Interference Protection Criteria for Realistic Channel Conditions

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***Abstract*—This paper describes a new National Telecommunications and Information Administration (NTIA) effort focused on the development of methods to determine appropriate interference protection criteria (IPC) as a means to resolve contention around spectrum sharing proposals being considered by NTIA and Federal Communications Commission (FCC).**

Keywords— Clutter, interference protection criteria, LTE, multipath, radio wave propagation, surveillance radar, target fluctuation,

I. Introduction

In 2002 the Federal Communications Commission (FCC) Spectrum Policy Task Force (SPTF) Interference Protection Working Group (IPWG) noted that interference protection criteria (IPC) were the source of contention for many spectrum sharing scenario proposals being considered by the FCC and National Telecommunications and Information Administration (NTIA) [1]. In response, NTIA compiled and published existing IPC for federal systems providing the services in Table I [2]. The report recommended development of methods for determining "appropriate" IPC for the federal systems. This paper describes a new NTIA project focused on the development of these methods.

First, the current IPC are described. Then the method used to estimate the key interfering signal power threshold (PT) criterion is explained. From this explanation it becomes clear that the current criteria are incomplete, and we recommend additional criteria needed to fill this gap.

Next, as an example, the methods used to investigate the PT for radar and cellular communication systems in the 3550-3650 MHz band are examined [3],[4]. Finally, we discuss research directions for investigating ways to determine more appropriate PTs for this scenario.

TABLE I SERVICES PROVIDED BY FEDERAL SYSTEMS

Service	Example
Fixed	Terrestrial point to point
Fixed satellite	Geostationary orbit
Radio Determination	Surveillance radars
Radio Determination Satellite	GPS
Mobile	Terrestrial cellular
Mobile Satellite	Low earth orbit
Science	Passive remote sensing

II. Interference Protection Criteria

IPC are commonly thought to be the maximum interfering signal power the receiver can tolerate. While this PT is indeed a crucial criterion, it is only one of many. As shown in Table II, there are a number of other specific IPC, i.e., reference bandwidth, percentage of time, percentage of locations, and special conditions needed for interpretation and application of the PT.

The reference bandwidth is the bandwidth the interfering signal power is to be measured in. Although it can correspond to the receiver bandwidth, it is not constrained to it. The percentages of time and location criteria take into consideration the statistical nature of radio wave propagation conditions. The special conditions criterion is somewhat open-ended so it can be adapted to the wide range of services.

TABLE II INTERFERENCE PROTECTION CRITERIA

Criterion	Description
Power Threshold	One or more levels of interfering signal power I, I/N, or S/I
Reference bandwidth	Bandwidth in which interfering signal power should be calculated or measured.
Percentage of Time	For each threshold, the percentage of time during which the threshold should (S/I) or should not (I or I/N) be exceeded.
Percentage of Locations	For each threshold, the percentage of locations at which the threshold should (S/I) or should not (I or I/N) be exceeded. Used in some services to protect operations within a service area.
Special Conditions	Information needed for interpretation or application of the thresholds, including as a minimum: whether the IPC are for aggregate or single-entry interference; the type of interfering signal (*e.g.*, noise-like) for which the IPC apply; and for I/N and S/I thresholds the definition of the N or S reference levels. May include duration of permissible threshold exceedance (*e.g.*, # seconds); specific category of victim or interfering stations; and frequency off-tuning associated with the thresholds.

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III. General IPC PT Estimation Method

In order to understand what criteria are needed to determine appropriate PTs, we turn to a discussion of how PTs are estimated and used in the communications radio link interference scenario depicted in Fig. 1.

As shown, the desired and interfering signal links look identical up to the receive antenna. Radio channel conditions in both include basic transmission loss (BTL) and multipath (MP). BTL is a mean power loss that has a deterministic component due to distance, and a random component that can vary with time, location, and "situation" [5]. Time variability can be caused by changes in the atmosphere. Location variability can be caused by building or terrain obstructions. Situation variability is attributed to the myriad ways a particular system can be deployed. MP is caused by scattering off the atmosphere or nearby objects. While MP can alter instantaneous power it does not alter mean power of well engineered radio links associated with BTL. External noise includes that created by natural phenomena and electrical devices. Other interfering signals include those other than the one being studied. As an example, a cellular system receiver must be able to operate in the presence of signals from surrounding cells.

PTs are typically estimated with hardware measurements or software simulations performed with test fixtures like the one shown in Fig. 2. The wanted or desired signal power, S, is set to a normally received or "baseline" value by suitable adjustments to the attenuator that includes all gains and losses from the transmitter to the receiver input. The wanted signal power stays constant throughout the measurement. The noise power, N, is referred to the receiver input. The interfering signal power, I, provided by a vector signal generator (VSG) is incrementally increased. With each increase in interfering signal power, a performance metric (PM) such as bit error rate (BER) is estimated at the receiver output. The filter (FLT) in the interfering signal path ensures that only power in the receiver's allocated band induces interference. Once the measurements are complete the PT corresponding to the allowed or required performance is found as shown in Fig. 3.

Not shown in either Figs. 1 or 2 are the filters that determine the receiver's frequency response and corresponding frequency dependent rejection (FDR). This can be determined by repeating this process over a range of frequency separations as shown in Fig. 4.

Ultimately the PT is used along with radio link power budget analysis and propagation models to determine statistical distributions of signal and interfering signal powers at the receiver location. These distributions are then used to determine the probability of interference and required frequency and distance separations.

Inspection of the PT estimation test fixture and method reveals two important points. First, BTL time, location, and situation variability are not included in the measurement. This variability is found through the radio link power budget analysis just described.

Second, replication of the PTs requires knowledge of the baseline and required performances, the radio channel conditions, and the settings of receiver functions meant to

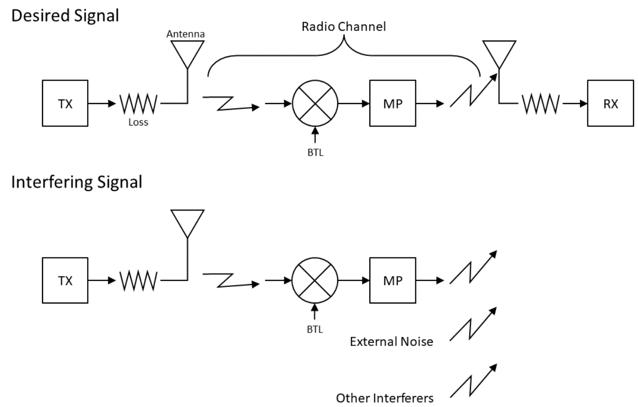

Fig. 1. Interference scenario.

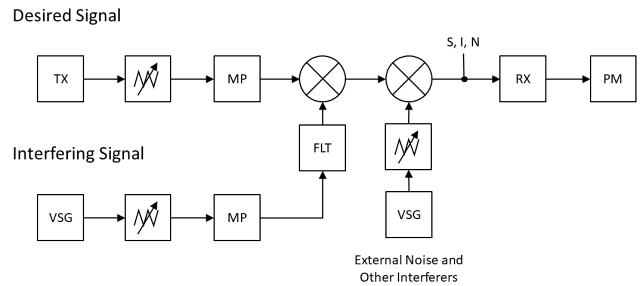

Fig. 2. IPC PT estimation test fixture.

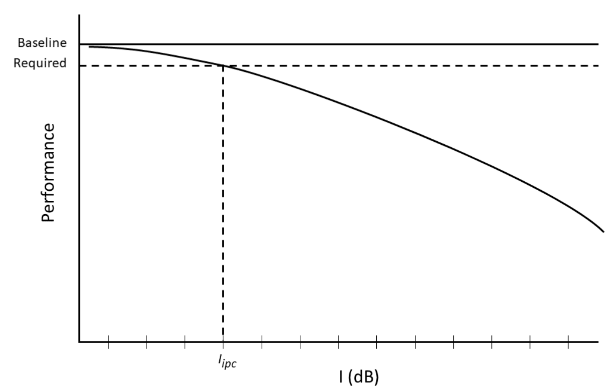

Fig. 3. Graph showing relationship between performance metric and INR. Baseline performance is evaluated without interference. The I_{ipc} is the PT.

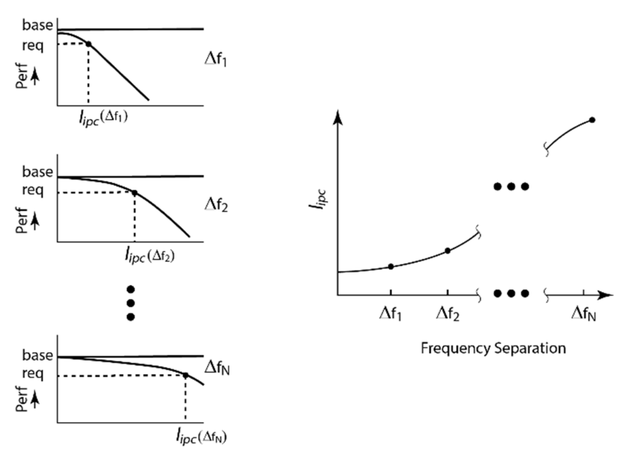

Fig. 4. IPC PT, I_{ipc}, as a function of frequency separation.

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mitigate radio channel effects known at the time the receiver was designed. None of these criteria is in Table II and all are too important to be relegated to the special condition category. Consequently, we are recommending these parameters, summarized in Table III, be added to the current IPC.

An example of the importance of distinguishing baseline performance from required performance is a geosynchronous satellite receiver which has the same required performance and signal-to-noise ratio (SNR) whether it is operating at high latitudes or at the equator. However, the baseline signal power is much greater at the equator than at the high latitudes. Consequently, the receiver at the equator has a much larger power margin and therefore should be able to mitigate more interference than the receiver at high latitudes. Recognition of the effect of baseline conditions on the PT is essential in achieving our goal of more appropriate PT.

IV. IPC PT ESTIMATION EXAMPLES

Two IPC studies that investigate the interference resulting from an air surveillance radar sharing spectrum with a Long Term Evolution (LTE) cellular communication system illustrate the importance of including the new IPC [6],[7].

The new IPC for the radar interference in an LTE receiver study are listed in Table IV. A throughput performance metric was used. The modulation and coding scheme (MCS) was enabled to match coding rate and modulation order to radio channel conditions and thereby maintain a constant block error rate (BLER). One of the stated objectives in this study was to not include propagation effects such as multipath so as to better isolate the effects of interference in the LTE receiver [8]. In addition, aggregate interfering signals from other LTE transmitters were not included. Consequently, except for the radar interfering signal, radio channel conditions were benign.

The key problem with this setup is that without external noise and multipath, all the MCS's ability to mitigate radio channel conditions is devoted unrealistically towards interference mitigation. How different would the PT be if external noise and multipath were included, MCS was disabled, and BLER was used as a performance metric? Research is needed to determine whether different radio channel conditions and receiver settings might provide more appropriate PT.

The new IPC for LTE interference in a radar receiver study are listed in Table V. This study used a probability of detection performance metric derived from visual counts of test targets on the radar's planned position indicator (PPI) display. The visual method was used primarily because the test engineers thought a human operator to be better at discriminating targets than the radar's own automatic target detecting and tracking function [9]. The radar had a manually set threshold rather than a constant false alarm rate (CFAR) function. While false alarms increased with interfering signal power, their numbers were too great for visual counting.

Radio channel conditions were benign with stationary, non-fluctuating targets without clutter. Automatic gain control (AGC) was on. Since there was no clutter, sensitivity time control (STC) and fast time constant (FTC) clutter mitigation functions were disabled. Previous experiments had shown that it is difficult to visually count fluctuating targets so they were not used [10]. Interestingly, non-fluctuating targets were reported to be an advantage in that they were more resilient to interference and produced a less conservative PT.

What is clear is that both omissions (i.e., target fluctuation and clutter) make the measurement less realistic and perhaps less appropriate. Complex shapes of most radar targets introduce fluctuations, and clutter—to some degree—is often present. While disabling STC and FTC clutter mitigation functions in the absence of clutter was an excellent idea, it is not clear that omitting clutter is the best idea. How different would the PT be if fluctuating targets were used in the presence of clutter and the clutter mitigation functions were enabled? Once again, this suggests research is needed to determine whether different radio channel conditions and receiver settings might provide more appropriate PT.

Both studies specified baseline performance but neither specified the required performance. If the baseline performance is assumed to be the same as required performance and the PT is interpreted to be the interference-to-noise ratio (INR) that drives the performance below that required, then the PT is ambiguous because it is dependent only on the uncertainty created by the limited number of Monte Carlo trials.

TABLE III RECOMMENDED ADDITIONS TO IPC CRITERIA

New IPC Criteria	Description
Baseline performance	Typical victim receiver performance
Required performance	Minimum performance demanded by the service
Radio channel conditions	Presence of multipath, external noise, and other interfering signals
Receiver function settings	Settings of receiver functions meant to mitigate radio channel conditions

TABLE IV RADAR INTERFERENCE IN AN LTE RECEIVER

Criterion	Description
Baseline conditions	48 Mbps throughput 10% BLER for downlink 30% BLER for uplink -75 dBm for downlink -85 dBm for uplink
Radio channel conditions	No external noise No multipath
Receiver function settings	MCS on 10% BLER for downlink 30% BLER for uplink

TABLE V LTE INTERFERENCE IN A RADAR RECEIVER

Criterion	Description
Baseline conditions	Pd 0.9 Probability of false alarm with minimal PPI display speckling
Radio channel conditions	No clutter No target fluctuation
Receiver function settings	AGC on STC off FTC off CFAR off

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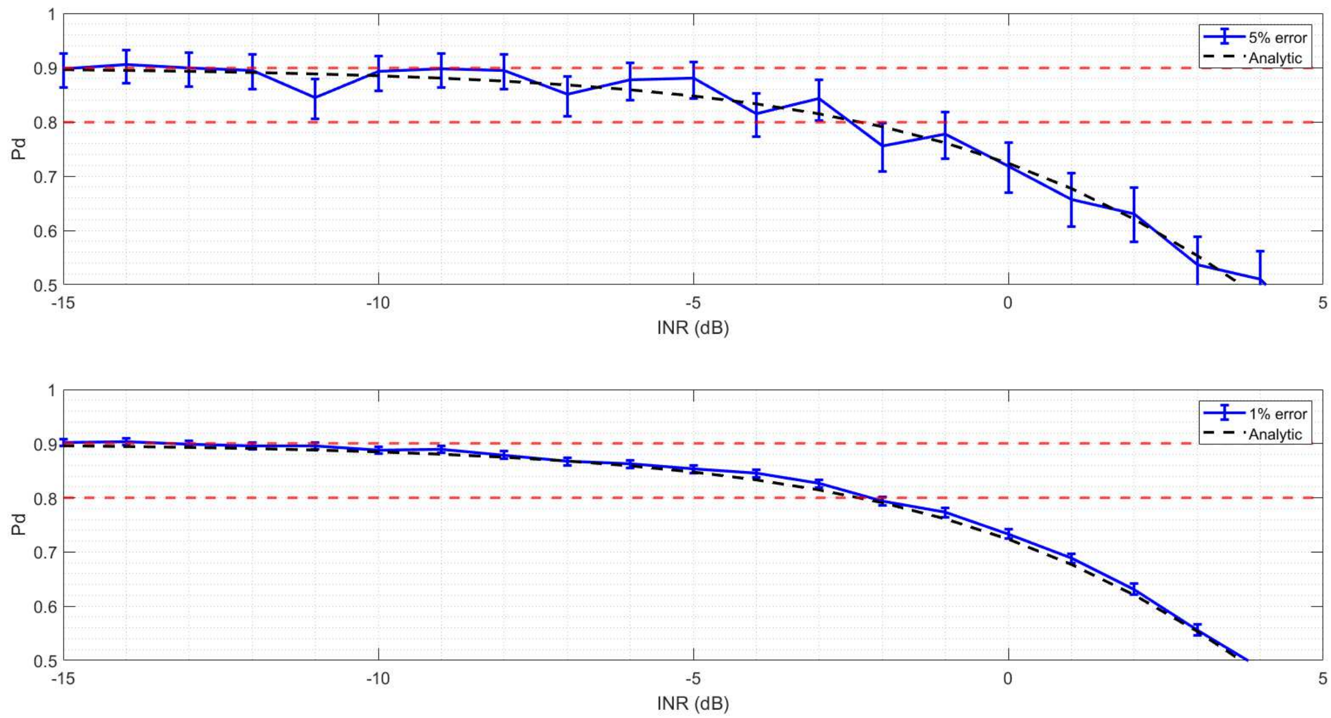

Fig. 5 Results of long range radar IPC test. Results from the top and bottom graphs were derived from 400 and 10,000 Monte Carlo trials, respectively. The error bars correspond to a 5% and 1% error at the 95% confidence interval.

This ambiguity is easily resolved if the baseline performance corresponds to what is normally encountered, which is typically greater than that required. Now the baseline SNR exceeds the required SNR and there is a power margin that can be used to mitigate interference.

For example, Figure 5 shows results of a long range radar IPC test for a Gaussian noise interfering signal. The radar transmitted two frequency diverse pulse trains that were received with 8 pulse integration, CFAR, and diversity combining. The target fluctuated with Swerling 1 statistics and the radio channel had refractive fading. The nominal radar link budget for a standard Swerling 1 target provided an SNR corresponding to a 0.9 probability of detection (Pd). The top and bottom graphs show results of the IPC test when 400 and 10,000 detection trials were executed at each INR. 400 trials, often used in field trials, corresponds to a 5% error at the 95% confidence level. 10,000 trials provide a 1% error at the same confidence level.

If the baseline performance is the same as the required performance, the PT would be -5 and -11 dB INR for 400 and 10,000 trials, respectively. If even more trials were used, the PT would decrease even more. However, if baseline performance corresponds to that of normal operating conditions and it is greater than that required, for example 0.8 Pd, the PT would be -1 and -2 dB INR for 400 and 10,000 trials, respectively. These results are summarized in Table VI.

TABLE VI. IPC PT FOR TWO DIFFERENT BASELINE PROBABILITY OF DETECTIONS

Baseline Pd	Required Pd	Trials	IPC INR PT (dB)
0.9	0.9	400	-5
0.9	0.9	10,000	-11
0.9	0.8	400	-1
0.9	0.8	10,000	-2

V. CONCLUSION

IPC PTs are a contentious problem for spectrum sharing analysis. In this paper we identified four new IPC which may minimize this contention by making the IPC PT estimation method more realistic. These are definitive (1) baseline performance, (2) required performance, (3) realistic channel conditions, and (4) receiver function settings that match these conditions. Distinguishing baseline conditions from those that are required is particularly important in achieving our goal of more appropriate PT.

By examining prior IPC PT estimation efforts, we have also identified areas where work is needed to determine how much of a difference the use of realistic conditions will have on PTs. These areas include the effects of multipath, aggregate interfering signals, and MCS algorithms on terrestrial cellular communication system PTs, and the effects of fluctuating targets, clutter, and clutter mitigation functions on surveillance radar system PTs.

Undoubtedly there will be a number of issues that arise in identifying which conditions should be considered realistic. However, resolution of these issues will undoubtedly yield more robust PTs.

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