allowed usages limit how the unlicensed device can be used. For instance usage could be specified for intermittent remote control applications. If the device is then used for high-speed data transport, then harmful interference is not the issue, rather, it is a non-compliant use. By specifying the compliant usages, extreme uses that might surely lead to noncompliance can be excluded (for instance operation of a device in an airplane). Permitted and excluded uses are specified as part of the license rules.

Similarly the deployment must also be defined. In one model interference is harmful only to the extent that it is caused by a single device. This model is consistent with the single device licensed receiver models. A single device is unlikely to cause enough interference events to cause harmful interference according to the aggregate licensed receiver models. In some cases it may be the usage of many unlicensed devices that is required in order to cause a widespread (or similar) interference. The aggregate of signals from multiple unlicensed devices may be required to generate an interference event in any single licensed receiver. Thus, an alternate model considers the collective interference of multiple devices. This model is for a given unlicensed device population defined

Table I.
If Model A has no harmful interference then Model B has no harmful interference with the Parameters C

Model A	Model B	Parameter C
Excessive	Widespread Excessive	$x_e = x_e,\ x_{we} > 0$
Widespread	Excessive Widespread	$x_w = x_w,\ x_{ew} > 0$
Excessive	Expected	$\bar{x} = x_e$
Widespread	Expected	$\bar{x} = x_w$
Excessive Widespread	Expected	$\bar{x} = x_w + x_{ew} - x_w\, x_{ew}$
Widespread Excessive	Expected	$\bar{x} = x_e + x_{we} - x_e\, x_{we}$

by geographic area, type of usage, and type of device. For some unlicensed uses it may be possible to show that each unlicensed device contributes some finite component to the interference and an exceedingly dense deployment might cause harmful interference. Therefore the deployment must specify what types of unlicensed user densities are allowed or are considered as harmful interference.

E. Remedy

If harmful interference is shown according to the above definitions, what are the possible remedies? First, it should be emphasized, that harmful interference caused by devices that are not following the unlicensed device rules has a clear remedy which is for these devices to cease operation. So, the question applies to the case when devices are following the unlicensed rules but yet harmful interference is determined. Broadly, the answer is to change either

a) the unlicensed device rules,

b) the definition of harmful interference, or

c) the rules for licensed use.

Changing the unlicensed device rules might be as simple as creating or adding to a list of unlicensed device excluded usages. At an extreme, the unlicensed operation rules might be abolished. Or, they might add stipulations on installation such as requiring professional installers. Or, they might change operational parameters such as allowed power levels. If there is an expectation that operational parameters might be changed over time, then, the unlicensed rules should contain provisions that mandate updating the firmware that controls the unlicensed device. These rules might integrate prompting mechanisms such as generating warnings or refusing to interoperate when a device with older firmware attempts to communicate with a device having a later firmware.

The second alternative is to redefine harmful interference. Over time, it might be shown that more harmful interference is acceptable (changing the parameters of the licensed receiver model) or that it can be measured in a better way (change the model itself). The unlicensed rules may spawn socially important applications that overshadow the original licensed usage and more leeway might be given to the unlicensed devices such as allowing more interference events. Another possibility is that the licensed user wants to claim harm even though no harmful interference is shown according to the measurement model. This might lead to a tightening of the parameters or the model.

Finally, the licensed use might be changed. For instance some licensed channels might be set aside for unlicensed use. In the case of the microwave links in the 1910–1930MHz band, a close substitute (fiber optic cables in this case) was found and a mechanism for moving these users out of the band was established. The licensed rules might be modified to better accommodate the unlicensed user. For instance, licensed receivers might be required to include a beacon so that unlicensed users can better avoid the licensed usage. Or, licensed users might be permitted higher transmit powers.

It should be clear that potential remedies should be considered at the time the unlicensed rules are formulated. If remedies are explicitly incorporated into the rules, then, licensed users will be more willing to accept the harmful interference potential and less likely to insist on extremely limiting definitions of harmful interference. Conversely, unlicensed device manufacturers are more likely to invest in a technology if the potential for it being banned or made obsolete is minimized and a potential future migration path is already defined.

III. A Standard for Harmful Interference in the TV Broadcast Bands

This section applies the concepts in the previous section to a framework for harmful interference in the TV broadcast bands. For the licensed operator, interference from unlicensed devices is unavoidable since both intentional and unintentional radiators can produce radio frequency power in the licensed band. This unwanted power can impact licensed performance if the unlicensed source is placed sufficiently close to the licensed receiver antenna. For instance operating a power saw or drill near a TV or radio readily produces strong “static”. The FCC has recognized that assuming a worst-case interference regime will not maximize the social benefit of the spectrum.[10] The Spectrum Policy Task Force concluded that for unlicensed devices, “Using typical worst case predictive interference models would significantly reduce the potential of these devices to operate.”[8] Licensed devices always have the potential of degraded performance from unlicensed devices. Yet, in practice most licensed devices work well. This suggests that the harmful interference of unlicensed devices should be measured according to their impact in practice and a conceivable device interference model is inappropriate.

In the Multichannel Video Distribution and Data Service (MVDDS) proceedings the FCC reiterated that “impacting some existing customers of a service to an extent that did not rise to the level of harmful interference was outweighed by the benefits of adding new services or capabilities to a frequency band.” ([9] para 32) In the proceedings, the FCC set operational parameters based on a criterion that MVDSS does not increases the baseline Digital Broadcast Satellite (DBS) outage rate by more than ten percent per year. This requirement is interpreted as an average standard and not for each individual receiver([9], para 84). “The ten percent benchmark represents an insubstantial amount of increased unavailability and does not approach a level that could be considered harmful interference.”([9] para 72) In this way the FCC set a standard that it deemed as conservative for the existing licensed operators while providing entry for other services. This suggests that a similar expected interference standard can be applied to unlicensed devices in the TV broadcast bands.

To determine a reasonable fraction of interference events, we look at Broadcast TV availability. Broadcast TV availability is not monitored by regulators but even if it were 100% available, other factors would limit its use by TV receivers. For instance, the availability of power from utilities varies (between utilities and from year to year) from 99.9% to 99.99%,[1] and so receivers and hence the broadcast service is unavailable for use for 0.1% to 0.01% of the time. DBS service is similar to TV and is considered "extremely reliable with typical service availabilities on the order of 99.8 to 99.9 percent."([9], para 67) Broadcast TV coverage is defined by the $F(50,90)$ curves which nominally provides 90% service availability to 50% of the users at the edge of each station's service [6]. When considering new higher power operation, broadcasters advocated "that a *de minimis* standard for permissible new interference is needed to provide flexibility for broadcasters in the implementation of DTV."[7] They argue that a 2% absolute increase in interference between TV stations is acceptable. This data collectively suggests that 99.9% is a conservative upper bound on the availability of broadcast service. This bound with the above FCC MVDSS 10% standard suggests a standard for the broadcast TV bands of no more than 0.01% (1 in 10,000) TV's can be adversely affected by the unlicensed devices on average. Given the range of availability values and the small fraction that results, this value is small in both a relative and absolute sense and exercises an abundance of caution.

So far, we have defined the licensed receiver model as an expected interference model with a limit on the expected fraction of measurement events classified as interference events at any time of $\bar{x} = 0.01\%$. It is expected that the unlicensed devices in this band will be widely deployed and used for a variety of communication including wireless broadband access and other wireless networking. An analysis model for this kind of usage presented in the next section shows that an unbounded deployment will exceed this definition of harmful interference. The model also shows it is well within the technology of the unlicensed devices to achieve unlicensed device densities in excess of 1000 devices per square kilometer in typical urban and suburban areas without violating this harmful interference standard. In dense urban areas unlicensed device densities in excess of 20,000 devices per square kilometer can be supported. These numbers are similar to their respective population densities. For instance, the density of New York County, the densest in the US, is 27,000 people per square kilometer.[13] Thus the unlicensed device model is a wide deployment of wireless networking devices deployed by residential users.

The main challenge in this measurement scenario is defining an evaluation method. Measurement events can be defined over an interval such as 1 minute. The monitoring sample could cover an entire year. The licensed receiver population can be defined to be a MTA. Individual TVs do not have the ability to measure and report

TABLE II.
DIFFERENT KINDS OF EVENTS.

Case	TV Sched.	TV Signal	Cable Signal	Line Power
Normal, t_{norm}	On	Good	Good	Good
Interference Event, t_{int}	On	Bad	Good	Good
Cable Outage Event, t_{co}	On	Good	Bad	Good
Broadcast Outage Event, t_{bo}	On	Bad	Bad	Good
Power Outage Event, t_{po}	On	X	X	Bad
Scheduled Outage Event, t_{so}	Off	X	X	X

interference. Therefore, a sampling approach must be taken with N monitoring stations placed at representative locations for the measurement population. It is outside the scope of this document to specify what is measured and how these measurements are classified as interference events. Relevant documents should be consulted for this aspect (e.g. [1]). The interference event definition should include both direct measures of the TV signal and also external measurements. Let us label a measurement event as "bad" if the TV signal is deemed unacceptable. Not all such events are interference events. The broadcast signal might have a scheduled (e.g. every night between 2am and 6am) or unscheduled outages (e.g. due to equipment failure). This can be monitored through knowledge of the TV schedule or through monitoring of the same broadcast channel via cable. Power outages also cause TVs to fail to receive signals. All of these factors can be easily measured over a measurement interval and produce the different classifications as shown in Tab. II. The total set of events that should allow TV reception are $t_{tot} = t_{norm} + t_{int} + t_{co}$. Let $x_i = t_{int}/t_{\mathrm{tot}}$ be the fraction of interference events for receiver i. Then $\hat{x} = \frac{1}{N}\sum x_i$ is the estimate of the expected interference. Harmful interference is claimed if $\hat{x} > \bar{x}$.

Unfortunately, t_{int} does not discriminate between other types of interference (e.g. natural sources) and unlicensed device interference. But, it does bound the interference events that can be attributed to the unlicensed devices. Who should be responsible for monitoring? The monitoring data is most valuable to the broadcasters since in additional to monitoring for harmful interference, they can monitor their general program quality as it is presented to their viewers.

What remedy is available when harmful interference is determined? The unlicensed devices that operate in the licensed TV bands are expected to be relatively capable devices able to avoid licensed channels, select different power levels, and generally have a sophisticated software model. In this case, a remedy for harmful interference would be to require manufacturers to include software updates as an integral feature in their design. These updates could either lower maximum transmit powers or tighten the criteria used in avoiding licensed TV bands. The latter might be preferable since it is less likely to affect existing unlicensed services. In rural areas higher power is important and there are plenty of unused spectrum opportunity alternatives even if the choice is more conservative. In urban areas, the devices are likely already operating below the maximum allowed power and

[1] Utilities measure the so-called SAIDI, minutes of sustained outages per customer per year. In [4], they range from 50 to 600 minutes per year or 99.99% to 99.9% reliability. Further within a single service provider, the SAIDI varies by large factors of at least two from year to year.

so the main opportunity to reduce interference is through better avoidance. The point is not to decide here what the precise remedy is, but, to show that it is something that could be included in the unlicensed rules.

So in conclusion we argue the measurement scenario for unlicensed device operation in the TV broadcast bands should be based on an expected increase in interference events of 0.01% in an unlimited deployment of unlicensed devices as measured by television signal monitors operated by TV broadcasters. The remedy would be based on including a method for post-purchase modification of the radio parameters.

IV. Interference Model

An interference model is developed in this section. The model computes the fraction of licensed devices made unavailable because of unlicensed operation. It considers factors such as the type of unlicensed signal modulation, antennas, ability to detect active licensed channels, power control, and activity levels of the licensed and unlicensed devices. Examples using the model suggest that the small increase in interference advocated in the previous section allows unlicensed device densities over 1,000 unlicensed devices per square kilometer. A high density apartment building example is also analyzed. It is found that there are mitigating factors in this case that supports over 20,000 unlicensed devices per square kilometer.

A. General Setting

The model considers a large area that is covered by some licensed broadcast service. There are many licensed receivers within the area. In this area is a deployment of unlicensed devices. The concern is the interaction of the transmitted unlicensed signals with the licensed broadcast signal at the licensed receivers. The combination of multiple unlicensed signals is not considered. Given that propagation tends to spread signal powers over many orders of magnitude, it is likely that one of the interfering signals is much stronger than the others and any interference event is a result of this one strongest signal. Conversely, a single unlicensed device, if it is well designed, is unlikely to interfere with many licensed receivers, if any. Hence, the interference is in the context of a widespread and dense deployment of the unlicensed devices and we examine the expected total number of licensed devices that will experience an interference event.

In this section we capture the notion of an interference event through a parameter $r_{\min}$. This is how close an unlicensed device can approach a licensed receiver before the licensed receiver performance degrades. It is performed under worst case conditions of the two device antennas aimed at each other and so on. In principle this is a simple measurement to make in a laboratory setting and could be the basis of a device compliance model.

But, $r_{\min}$ is a worst case measurement. The unlicensed devices can have mechanisms to avoid interference. They might have mechanisms for avoiding the broadcast channels; use directional antennas; control their power to only what is needed; transmit only part of the time; and use sophisticated modulation schemes. Further some licensed devices may obtain their signal from cable or a recording device and thus be unlikely to receive significant interference. The model is designed to capture these factors.

B. Model Summary

Mathematically, the model consists of a series of factors that account for the different elements that influence the number of disrupted licensed devices:

$$F = r_{\min}^2 PCEG_{UL}G_L MN_{UL} / A$$

where

F	is the expected fraction of licensed devices with service disrupted.
$r_{\min}$	is the minimum separation between the unlicensed and licensed device in order to prevent the unlicensed device from interfering with the licensed device under typical operating conditions near the boundary of the broadcast coverage area. This is done under worst case conditions of the licensed device transmitting at maximum power on the same channel as the licensed device with both devices antennas pointing at each other.
P	accounts for the use of power control by the unlicensed device. $P \le 1$.
C	accounts for the ability of the device to avoid communicating on the same and adjacent channels as the licensed device. $C \le 1$.
E	is the fraction of devices on and eligible to interfere with each other $E \le 1$.
G_{UL}	accounts for the antenna gain pattern of the unlicensed device. $G_{UL} \le 1$.
G_L	accounts for the antenna gain pattern of the licensed device. $G_L \le 1$.
M	captures all the model constants. A typical value is $M = 2.9$.
N_{UL}	is the number of unlicensed devices in the area.
A	is the size of the area.

Most of the factors are less than or equal to one. In some cases they are very small and are the key to achieving a small F. The last four factors are outside the influence of the unlicensed device designer. But the first five factors can be affected by the unlicensed device design. Different modulation techniques, maximum transmit power, etc. can all affect $r_{\min}$. The sophistication of power control algorithms affects P. The fidelity of channel detection techniques strongly affects C. The level of device activity affects E. The unlicensed device's antenna affects G_{UL}. The model details are in Appendix A.

C. Examples

To help interpret the model we give several examples. For the examples we will use an unlicensed device density of $N_{UL}/A = 1000$ devices/km^2.

Consider a low power device operating under the following conditions: r_{min} = 100m; the unlicensed devices have an omnidirectional antenna; the licensed antennas are approximated by 60 degree ideal sectorized antennas; the broadcast pathloss exponent is a = 2, the pathloss exponent for unlicensed devices is b = 4; the joint shadow fading is σ = 7dB; and power is controlled uniformly over a log scale between max power and 20dB below max power. The fraction of: unlicensed devices turned on is 25%; licensed devices turned on is 25%; and licensed devices listening to broadcast channels is 25%. As a reference, we consider the worst case that the licensed device is using a random channel. In this case, P = 0.39; C = 0.02; E = 0.016; G_{UL} = 1; G_L = 0.17; and M = 2.9. Combining these factors yields an expected fraction of disrupted licensed devices of about 6/10,000. This suggests that even limited additional work to avoid using known TV channels would reduce the expected number of disrupted devices to an insignificant level. For instance if the unlicensed device could determine the presence of and avoid licensed broadcast channels (and adjacent channels) 90% of the time and the remaining 10% of the time the channel choice is random, then C = 0.0022, and the fraction of disrupted licensed devices is less than 1/10,000. We emphasize that these number are for device densities that correspond to millions of unlicensed devices across a major metropolitan area. A suburban or rural area, which we might expect to have factors of 10 to 100 lower density, would have similarly reduced fraction of disrupted devices. For example a rural area with 100 devices per square kilometer would have a fraction of disrupted devices less than 1/10,000 even if the unlicensed devices chose channels randomly.

Consider next a high-power device operating under the same conditions as for the low power device except that: r_{min} = 10km; the unlicensed antennas are high-gain 30 degree sectors; b = 2; the fraction of unlicensed devices turned on is 50%; and again random channel selection. In this case, P = 0.21; C = 0.02; E = 0.031; G_{UL} = 0.083; G_L = 0.17; and M = 5.8. Combining these factors yields an expected fraction of disrupted devices of close to 1. This implies the unlicensed devices must be much more reliable in detecting and avoiding broadcast channels. For instance, if the licensed channel could be detected and avoided 99.99% of the time (all but 50 minutes per year) then, $C = 2.\mathrm{x}10^{-6}$ and the expected fraction of disrupted licensed devices is less than 1/10,000. The same level could be achieved in a rural area if licensed channels could be detected 99.9% of the time (all but 8 hours per year).

The greatest potential for interference exists in dense settings, for instance in apartment buildings where the effective density could be above 1000 devices per square kilometer. There are several mitigating factors in this case. Such buildings are more likely to have wired Internet access (i.e., less likely to be high-power unlicensed devices). Similarly, they are more likely to have cable TV. Such buildings are often in urban areas where broadcast signals are stronger and easier to detect. For low-power devices used within these apartments, the communication distances are likely much smaller and thus require less transmit power. Social factors should not be ignored either. If some neighbor is too loud, you can ask them to be quieter. Similarly, if a neighbor places a wireless device too close to your TV, you can ask them to move it. General guidelines used in Part 15 rules development are (a) self-interference between two devices operated by the same household is not considered; and (b) between households a working assumption is 10m separation and wall attenuation of at least 10dB. The original NPRM [5] footnote 50 reiterates this assumption. This suggests that some disrupting interference in such high density settings may not be considered harmful interference.

We can incorporate these factors into the model by assuming half as many licensed devices listening to broadcast channels, channel detection can be twice as accurate, the power is controlled uniformly over a log scale between 10dB below max power and 20dB below max power, and half of all potential disruptions can be solved by social means (i.e., P = 0.19; C = 0.0012; and E = 0.0039). With these changes to our illustrative examples, more than 20,000 unlicensed devices per square kilometer could be supported without exceeding the harmful interference threshold.

D. Discussion

The interference model shows that high-power and low-power unlicensed devices can successfully coexist with licensed devices. The model estimates the fraction of licensed devices disrupted by the presence of the unlicensed devices. It incorporates a range of factors that can influence the final result. All of the factors can be easily estimated or directly measured. In particular, one of the most influential factors, r_{min}, could be measured through direct measurement. This suggests that a device compliance model can be developed based on factors inherent to the device. In other words, the definition of compliance could be defined in terms of a bound on r_{min} as measured in a lab.

The examples indicate high-power devices will need to pay special attention to how they choose transmit channels since they have a strong potential to interfere over a large area if they choose an active licensed channel. Low-power devices can be much less reliable in this procedure and yet have minimal impact on licensed devices. They are helped by being lower power. Because they are envisioned as being used indoors or at ground level, the walls and clutter (as expressed by the larger pathloss exponent) provide more isolation. But, since the licensed channel avoidance procedure is likely to be more ad hoc its reliability may be more difficult to assess.

The examples in this paper assume a harmful interference standard defined as no more than 1 in 10,000 licensed devices will suffer interference events on average because of the unlicensed devices. Such a standard exercises an abundance of caution considering that other sources of interference may cause more than 10 times as many interference events. It should be clear from the model that such extreme caution imposes direct and substantial penalties on the deployment of unlicensed devices. For instance, if the harmful interference standard admitted 10 times more interference events, the model would immediately support a 10 times higher unlicensed device density. Alternatively, it would ease the design challenge for the same density by a factor of 10. For instance, using a 1 in 1000 standard in the illustrative example of a high-power device, the unlicensed devices would have to detect and avoid licensed devices 99.9% of the time (i.e., incorrect no more than 8 hours per year) instead of 99.99% of the time (i.e. incorrect no more than 50 minutes per year). Therefore, the harmful interference standard in the previous section should be considered a model and the specific interference level should be set with careful consideration.

V. Conclusion

This paper considers the process of formulating rules for unlicensed devices to operate in licensed service bands. The current process does not directly address the issue of harmful interference and leaves a significant uncertainty for the licensed operators and unlicensed device manufacturers. This paper develops the notion of a measurement scenario for assessing harmful interference. The framework starts with a definition of an interference event. It then consists of a menu of options for how the licensed receiver, unlicensed devices, interference evaluation and remedy are taken into account. The key idea is that the process of making definitions and choices within this framework is made when the unlicensed rules are formulated in order to provide specific protections to the licensed operators and to provide assurances and design goals to the unlicensed device manufacturers.

This process was applied to the specific case of the NPRM on unlicensed operation in the TV broadcast bands. A set of choices was selected in order to exemplify how the process could be applied. Some details were left open. Further proceedings would be required for the FCC to make a fully informed and complete set of choices.

An analytic interference model is developed so that rules can be assessed a priori and the dependency on different choices and parameters can be better assessed. The model suggests that when applied to the NPRM licensed and unlicensed devices can coexist at densities exceeding 1000 unlicensed devices per square kilometer. When applied to a worst-case scenario of a high-density apartment building, it is found that densities over 20,000 devices per square kilometer can be supported. The model also shows clearly the tradeoff between protecting licensed users from potential harm and the extent that unlicensed devices can proliferate. Modest increases in potential harm to licensed users yields large increases in the number and easier implementation for the unlicensed devices.

Appendix A: Analytic Model Details

A. *Model Assumptions*

The model considers licensed receivers and unlicensed devices spread over a large area such as a metropolitan or rural area. A conceptual notion is that this area consists of the area covered out to some maximum distance (such as to the Grade B contour of a typical broadcast station). The shape of this contour is not particularly important as long as it is reasonably compact. A key concept is $r_{\min}$, the minimum non-interfering distance separation between unlicensed transmitter and licensed receiver when the licensed device is transmitting at full power on the same channel as the receiver is listening and both devices antennas are pointed toward each other. This, of course, is the worst case situation and other factors come into play to mitigate this situation. It is precisely the point of this model to make these factors explicit so that the mitigating role of smart unlicensed devices can be expressed concretely. The basic model makes the following assumptions [12]:

1. Only two-dimensional scenarios are considered.
2. Received power at a licensed device from an unlicensed transmitter is $P_{int} = K_{int}\, g_{UL}\, g_L\, P_{UL} S_{int}/r^b$, where K_{int} is a constant related to antenna heights, cable losses, and other constants; g_{UL} and g_L are the unlicensed and licensed device antenna gains along the path connecting them; P_{UL} is the transmit power; r is the separation between the unlicensed transmitter and licensed receiver; b is the pathloss exponent for signals between the unlicensed and licensed device; and S_{int} is the shadow fading factor representing the variation in received power due to terrain, clutter, and other environmental factors.
3. Received power at a licensed device from a broadcast tower is $P_{sig} = K_{sig} S_{sig}/R^a$, where K_{sig} is a constant related to broadcast power, antenna heights, cable losses, etc.; R is the separation between the transmitter and receiver; a is the pathloss exponent between the transmitter and receiver; and S_{sig} is a shadow fading factor representing the variation in received power due to terrain, clutter, and other environmental factors. The specific effects for the broadcast power and antenna gains are not broken out as separate factors since they will likely be constants and not vary over time.
4. The licensed device is disrupted if $P_{sig}/P_{int} < T$ for some defined threshold T. This threshold depends on the nature of the interference signal, and whether it is in the same channel as the licensed receiver or another nearby channel. Combining the previous assumptions, the signal to interference ratio is $P_{sig}/P_{int} = K\, S\, r^b/(g_{UL}\, g_L\, P_{UL}\, R^a)$, where $K = K_{sig}/K_{int}$, and $S = S_{sig}/S_{int}$.
5. The shadow fading S is well modeled by a log-normal distribution with standard deviation of log S, σ. If S_{sig} and S_{int} are both log normal with log standard deviations σ_{sig} and σ_{int}, then their ratio is also log normal. In practice, S_{sig} and S_{int} are correlated. A TV in the basement will receive weaker signals from both the broadcaster and the unlicensed device. Thus, $\sigma^2 < \sigma_{sig}^2 + \sigma_{\text{int}}^2$.

6. The licensed devices are uniformly distributed over the broadcast coverage area. The coverage area is a circle of radius R_B. The probability a device is within R of the center is $\frac{R^2}{R_B^2}$. Let A be the coverage area, N_L the number of unlicensed devices in this area, and N_L/A the average density of licensed devices. For simplicity, all broadcast channels have the same coverage area.
7. The unlicensed devices are uniformly distributed over the broadcast coverage area and the number of these devices is N_{UL}. The licensed and unlicensed device separation, r, is small relative to the radius of the broadcast coverage so that edge effects at the limit of licensed coverage can be ignored.
8. A device which is turned off can not disrupt or be disrupted. A licensed device not using the broadcast channel (e.g. using cable) can not be disrupted.
9. Unless otherwise stated, antennas have a uniform random azimuth orientation.

Some notes on these assumptions are in order. The limitation to two-dimensional does not apply well to built-up metropolitan areas such as New York City. It does apply to urban environments with few high-rise buildings and typical suburban and rural environments. Later work will expand this model to three-dimensional environments.

The pathloss exponent is allowed to differ for the unlicensed and broadcast transmitters. It is expected that the broadcast transmitter will be close to a free-space pathloss model (a = 2). The unlicensed device will differ depending on the device. For low-power devices without special antenna mounting, the pathloss will be closer to the two-ray ground model (b = 4). For higher power transmitters mounted on outdoor poles, it will be between 2 and 4 depending on antenna height and location.

Shadow fading can have log-normal standard deviations as large as 10dB for both S_{sig} and S_{int} suggesting a total of 14dB for the log normal standard deviation for their ratio. Because of correlations between them we might expect a total variation equal to half of this value or 7dB.

With the uniform distribution of unlicensed devices the expected number of licensed devices in a ring of thickness dr and radius r from the unlicensed device is $2\pi r\, N_L/A\, dr$.

B. Model Derivation

There are three main random variables in this model. The distance of the licensed device to the broadcast transmitter, R; the distance from the licensed device to the unlicensed transmitter, r; and the shadow fading value S. Once these are accounted for, secondary random variables can be easily admitted.

We are interested in computing expected number of licensed devices disrupted by an unlicensed device. We compute the expected number disrupted by a single unlicensed device and then scale to multiple unlicensed devices. Consider a single unlicensed device. Given r and S, a licensed device is disrupted if $\frac{P_{sig}}{P_{\text{int}}} = \frac{SKr^b}{g_{UL}g_L P_{UL} R^a} < T$, i.e. $R > \left(\frac{SKr^b}{g_{UL}g_L P_{UL} T}\right)^{1/a}$. T is the threshold given the current channels of the licensed and unlicensed devices; and the modulation scheme used by the unlicensed device. It follows from assumption 6:

$$\Pr\left\{R > \left(\frac{SKr^b}{g_{UL}g_L P_{UL} T}\right)^{1/a}\right\} =$$

$$\begin{cases} 1 - \frac{1}{R_B^2}\left(\frac{SKr^b}{g_{UL}g_L P_{UL} T}\right)^{2/a} & \text{if } \left(\frac{SKr^b}{g_{UL}g_L P_{UL} T}\right)^{1/a} \le R_B \\ 0 & \text{otherwise} \end{cases}$$

The expected number of licensed radios at a distance r to $r + dr$ is $N_L/A\ 2\pi r\ dr$. To get the total expected users disrupted by the unlicensed device we integrate over all distances r, and for each r, over all possible S.

$$D = \int_0^\infty\int_0^\infty \frac{N_L}{A} 2\pi r \Pr\left\{R > \left(\frac{sKr^b}{g_{UL}g_L P_{UL} T}\right)^{1/a}\right\} p_S(s)\, dr ds$$

where p_S is the distribution of S. Switching the order of the integration and integrating yields:

$$D = \pi \frac{N_L}{A}\left(\frac{R_B^a g_{UL} g_L P_{UL} T}{K}\right)^{2/b} \frac{b}{b+a} e^{\frac{2\sigma^2}{b^2}}.$$

This is the expected number of licensed devices disrupted by a single unlicensed device. For N_{UL} unlicensed devices, we conservatively overestimate the number of disrupted devices as N_{UL} times larger. This is an overestimate in that if two different unlicensed devices disrupt the same licensed device it counts as two licensed devices disrupted.

An alternative form of this equation is derived as follows. Consider the worst case when a licensed device is at the edge of the broadcast area, the unlicensed device is at maximum power on the same channel as the licensed device with both antennas pointing at their maximum gain towards each other. Let S = 1 and consider the distance r_{min} that would just meet the signal to interference criteria for an interferer on the same channel. In this case (with obvious notation):

$$\frac{P_{sig}}{P_{\text{int}}} = \frac{K r_{\min}^b}{g_{UL}^{\max} g_L^{\max} P_{UL}^{\max} R_B^a} = T_S$$

$$r_{\min} = \left(\frac{g_{UL}^{\max} g_L^{\max} P_{UL}^{\max} R_B^a T_S}{K}\right)^{\frac{1}{b}}$$

Combining these results we get

$$D = \pi \frac{N_L N_{UL}}{A} r_{\min}^2 \left(\frac{g_{UL}}{g_{UL}^{\max}} \frac{g_L}{g_L^{\max}} \frac{P_{UL}}{P_{UL}^{\max}} \frac{T}{T_S}\right)^{\frac{2}{b}} \frac{b}{b+a} e^{\frac{2\sigma^2}{b^2}}$$

The role of the broadcast path loss exponent, a, is somewhat subdued in this equation. This is because it is implicitly subsumed in the definition of the coverage area. A bigger a would lead to a smaller coverage area and vice versa. Here it reflects how quickly the licensed signal power increases above the threshold as the center of the coverage area is approached. Since most licensed devices are closer to the edge than the center this effect has only a small impact on the final result.

There are four final random variables that need to be considered: the distribution of the unlicensed and licensed antenna gains; the distribution of unlicensed power levels; and the distribution of device thresholds. These are assumed to be independent of each other and the other random variables.

The unlicensed antenna has an antenna pattern, $g_{UL}(\theta)$. The expected contribution to the number of disrupted receivers is:

$$\int_0^{2\pi} (g_{UL}(\theta))^{2/b} p_{g_{UL}}(\theta) d\theta = \frac{1}{2\pi}\int_0^{2\pi} (g_{UL}(\theta))^{2/b} d\theta$$

where the orientation of the distribution $p_{g_{UL}}$ is assumed to be uniform and independent of the location of the licensed device. A receiver detection technique might lead to null steering or other techniques so that the antenna angle distribution would not be independent but this is not considered. Define

$$G_{UL} = \frac{1}{2\pi}\int_0^{2\pi} \left(\frac{g_{UL}(\theta)}{g_{UL}^{\max}}\right)^{2/b} d\theta$$

Typical values are

$G_{UL} = 1$ if the antenna is omnidirectional

$G_{UL} = w/360$ if the antenna is an ideal sectorized antenna of width w in degrees.

Similarly we define the licensed antenna gain factor:

$$G_L = \frac{1}{2\pi}\int_0^{2\pi} \left(\frac{g_L(\theta)}{g_L^{\max}}\right)^{2/b} d\theta$$

Power control would result in a distribution of power levels. Similar to the antenna gains we define the power control gain factor:

$$P = \int_0^{P_{UL}^{\max}} \left(\frac{P_{UL}(x)}{P_{UL}^{\max}}\right)^{2/b} p_{P_{UL}}(x) dx .$$

where $p_{P_{UL}}$ is the distribution of power levels. Example values are

$$P = 1$$

if the unlicensed device always transmits at maximum power;

$$P = b/(b+2)$$

if power is uniform between 0 and $P_{UL}^{\max}$;

$$P = \frac{b}{2}\frac{1-\left(P_{UL}^{\min}/P_{UL}^{\max}\right)^{2/b}}{\ln P_{UL}^{\max}/P_{UL}^{\min}}$$

Table III.
Isolation between DTV channels i channels apart

i	T_i/T_s(dB)
0	0.0
+/–1	48.5
+/–2	74.2
+/–3	78.2
+/–4	84.2
+/–5	86.2
+/–6	80.2
+/–7	87.2
$\|i\|>7$	90.2

if $\ln P_{UL}$ is uniform between $\ln P_{UL}^{\min}$ and $\ln P_{UL}^{\max}$ (i.e. it is uniform in dB between the min power in dB and the max power in dB).

The distribution of required thresholds depends on the likelihood of choosing the same channel, or one of the neighboring channels, or more separated channels. Even if the unlicensed device is working on a channel far removed from the channel used by the licensed device, a sufficiently strong signal can overwhelm the receiver. So, all channels must be considered. Therefore we define:

$$C = \sum_i p_i (T_i/T_S)^{2/b}$$

where if N is the channel used at a licensed receiver, p_i is the probability of the unlicensed device being on channel $N + i$, and T_i is the threshold required in this case. For instance, Table III lists values for DTV[2].

As a worst case example, let the channels be chosen randomly and we ignore effects at the edge of the licensed band. Then

$$C = 0.020 \quad \text{if } b = 2$$
$$C = 0.020 \quad \text{if } b = 4$$

If the unlicensed radio avoids the same and adjacent channels of the licensed receiver (i.e. is at worst at N +/– 2) then at worst:

$$C = 3.8\text{x}10^{-8} \quad \text{if } b = 2$$
$$C = 2.0\text{x}10^{-4} \quad \text{if } b = 4$$

If the unlicensed radio can always avoid any channel within +/– 7 of a receiver channel, then

$$C = 9.6\text{x}10^{-10} \quad \text{if } b = 2$$
$$C = 3.1\text{x}10^{-5} \quad \text{if } b = 4$$

We let all the model factors be denoted by M

$$M = \pi \frac{b}{b+a} e^{\frac{2\sigma^2}{b^2}}$$

Then

$M =$ 5.8 if $a = 2$, $b = 2$, and $\sigma = 7$dB

$M =$ 2.9 if $a = 2$, $b = 4$, and $\sigma = 7$dB

Licensed receivers or unlicensed transmitters may simply be turned off and not part of creating or suffering interference. A licensed receiver may be receiving its signal via cable and not through over-the-air broadcasts. The last factor captures the fraction of devices eligible to participate in the device interaction:

$$E = F_{ONUL} F_{ONL} F_{BC}$$

where F_{ONUL} is the fraction of the unlicensed devices that are turned on at any time, F_{ONL} is the fraction of licensed receivers that are on, and F_{BC} is the fraction of receivers that listen to over-the-air broadcasts as opposed to cable TV.

Putting all these factors together and noting $F = D/N_L$ yields the main result:

$$F = r_{\min}^2 PCEG_{UL}G_L MN_{UL} / A$$

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