RADIO FREQUENCY RECEIVER PERFORMANCE

A 5G Americas White Paper

Feb. 2023

Contents

Executive Summary

This white paper provides a timely technical analysis of receiver performance with 5G Americas providing contributions and recommendations toward positive outcomes regarding coexistence. The FCC Notice of Inquiry released in April 2022, “Promoting Efficient Use of Spectrum through Improved Receiver Interference Immunity Performance”, highlights this issue. Some services initially utilized large fallow spectrum bands, but greater usage of those bands has created new sources of out of band interference. Legacy receivers that were designed for the original benign conditions may not be adequate under new harsher conditions. Regulation focuses on transmitters, but adding restrictions to only newly deployed systems to compensate for inadequate legacy receiver performance can become counterproductive. Receiver performance considerations must be prioritized; receiver performance should evolve over time as spectrum becomes increasingly crowded. This would entail upgrades or replacements to equipment over time. Effective self-policing negates additional regulator intervention in industries like mobile networks that have a well-functioning system of evolving standards, and market forces that encourage equipment upgrades for better performance. However, other industries that lack such mechanisms may require regulator attention. Each situation should be examined on a case-by-case basis with policies crafted accordingly. Ultimately, the industry would benefit greatly from a clear, long term spectrum plan designed to enable a predictable timeline of equipment upgrades.

1. Introduction

Ericsson's latest Mobility Report projects that mobile networks will carry four times the data of today's networks by 2025[1]. This will add new demands on service providers to increase network capacity. Wireless networks are expanding beyond smartphones to serve a myriad of use cases that are bandwidth intensive (FWA, XR, AR, and Cloud gaming), and require additional spectrum deployments from operators. Spectrum scarcity makes spectrum repurposing much more challenging, and future improvements are unlikely. Adjacent services will need to operate in closer proximity to each other to increase efficient use of spectrum and meet various spectrum demands.

Administration's spectrum policies focus on regulating transmitters rather than receivers when regarding decisions about adjacent service coexistence, and the resulting efficiencies of those radio systems. Creating an improved spectrum management environment that achieves a balance of policy transmitters and receivers will play a critical role in improved utilization of scarce spectrum.

Considering that adjacent bands may be occupied by disparate systems (e.g., altimeters and 5G mobile networks), a rational approach is to consider receiver immunity performance for those different systems which can ensure their mutually beneficial coexistence while also operating independently. Adopting decisions that are technologically neutral, and that allow for evolution to new radio applications will be central to addressing the growth in spectrum demand.

A variety of appropriate approaches can be employed to address receiver immunity performance in the marketplace. In some cases, the industry uses voluntary standards and market-based incentives to address performance. Other industries have generally not set receiver specifications or evolved them over time. The most critical components are holistic policies that address a path for legacy receivers upgrades that promote coexistence, and are also not susceptible to transmitters operating in their prescribed manner. Without holistic technology policy, some receivers may be developed without regard to adjacent band services or efficiency improvements over time.

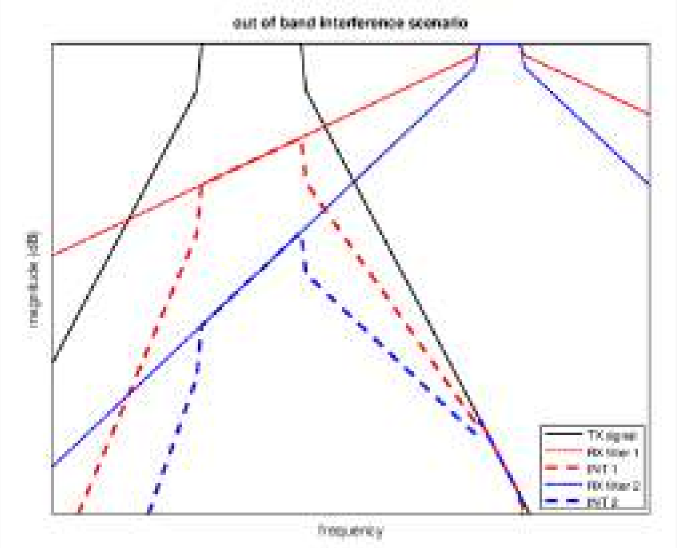
When developing policies to facilitate the timely introduction of new services and technologies, it is important to balance the protection of existing services in an environment where appropriate information is available that allows for decision making. Regulators' inability to acquire appropriate receiver characteristics from incumbents should not impede the introduction of new services.

The following sections describe the technical background of the receiver immunity problem. Particularly: the receiver characteristics that need to be abstracted and incorporated in an evaluation, the receiver characteristics in a coexistence study, industry/policy considerations, and recommendations representing guidance to administrations to aid in formulating policy.

1.1 The basic problem of out of band interference

In a simplistic and basic out of band interference (OBI) scenario, the main lobes of the transmit signal and receive filters are not adjacent, which roughly captures the case of 5G deployments in the C band, and altimeters. This is illustrated in Figure 1, with frequency represented on the x-axis, and magnitude in decibels (dB) represented on the y-axis. The transmit signal represents the source of interference as seen by the receiver, and may be a single signal or the accumulation of multiple transmit co-channel signals. In this case, it makes no difference to the receiver which experiences the cumulative signal.

Figure 1. Out of band interference scenario.



Two receive filters are displayed, where filter 2 is more selective than filter 1. In the frequency domain, the interference signal experienced by the receiver after the receive filter is the product of the transmit signal and the receive filter (equivalently the sum on a dB scale).

In the absence of the out of band signal, the SNR (signal to noise ratio) after the receive filter is where is the power of the desired signal at the receiver, and is the noise power. In the presence of the out of band signal, the resulting interference after the receive filter is denoted , and causes the SNR to decrease. In essence, mitigating the effect of OBI requires reducing .

In the absence of the out of band signal:

$$\text{SNR} = \frac{S}{N}$$

In the presence of the out of band signal:

$$\text{SNR} = \frac{S}{N + I}$$

1.1.1 Effect of the receive filter

With either receive filter, first note that the interference signal is dominated by the contribution from the main lobe of the transmit signal. Secondly, the out of band selectivity of the receive filter dominates the amount of interference that makes it past the receive filter, including the contribution from the main lobe of the transmit signal. This is again illustrated in Figure 1, where the interference signal through the tighter filter 2 is smaller than the signal through filter 1. This translates into a smaller interference power .

A more selective receive filter is the natural and straightforward solution to the problem of OBI. In mobile networks, tight receive filtering is imperative when the working assumption is that adjacent spectrum is occupied (e.g., by other carriers from the same operator or other operators, or by some other user of the spectrum). Receive filters are specific to the individual spectrum band and adjacent band uses. Filters increase the cost of receivers, and vendors will take all relevant parameters into account when designing receivers—including expected future services. A clear understanding of the spectrum environment is crucial for improving receiver performance.

1.1.2 Effect of transmit signal

The observation that the dominant contribution to interference stems from the main lobe of the transmit signal, which implies that the only way for the transmitter to help the receiver is by effectively reducing its interference power seen at the receiver. In Figure 1, this would translate to shifting the whole transmit signal down, and as a result, the whole interference signal would also shift down. This power reduction can be achieved in multiple ways:

- Reducing transmit signal power (e.g. base station output power)
- Increasing distance to the receiver (e.g. via exclusion zone)
- Spatially shaping the signal away from the receiver (e.g. via base station antenna down tilt)

Such techniques are available and feasible, but also reduce utilization of spectrum allocated to the operator of the transmitter. Spectrum is a scarce resource for mobile networks, so its utilization is crucial for enabling the network operator to address traffic demands from users, and making returns on its investments in spectrum licenses and infrastructure. Ultimately, placing the burden of solving the OBI issue on the transmitter is unproductive.

2. Current and previous work on receiver standards

This section summarizes current and previous relevant work, including the aforementioned FCC Notice of Inquiry (NOI), previous FCC related activities, Technological Advisory Council white papers and workshops, and a European Electronic Communications Committee report on receiver performance.

2.1 FCC Notice of Inquiry on Receiver Performance Specification

In this Notice of Inquiry (adopted April 21, 2022[2]) the Commission takes a fresh look at the role of receiver performance in its spectrum management responsibilities with the goal of facilitating new opportunities for use of the nation's spectrum resources. While the Commission has typically focused its rules on the transmitter side of radio systems, receivers and receiver interference immunity performance play an increasingly critical role in enabling more efficient spectrum use. The FCC seeks through its Notice of Inquiry to develop an up-to-date record on the role of receivers in spectrum management and how it might best promote improvements in receiver interference immunity performance that would serve the public interest. The Commission recognizes that a variety of approaches may be appropriate, whether through industry-led voluntary measures, FCC policy and guidance, or rule requirements. In this important first step the Commission seeks to compile a comprehensive record on the various issues that it should consider.

Many of the commenters in the record addressed topics including:

- The role of receiver performance in spectrum management;
- Comments on the NOI's suggested approaches to receiver performance—including industry-led standards, FCC policy guidance, interference limits or harm claim thresholds, and on receiver performance mandates (including FCC authority);
- Suggestions for other incentives or solutions the FCC should pursue;
- Comments related to specific bands or services;
- How the FCC should deal with legacy devices and the timelines for implementing any receiver performance improvements; and
- The disclosure of technical information related to transmitter or receiver characteristics.

Overall, most commenters agree that receiver performance affects spectrum management. Commenters appear to have the most agreement around the notion that in FCC rulemakings, adjacent-band issues need to be better addressed. However, commenters have sharply divided views on whether the FCC should take any or some of the additional steps related to potential regulations on receivers.

Of the proposed solutions in the NOI, industry-led standards and voluntary FCC policy guidance have the most support in the record (though the implementation envisioned varies). Some commenters encourage the FCC to implement interference limits or harm claim thresholds, but even so, there is near universal agreement among those who commented on the issue that doing so would be challenging. Many commenters express particular views about specific services—including highlighting how well the service performs (e.g., 5G/unlicensed) or noting that the service would face special challenges to the implementation of receiver performance requirements (e.g., satellite, public safety, passive services).

2.2 Previous FCC activity on receiver standards

The FCC issued an NOI in 2003 on receiver standards. This NOI was officially terminated in 2007 with no action. The 2003 NOI identified the following key parameters:

- Selectivity
- Sensitivity
- Dynamic Range
- Automatic RF gain control
- Shielding
- Modulation Methodology
- Signal Processing

The FCC has a number of regulations on receivers in specific bands:

- 800 Mhz public safety
- 900 Mhz
- Dig Tv
- CBRS
- 3.7 GHz
- Part 80 Maritime
- Part 87 Aviation
- Part 97 Rescue services

2.3 Technological Advisory Council White Papers and Workshops

The Commission's Technological Advisory Council (TAC) has investigated and issued a number of whitepapers examining various technical issues concerning receiver performance from 2011-2015.

2.3.1 White Paper on Spectrum Efficiency Metrics

In 2011, the Commission's TAC released a white paper on "Spectrum Efficiency Metrics." The conclusion of the white paper was a recognition that both the receiver and transmitter play a critical role in evaluating of spectrum efficiency[3].

2.3.2 White Papers on Interference Limits Policy and Harm Claim Thresholds

In 2013, the TAC released a white paper on "Interference Limits Policy" which explored an interference limits policy that was believed could promote more transparent consideration of receivers in spectrum management and promote better receiver performance.

The paper introduces the concept of harm claim threshold (HCT) and defines it as 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. By establishing harm claim thresholds on in-band and out-of-band interfering signals receivers can be brought into the policy picture with minimal regulatory intervention. 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.

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.

A harm claim thresholds approach has its limitations. 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. 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.

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. 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, a combination of the two[4].

2.3.3 White Paper on Harm Claim Thresholds

In 2014 the TAC released a white paper on "Harms Claims Thresholds" that provided additional discussion of the harm claim threshold approach. According to the paper, harm claim thresholds provide added clarity about the rights and responsibilities of radio service operators regarding harmful interference. This will be particularly useful in, and at the boundaries of, bands with many diverse and frequently emerging new device types. In new allocations, harm claim thresholds would most likely represent the typical strongest signal levels generated by existing neighboring band operations; thus, transmissions by incumbent neighbors would not exceed the chosen harm claim threshold and would not trigger harmful interference claims[5].

2.3.4 Introduction to Interference Resolution, Enforcement and Radio Noise

In June 2014, the TAC issued a white paper providing insights into Interference Resolution, Enforcement, and Radio Noise issues. The original focus of the group was primarily on interference resolution and enforcement in spectrum under the sole jurisdiction of the FCC, rather than in spectrum that is shared between non-federal and federal users.

Section II discusses a taxonomy of interference types by categorizing interference into in-band or out-of-band interference, co-channel and adjacent channel interference, harmful and non-harmful interference, and whether or not the interference is produced by intentional or unintentional radiators of RF energy.

Section IV discusses challenges/opportunities associated with rapidly changing technical and market trends. As an example, it contrasts early wireless mobile telephone systems and private land mobile radio systems that typically used high power base stations on high antenna sites and were noise limited with today's interference-limited wireless system and concludes that today's low power/low antenna height network architectures, coupled with the high mobility and low power of individual end user devices, make spectrum monitoring from a limited number of fixed locations problematic[6].

2.3.5 White Paper on Risk-informed Interference Assessment

In 2015, the TAC released a white paper on "Risk-Informed interference Assessment." The approach described in the paper was a statistical approach to identify when interference might occur vs. worse case analysis[7].

2.3.6 White Paper on Basic Principles for Assessing Compatibility of New Spectrum Allocations

In 2015, the TAC released a white paper on "Basic Principles" for assessing compatibility and new spectrum allocations. The paper provided a set of basic principles that were considered helpful for all involved parties to consider and could serve to establish clearer expectations of incumbent services as well as new services entering the spectrum[8].

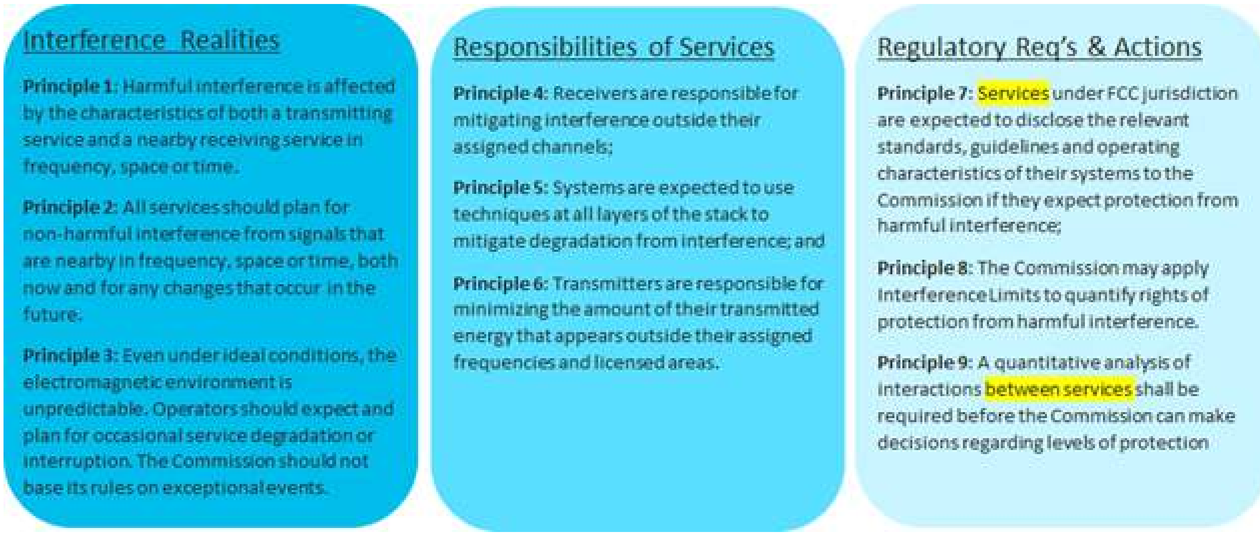
2.3.7 A Quick Introduction to Risk-Informed Interference Assessment

In April 2015, the TAC issued a white paper proposing the use of quantitative risk analysis to assess the harm that may be caused by changes in radio service rules and notes that in judging whether to allow new service rules, the FCC has to balance the interests of incumbents, new entrants, and the public. The trade-off between the benefits of a new service and the risk to incumbents has to date been essentially qualitative[9].

Risk is defined as "the combination of likelihood and consequence for multiple failure scenarios, inspired by the 'risk triplet' introduced by Kaplan & Garrick (1981)." What can go wrong? How likely is it? What are the consequences? By contrast, a so-called worst-case analysis focuses on the single scenario with most severe consequence, regardless of its likelihood. Risk-informed interference assessment is the systematic, quantitative analysis of interference hazards caused by the interaction between radio systems.

The second TAC Whitepaper in 2015 created a list of recommendations for interference realities, responsibilities of Services and Regulatory Actions:

Figure 2. Risk-Informed Interference Assessment Recommendations



2.4 Other Relevant Studies, Analyses, and Memoranda

2.4.1 NOI on Receiver Performance Specifications

FCC NOI on receiver standards and comments in 2003 that explored how to determine the right balance for requiring either or both transmitters, and whether receivers should comply with certain standards or not. The FCC proposed that a holistic approach that considers all receivers, including federal services, was needed.

Other activity relative to spectrum:

- NTIA report in 2003 promoting robust receivers
- NTIA CSMAC 2010: Fostering spectrum sharing and improving spectrum efficiency report
- FCC Economists'' paper 2011: Forward looking interference regulation- focused on “self-protect”
- Silicon Flatirons Reports 2012/2013: Efficient interference management related to receivers

2.4.2 PCAST Report on Spectrum Sharing

In 2012, the President's Council of Advisors on Science and Technology (PCAST) issued a report that dedicated significant discussion to the important role of receivers and receiver performance for spectrum management and promoting more efficient use of spectrum[10].

2.4.3 GAO Report on Receiver Performance

In 2013, the Government Accountability Office (GAO) issued its report discussing challenges related to improving receiver performance, including the lack of coordination across industries when developing voluntary standards, the lack of incentives for manufacturers or spectrum users to incur costs associated with using more robust receivers, and the difficulty of accommodating a changing spectrum environment[11].

2.4.4 Presidential Memorandum on Wireless Innovation

The 2013 Presidential Memorandum encouraged the creation of criteria to encourage spectrum efficiency[12].

2.5 CEPT/ECC

The European Electronic Communications Committee (ECC) has developed a report that examines the role that receiver performance plays in spectrum sharing and compatibility studies[13]. Receiver performance has been a limiting factor in some coexistence studies previously performed by CEPT/ECC[14]. It was concluded that in these cases improvements in the receiver performance could have improved the conclusion of the sharing study.

On June 2017, the Radio Equipment Directive (RED), 2014/53/EU1 directive went into effect[15]. The RED establishes a regulatory framework for placing radio equipment on the market and stipulates for instance essential requirements for receivers, as well as transmitters and their efficient use of spectrum.

To support this Directive, ETSI has developed and maintains a set of Harmonized Standards for the information and communications technology sector. These standards specify receiver parameters and provides a minimum set of conformance requirements. The use of these standards remains voluntary but conformance with RED is mandatory.

This report identifies which receiver parameters are considered critical for sharing and compatibility studies. However, it was noted that some standards do not provide enough information for these studies. The lack of sufficient and appropriate receiver performance parameters remains a significant problem and could cause delays in the use of the spectrum. If this information is not available through other means, relevant measurements carried out on equipment may be necessary. This report also provides information on the methodologies for conducting various studies including the use of receiver parameters when modeling receiver performance.

The report proposes that the ECC should develop a Recommendation that stipulates appropriate receiver performance when considering sharing and compatibility between different adjacent systems. The EU defined receiver characteristics as:

- Sensitivity
- Co-channel rejection
- Selectivity
- Blocking
- Spurious response rejection
- Intermodulation
- Dynamic Range
- Reciprocal mixing
- Desensitization Signal interference handling

3. Technical background

This section summarizes the technical background of the OBI problem, namely the receiver parameters that need to be abstracted and incorporated in an evaluation.

Efficient spectrum usage requires that characteristics and necessary performance of both the transmitter and receiver be considered. In the past, focus has been targeted to transmitters, but receivers are also critically important. In case of a receiver's inability to attenuate adjacent signals, improvement to a transmitter's unwanted emission performance will not improve or have a positive impact on overall coexistence.

Figure 3. Impact of an interfering transmitter and a victim receiver on the reception of wanted signals[16]

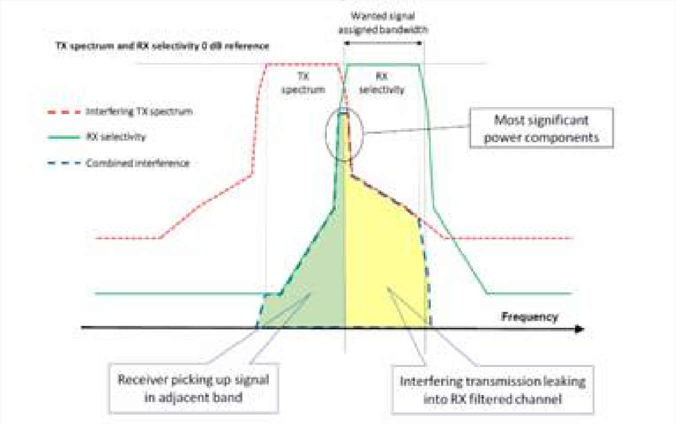


Figure 3 demonstrates that ACS (Adjacent channel selectivity) and ACLR (Adjacent channel leakage power ratio) are ratios of spectral power density integrals, and the most significant components of both will impact the reception of the wanted signal. There should be a balance between the resilience to interference of the receiver (described by ACS), and the effects of interference from the transmitter (described by ACLR) to avoid one of them being the dominant factor in a compatibility scenario.

3.1 Characterization of Receiver Parameters

The radio frequency performance of a receiver is characterized by several different receiver parameters. Each parameter describes how a receiver behaves in a particular scenario. Characterization of the receiver is important for understanding how it behaves in the presence of interference, and in sharing and coexistence scenarios. It is important that receiver parameters are controlled and quantified to minimize the risk of radio receivers being subject to harmful interference.

3.1.1 Receiver Noise Floor

A receiver noise floor can be described as the level of noise in the system prior to the introduction of any wanted signals. It can be described mathematically:

$$N(dBm) = 10\log_{10}(KTB) + NF + 30$$

where

- N = Receiver noise floor
- K = Boltzman constant in Joules per Kelvin (1.38×10^{-23})
- T = Temperature in Kelvin
- B = Receiver bandwidth in Hertz
- $10\log_{10}(KTB)$ = thermal noise in dBW
- NF = Noise figure

The noise figure (NF) is the ratio of the additional noise that is generated at different stages of the receiver to the thermal noise in the input of the receiver:

$$NF(\text{dB}) = 10\log_{10} F_n = 10\log_{10} SNR_{in} / SNR_{out}$$

where

- F_n = Noise factor
- SNR_{in} = Signal to Noise at the input of the receiver
- SNR_{out} = Signal to Noise at the output of the receiver

3.2 Receiver Sensitivity

The sensitivity of a receiver defines the minimum input signal at the nominal frequency of the receiver able to produce a minimum specified output performance. Higher sensitivity means that the receiver can detect lower-level signals. However, that can result in the receiver being highly sensitive to picking up low level signals which must be eliminated by the selectivity of the receiver.

3.3 Receiver Linearity

Linearity of a receiver defines the ability to provide an output signal that is directly proportional to the input within its defined range. Linearity is important in receiver's design but could be complicated to measure in a complete receive system. Non-linearity in a receiver's internal circuitry gives rise to performance limitations. For instance, it may affect the receiver overloading and intermodulation performance. A linearity figure is normally expressed as second and third order intercept points (IP2 and IP3) in dBm or dBc.

3.4 Dynamic Range

The dynamic range of a receiver is the range over which it can operate as intended, both low and high. The lower end is typically the receiver sensitivity, while the upper range determines how strong a received signal can be before signal quality degradation due to overload.

3.5 Protection Ratio

The protection ratio is the minimum value of the wanted-to-unwanted signal ratio (usually expressed in decibels) at the receiver input, and determined under specified conditions such that a specified reception quality of the wanted signal is achieved at the receiver output. Usually, the protection ratio (PR) is specified as a function of the frequency offset between the wanted and interfering signals over a wide frequency range. The co-channel protection ratio is where the interferer is incident within the bandwidth of the wanted signal on the same frequency. The adjacent channel protection ratio is where the interferer and the wanted signal are on adjacent frequencies.

3.6 Selectivity

Selectivity of a receiver is its ability to reject unwanted signals in adjacent frequency ranges. Several elements (e.g., filters and active circuits in the receive chain) contribute to the overall selectivity in modern digital receivers and it is not easily tested as a “stand-alone” function.

3.7 Blocking and overloading

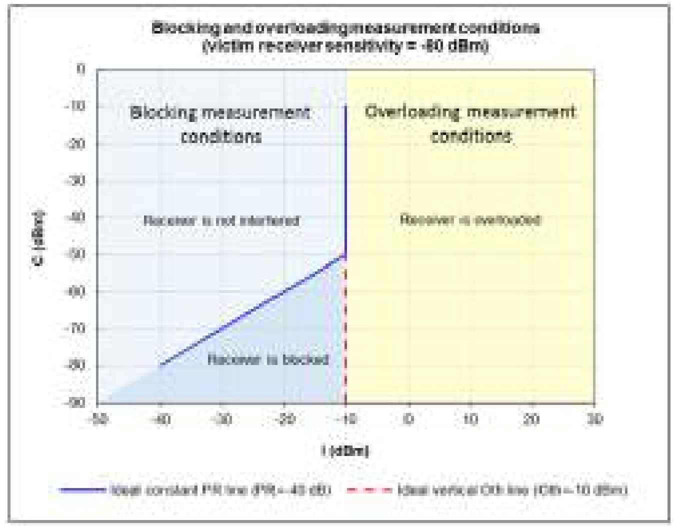
Figure 4 shows the C(I) curve of an ideal receiver with a protection ratio (PR) of -40 dB and an overloading threshold of -10 dBm.

In this example below, it can be seen that:

- if the interfering signal level is lower than -10 dBm, the receiver operates in its linear range and consequently, it is interfered (desensitized) with by the interfering signal if and only if the C/I ratio is lower than its PR;
- while, if the interfering signal level is higher than -10 dBm, the receiver front-end is fully overloaded and consequently, it is unable to receive anything at all, independent of the wanted signal level.

The blocking response of the receiver cannot be measured under “Overloading” measurement conditions. Consequently, it should not be measured at wanted signal levels more than 30 dB above the receiver sensitivity, depending on the receiver.

Figure 4. Receiver blocking and overloading measurement ranges[17]



Conversely, the overloading threshold of a receiver cannot be measured under “Blocking” measurement conditions. Consequently, the overloading threshold of the receivers should be measured at a wanted signal levels more than 30 dB above the receiver sensitivity, depending on the receiver.

For most existing mobile and broadcasting systems, the blocking response of the receivers is measured at a wanted signal level equal to the receiver sensitivity +3 dB to +16 dB depending on the system configuration. At such wanted signal levels, most of the receivers operates in their linear range and are interfered (desensitized) with by the interfering signal only and only if the C/I ratio is lower than their PR.

3.8 Spurious response rejection

Spurious response rejection is the capability of the receiver to receive a wanted modulated signal without exceeding a given degradation due to the presence of an unwanted modulated signal at any other frequency, at which a response is obtained. Spurious responses are caused by harmonics and/or mixing products of internal oscillators, which can lead to a sensitivity reduction on certain frequencies.

4. Receiver impact in coexistence

This section focuses on the receiver impact when considering coexistence between users of the spectrum, which becomes apparent in conducting coexistence studies. In particular, pessimistic assumptions about receiver performance in the presence of interference can lead to unrealistic requirements on interfering transmitters. Modeling of the traffic and the propagation environment plays a crucial role in coexistence studies, and we argue for model transparency and reproducibility. We also highlight the need to select the key receiver characteristics relevant for different services.

The main objective in conducting coexistence studies is typically to introduce new services either adjacent-channel or co-channel relative to one or more incumbent services. The coexistence study will determine the level of interference protection that would be granted to the incumbent service.

4.1 Coexistence study considerations

Co-existence studies should consider many elements and components. The determination of an interference protection limit to the incumbent relies on modeling using realistic system specifications and equipment operation, so knowledge of the characteristics of both transmitters and receivers is necessary. Transmitter emission masks are typically defined in Federal Regulations and Industry Standards, whereas Spectrum masks for receivers are not.

As noted in ECC Report 310, "Characterization of the receiver is important for understanding how it behaves in the presence of interference and in sharing and compatibility scenarios. It is important that receiver parameters are quantified to [sic] minimize the risk of radio receivers being subject to harmful interference". "This includes detailed information about the operations of such services, a prediction of the level at which interference will become harmful to each service, and quantitative modeling about the interactions between services over a wide variety of expected conditions"[18].

Also noted in the same ECC Report 310, "a receiver should have characteristics that allow it to operate as intended and to protect it against the risk of harmful interference, in particular from shared or adjacent channels". It is expected that receivers should have the capability to reject interfering signals at a prescribed interference level transmitted outside the receiver's assigned frequencies.

In some cases, a pessimistic assumption on the receiver performance disproportionally attributes more restrictions on the transmitter, even if they are not realistic.

To conduct a proper study, disclosure of the relevant standards, guidelines, and operating characteristics is needed. Information on typical performance may be available from technical standards and documentation from equipment suppliers. This information, if considered proprietary, may need to be anonymized. The information is not always accessible; therefore, the characteristics of the equipment and its performance may require field and bench measurements. In some cases, the FCC regulations will dictate the performance requirements for transmitters. ITU-R Recommendations and information held by the regulator, especially NTIA when considering federal systems, can also be a source for the desired information.

To conduct coexistence studies when the actual receiver performance characteristics are not provided, a protection value is normally provided via receiver desensitization, which is specified as interference-to-thermal-noise (I/N) with a value such that an increase of 1 dB in the interference (I) will desensitize the receiver. Specifically, I is the interference level in dBm and N is the thermal noise floor of the receiver in dBm. The α is the protection ratio in dB. The equation is $I\text{-}N \geq \alpha$.

The reason for using I/N is that this eliminates the need to provide many system parameters – but if the receiver is inherently a poorly performing one, then the absolute I/N value is made so small that measuring it in practice is next to impossible–even with a power meter. For example, an I/N = -12.5 dB has been used by the satellite community, which amounts to measuring about 0.25 dB. Measurements of equipment can be used to give a more realistic understanding of the impact of the interferer based on the signal strength and type of the interferer. This is particularly true for interference cases not directly covered in the technical documentation[19]. Measurements may not always provide complete answers but can provide data points that can be used in the analysis and simulations for the purpose of validation or prediction.

When considering coexistence, there are specific receiver performance parameters that are more critical to consider when allowing introduction of new services in the adjacent or neighboring bands without causing unacceptable interference. For instance, if we consider earth exploration satellite service as an incumbent in the adjacent band and the service is passive, the satellite receiver is designed to listen to, or monitor and gather environmental information like temperature, humidity, pollution, and precipitation rate. The remote sensing techniques require a sensitive receiver. Gathered information is then transmitted to earth stations for processing. The higher the sensitivity means that the satellite and receiver receivers can detect lower-level signals. However, that can result in the receiver also being highly sensitive in terms of picking up adjacent signal that must be suppressed by the selectivity of the receiver.

Another example is GPS, which is used for general location and navigation, general non-certified aviation, and high-precision devices used globally. When looking at coexistence with GPS from an adjacent channel perspective, steps were taken by the FCC to identify technical and operational measures to reduce the risk of overload interference to GPS devices. In evaluating harmful interference issues concerning the compatibility of adjacent band operations, understanding receiver design and filter selectivity is important, particularly with regard to receiver overload interference. That is, a receiver may include a front-end filter that receives signals (whether GPS or some other signals) that fall well outside of the radionavigation-satellite service (RNSS) allocation[20].

4.1.1 Understanding various service categories

Each service category presents different use cases with different dependencies on the RF environment. Receiver performance is unique to a specific type of service and operations and relates to both the in-band and out-of-band environments. Each service category presents different use cases with different dependencies on the RF environment.

- Per the FCC, “When the transmitter details are compared to a receiver system at a “victim” location, it is possible to estimate whether the transmitter is operating within its license limits and what might be done to ameliorate harmful interference”[21].
- Per the FCC, “A spectrum user that refuses to provide such information cannot expect the Commission to provide as much protection from interference as it could with all of the details”[22].
- It is important to design systems to operate effectively as if other systems occupied the adjacent channels.
- FCC regulations for many transmitters require that out-of-band emissions (OOBE) not be greater than -13 dBm.
- Per the FCC, “Deploying a receiver without proper filtering or dynamic range because no neighboring systems are located nearby at the time of installation would be considered poor engineering practice, and future interference can be expected”[23].
- Receivers have a technology life expectancy; it is not realistic to expect receiver design to be relevant for many decades. It is very important that technology refreshes are made to take advantage of new innovations and to coexist in an ever-evolving spectrum environment.

4.1.2 Modeling issues and opportunities

Quantitative studies of the interactions between radio services to set interference limits (or to conduct inter-service coexistence or compatibility analyses more generally) require the development and assessment of often highly complex models. These models, or combinations of models, are based upon empirical, computational, and statistical techniques.

For example, a model for predicting the strength of interfering signals at the antenna input of a receiver might involve models or assumptions for the transmission line losses at the transmitter, models for predicting the gain of the transmitting antenna based upon its physical and electric characteristics, and propagation models for estimating the signal attenuation between the transmitting antenna and the receiving antenna. The propagation model, in turn, may utilize inputs specifying the characteristics of the intervening terrain and/or clutter. Models that have been standardized by 3GPP or ITU should be used whenever possible.

Additional aspects to consider are system loading, and reflecting a proper ratio between uplink and downlink traffic when modeling TDD. Both average and peak traffic models should be modeled. System characteristics include down-tilt and adaptive antennas. The model should consider the parameters of frequency, space and time that can be manipulated to decrease interference and whether the system is indoors and therefore increased losses or whether the system is outdoors using higher power[24].

Characterization of the receiver is important for understanding how it behaves in the presence of interference and in sharing and compatibility scenarios. Pessimistic assumptions about receiver performance in the presence of interference can lead to unrealistic requirements on interfering transmitter. When considering coexistence, there are specific receiver performance parameters that are more critical to consider when allowing introduction of new services in the adjacent or neighboring bands without causing unacceptable interference. Each service category presents different use cases with different dependencies on the RF environment. Therefore, it will be necessary to decide which receiver parameters should be defined to support the coexistence study.

To build confidence and ensure that the right conclusions are reached, models and assumptions should be understandable, transparent and reproducible.

5. Industry and policy considerations

The FCC released its Notice of Inquiry to in part seek to update the record with the intention of possible improvement in spectrum efficiency by considering the role that receiver performance plays. Traditionally, the FCC regulations for operation of wireless systems has been on transmitters.

The Commission seeks comment on various approaches to consider as it moves forward in determining if and how to incorporate receiver interference immunity performance into spectrum policy.

It is clear that a single policy will not address the variety of possible scenarios including adjacent dissimilar systems, public safety, consumer products, etc. In addition, poor receiver performance is not a problem across all spectrum bands. Therefore, one size fits all approach is not pragmatic. In certain industries, operators have incentives to continually deploy new equipment with impoved receivers[25]. The receiver performance parameters can be easily measured and enforced and also provide a reasonable characterization of receiver performance and potential related enforcement, such as noise floor. One such specification is receiver selectivity. Selectivity is the ability of the receiver to reject interference from adjacent bands, and can be estimated based on other receiver parameters like Adjacent Channel Interference Ratio (ACIR), Adjacent Channel Leakage Power Ratio (ACLR) and blocking. 5G NR core requirements are specified in TS 38.104.[26]. The test procedures are specified in TS 38.141-1 for the conducted requirements and in 38.141-2 for the over the air (OTA) requirements.

$$\mathrm{ACIR} = \frac{1}{\frac{1}{\mathrm{ACLR}} + \frac{1}{\mathrm{ACS}}}$$

ACIR, ACLR, and Adjacent Channel Selectivity (ACS) measured values.

3GPP's work in this area has helped to improve interference immunity in the commercial wireless sector in an efficient and effective way. And as part of these efforts, 3GPP and its contributors have been careful not to constrain innovation. While receiver specifications help improve overall interference immunity performance, 3GPP specifications afford commercial wireless stakeholders the continued flexibility to design their own receiver solutions.

5.1 Interference Limits Policy

In 2013, the TAC issued a White Paper on Interference Limits Policy[27]. The paper explored the concept of "Interference Limits" policy on in-band and out-of-band interference. According to the whitepaper, the benefit of such an approach is that interference limits related policy would consider the wireless system from both a receiver and transmitter perspective. From an implementation perspective, receivers would have the capability to reject interfering signals at a prescribed interference level transmitted outside the receiver's assigned frequencies before a harmful interference could be claimed. The flexibility in this harm threshold approach is stated in the TAC whitepaper that such a policy does not dictate how the rejection would be accomplished; manufacturers would have the flexibility to design receivers and deploy systems cognizant of the threshold.

Although the harm threshold should be studied further, there are many challenges and implications to transmitters that would be adverse and have consequences to the cellular industry. There is a danger that the harm claim threshold is not implemented as a receiver requirement, but in reality, as a transmitter requirement. As an example, 5G Americas released a white paper on coexistence with radio altimeters. The United States and many other countries are deploying mid-band spectrum in the 3300-4200 MHz range. Yet the aviation industry in the United States has raised concerns regarding the effect of 5G deployed in the 3700-3980 MHz range on radio altimeter use in aircrafts and helicopters in the 4200-4400 MHz range, which is 220 MHz away in frequency. The TAC whitepaper proposed that the "limits [harm threshold] can be chosen to reflect incumbent needs", or the "FCC would encourage a multi-stakeholder consultation process to work out boundary issues." [NOI 3] As described in the 5G Americas whitepaper, multi-stakeholder processes to work on coexistences boundary issues do not necessarily produce public interest results. For instance, the 5G Americas whitepaper identified significant shortcomings in the aviation produced studies, but these studies have been promulgated with objections from the 5G community. A number of factors in the studies resulted in artificial situations which did not resemble real-world landing scenarios and coexistence conditions for 5G and radio altimeters. These concerns have been raised by the commercial industry. However, the coexistence results are based on the testing of nine altimeters by aviation that produced an Interference Tolerance Mask for each of the three usage categories, representing the worst-case data point from all altimeters and test conditions. Moreover, the underlying test data was not disclosed in the study, the identity of the radar units tested are unknown, and the age and commercial status of the altimeters has not been provided.

If an interference limits policy had been in place, it would be the responsibility of the 5G transmitter to meet the lowest performing receivers from the worse performing category, irrespective of 5G industry input into the multi-stakeholder group. In other words, receiver protection rights would have been explicitly conditioned on their ability to cope with interference. There is no incentive to improve these receivers. The harm threshold policy ultimately and in some cases disproportionally attributes more restrictions on the transmitter that has the responsibility to ensure that the prescribed threshold are being met, even if they are not realistic.

Another basic challenge is how to set HCTs. This is not a simple task, and would require an environmental sensing study for each and every band. Even if HCTs were created, the burden of proving a HCT was violated is on the victim. To collect and prove such a violation puts a burden on the victim in terms of equipment and analysis. This is estimated to be more than many small wireless operators can afford economically. Last HCTs may actually discourage innovation by allowing vendors to focus on the lowest performing levels as stated above.

It becomes even more challenging when considering enforcement where harm threshold is calculated based on a probabilistic function that considers both in-band and out-of-band interference across a designated geographical region and the percentage of instances where harm threshold is exceeded. Specifically, enforcement of the prescribed threshold, as proposed in the TAC whitepaper, is calculated by distributing N measurement points evenly over a verification area, and counting the percentage of measurements when signal strength exceeds E. This proposed measurement procedure raises concerns for deployment of commercial cellular system. First, it is not clear how the statistical measurement would take place assuming an NR AAS system. The use of beamforming, which was not contemplated in the TAC 2013 report, creates some uncertainty in the proposal where the distribution of the measurement points, with its higher power in the macro case, may not conform readily to a uniform distribution across the verification area.

Measurements in the field are notoriously difficult and unwanted emission requirements for massive MIMO base station are expressed as total radiated power. Strict interference limits based on some existing receiver performance in some bands would restrict the massive MIMO radiated power. The codification of statistical metrics within regulations could also create regulations based on uncertain knowledge and may affect certification of equipment under onerous terms. If the interference is intermittent it makes it even harder to prove a violation of the HCT.

It is imperative that any band-specific consideration of a harm claim threshold involve stakeholders representing all interests, including both in-band operators and users or prospective users in neighboring bands whose transmitters will be affected. Implementing a spectrum efficiency policy with harm threshold elements is not without its challenges. The process to set an acceptable interference limit is expected to be a contested one, but necessary on a case-by-case basis. A harm claim threshold process should foremost drive improvements in receiver performance, and a process involving in-band incumbents only risks codifying the status quo and imposing restrictive de facto limits on transmitters in neighboring frequency bands instead. Above all else, harm threshold policies could be considered for target services and allocations in which operators lack market incentives for spectrally efficient receiver operations.

In some cases there may be simpler approaches to characterizing the responsibilities of incumbent receivers, improving receiver immunity performance, and advancing effective spectrum management. For instance, cross-industry discussions may help incumbents keep abreast of state-of-the-art developments in spectrum-based services and the ways in which receiver performance should evolve to accommodate these advancements. Such cross-industry information sharing would provide opportunities for stakeholders to identify and troubleshoot risks to new and innovative spectrum technologies and advance the public interest.

Recommendations:

The following recommendations represent guidance to administrations to aid in formulating policy:

I. General policy

A. The regulator should consider both transmitter and receiver performance as part of its spectrum management policy.
B. When allocating spectrum for new services, the regulator should closely examine potential bands by including consideration for receiver performance in the band and adjacent bands.
C. Any band-specific consideration for new services should include all stakeholders representing all interests, including the regulator (s) and both in-band operators and users or prospective users in neighboring bands whose transmitters will be affected.
D. The regulator should consider different approaches to improving receiver performance based on the particular circumstance of a given band or service. No “one-size-fits-all” solution is possible as each approach must consider aspects like propagation characteristics and services and devices requirements. 5G Americas encourages the regulator to refrain from imposing heavy-handed, inflexible receiver performance mandates that would increase costs and inhibit innovation.
E. The regulator should refrain from mandating receiver performance standards in bands where competitive market forces (for example, bands where 3GPP technologies are deployed) are continually motivating equipment makers to support more uses and services.

II. Execution

A. The regulator should rely upon established industry voluntary standards, particularly where market forces already incentivize the efficient use of spectrum.

B. The regulator should use standardized coexistence models used by 3GPP, ITU, etc. whenever possible. Modeling should use realistic system specifications and equipment operation whenever possible. It is recognized that transparency of all the key elements of an analysis, including assumptions, model structure (e.g. formulas), data sets, is necessary to avoid conflicting interference results.

III. Upgrade path

A. As demands for spectrum increase, the regulator should develop policies to address a path for legacy receivers to be upgraded so that they can promote coexistence and are not susceptible to transmitters operating in their prescribed manner.

B. The regulator should issue a policy statement (or similar) on receiver performance to establish clear and transparent expectations for stakeholders and lay the foundation for future actions to promote sound spectrum management.

C. The regulator should develop a long-range spectrum plan, which would benefit the industry greatly from both a clarity and design needs perspective. It would enable a predictable timeline of equipment upgrades.

Conclusion

This white paper provided a timely technical analysis of receiver performance and allows 5G Americas to make positive contributors to the solution, in light of the FCC NOI of April 2022. As new spectrum bands are coming into use, legacy receivers that were designed for the original benign out of band interference conditions may not be adequate under the new tougher conditions. This paper provided an overview of the NOI and previous work of relevance from the FCC and CEPT; summarized the technical background of the OBI problem, in particular the receiver parameters that need to be abstracted and incorporated in an evaluation; discussed coexistence studies to determine the level of interference protection that would be granted to the incumbent service; and discussed industry and policy considerations regarding the role of receiver performance. Finally, it provided recommendations as guidance to administrations to aid in formulating policy, in particular the idea that receiver performance should evolve over time, as spectrum becomes increasingly crowded. This would entail the expectation of upgrading or replacing equipment over time. Additionally, a long range spectrum plan would benefit the industry greatly from both a clarity and design needs perspective. It would enable a predictable timeline of equipment upgrades. We caution that situations need to be taken case by case, and policies crafted accordingly with the lightest touch possible.

Appendix

Acronyms

ACIR: Adjacent Channel Interference Ratio

ACLR: Adjacent channel leakage power ratio

ACS: Adjacent channel selectivity

CEPT: European Conference of Postal and Telecommunications Administrations

DTV: Digital television

ECC: Electronic Communications Committee

FCC: Federal Communications Commission

GAO: Government Accountability Office

HCT: Harm claim threshold

MIMO: Multiple-Input Multiple-Output

NF: Noise figure

NOI: Notice of Inquiry

NTIA: National Telecommunications and Information Administration

OBI: Out of band interference

OOBE: Out of band emissions

OTA: Over the air

PCAST: President's Council of Advisors on Science and Technology

PR: Protection ratio

RED: Radio Equipment Directive

RF: Radio Frequency

RNSS: Radionavigation-satellite service

SNR: Signal to noise ratio

TAC: Technological Advisory Council

TDD: Time Division Duplex

Acknowledgments

5G Americas’ Mission Statement: 5G Americas facilitates and advocates for the advancement and transformation of LTE, 5G and beyond throughout the Americas.

5G Americas’ Board of Governors members include Airspan Networks, Antel, AT&T, Ciena, Cisco, Crown Castle, Ericsson, Intel, Liberty Latin America, Mavenir, Nokia, Qualcomm Incorporated, Samsung, Shaw Communications Inc., T-Mobile USA, Inc., Telefónica, VMware and WOM.

5G Americas would like to recognize the significant project leadership and important contributions of group leader Ali Khayrallah, Senior Scientist, Ericsson, along with many representatives from member companies on 5G Americas’ Board of Governors who participated in the development of this white paper.

Endnotes

1 https://www.ericsson.com/49d3a0/assets/local/reports-papers/mobility-report/documents/2022/ericsson-mobility-report-june-2022.pdf

2 See Notice of Inquiry in ET Dkt. No. 22-137; Promoting Efficient Use of Spectrum through Improved Receiver Interference Immunity Performance. (April 21, 2022) https://docs.fcc.gov/public/attachments/FCC-22-29A1.pdf

3 TAC Sharing Work Group, "Spectrum Efficiency Metrics White Paper," Group (White Paper on Spectrum Efficiency Metrics), found at https://transition.fcc.gov/bureaus/oet/tac/tacdocs/SpectrumEfficiencyMetricsV1-12-20-11.docx.

4 TAC Receivers and Spectrum Working Group, "Interference Limits Policy – The use of harm claim thresholds to improve the interference tolerance of wireless systems," (Feb. 6, 2013) (White Paper on Interference Limits Policy), found at https://transition.fcc.gov/bureaus/oet/tac/tacdocs/WhitePaperTACInterferenceLimitsv1.0.pdf.

5 TAC Spectrum / Receiver Performance Working Group, "Interference Limits Policy and Harm Claim Thresholds: An Introduction" (Mar. 5, 2014) (White Paper on Harm Claim Thresholds), found at https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting61014/InterferenceResolution-Enforcement-Radio-Noise-White-Paper.pdf .

6 TAC Receivers and Spectrum Working Group, "Introduction to Interference Resolution, Enforcement and Radio Noise" (June 10, 2014), found at https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting61014/InterferenceResolution-Enforcement-Radio-Noise-White-Paper.pdf

7 TAC Spectrum and Receiver Performance Working Group, "A Quick Introduction to Risk-Informed Interference Assessment" (Apr. 1, 2015) (White Paper on Risk-informed Interference Assessment), found at https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting4115/Intro-to-RIA-v100.pdf . The TAC emphasized that its proposed approach is risk-informed and not risk-based.

8 TAC Spectrum and Receiver Performance Working Group, "Basic Principles for Assessing Compatibility of New Spectrum Allocations" (Dec. 15, 2015) (White Paper on Basic Principles for Assessing Compatibility of New Spectrum Allocations), found at https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting121015/Principles-White-Paper-Release-1.1.pdf

9 See TAC Spectrum and Receiver Performance Working Group, "A Quick Introduction to Risk-Informed Interference Assessment." (April 1, 2015), found at https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting4115/Intro-to-RIA-v100.pdf.

10 PCAST Report to the President, "Realizing the Full Potential of Government-held Spectrum to Spur Economic Growth" (PCAST Report), at 33, found at https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf; see id. at 33-38; 107-21 ("Appendix D: Better Sharing Through Receiver Regulation").

11 GAO Report 13-265, "Spectrum Management – Further Consideration of Options to Improve Receiver Performance" (Feb. 2013) (GAO Report on Receiver Performance), found at https://www.gao.gov/products/gao-13-265 , at 34-37. GAO is an independent, non-partisan agency that works for Congress, among other things assisting Congress with reports and recommendations to help improve performance and accountability of the Federal government. https://www.gao.gov/about.

12 See "Memorandum on Expanding America's Leadership in Wireless Innovation" (June 14, 2013) (Memorandum on Wireless Innovation), Section 4, found at https://www.govinfo.gov/content/pkg/DCPD-201300421/pdf/DCPD-201300421.pdf. This memorandum was revoked in 2018. See "Presidential Memorandum on Developing a Sustainable Spectrum Strategy for America's Future" (Oct. 25, 2018), Section 6(e), found at https://trumpwhitehouse.archives.gov/presidential-actions/presidential-memorandum-developing-sustainable-spectrum-strategy-americas-future/.

13 See ECC Report 310. Evaluation of receiver parameters and the future role of receiver characteristics in spectrum management, including in sharing and compatibility studies ECC Report 310 (cept.org)

14 See Ofcom UK commissioned a study concerning interference of LTE operating in 2.3 GHz on license-exempt services (e. g. Zigbee). As shown in this report, receiver designs played an important role in the efficient use of spectrum. https://www.ofcom.org.uk/__data/assets/pdf_file/0020/55181/harmful_interference.pdf

15 Directive 2014/53/EU of the European Parliament and of the Council of 16 April 2014 on the harmonization of the laws of the Member States relating to the making available on the market of radio equipment and repealing Directive 1999/5/EC.

16 ECC Report 310 https://docdb.cept.org/document/category/ECC_Reports?status=ACTIVE

17 ECC Report 310 https://docdb.cept.org/document/category/ECC_Reports?status=ACTIVE

18 ECC Report 310 https://docdb.cept.org/document/category/ECC_Reports?status=ACTIVE

19 See https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting121015/Principles-White-Paper-Release-1.1.pdf

20 See https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting121015/Principles-White-Paper-Release-1.1.pdf

21 See https://docs.fcc.gov/public/attachments/FCC-20-48A1.pdf

22 See https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting121015/Principles-White-Paper-Release-1.1.pdf

23 See https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting121015/Principles-White-Paper-Release-1.1.pdf

24 See https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting121015/Principles-White-Paper-Release-1.1.pdf

25 See, e.g., Third Generation Partnership Project, “3GPP TS 38.104 (2022-03),” 98-102 (referencing receiver sensitivity specifications for 5G NR base stations).

26 See 3GPP Base Station (BS) radio transmission and reception. https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3202

27 See https://transition.fcc.gov/bureaus/oet/tac/tacdocs/WhitePaperTACInterferenceLimitsv1.0.pdf