MITRE

Receiver Interference Immunity: Issues and Recommendations

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Executive Summary

Overview

The National Telecommunications and Information Administration (NTIA) commissioned The MITRE Corporation (MITRE) to study radio-frequency (RF) receiver interference immunity performance ("receiver performance") and prepare this report. Based on extensive research, internal expertise, and consultations with subject matter experts from government and industry, the report makes the following findings and recommendations:

Key Findings

The complexity and diversity of the environments in which receivers operate preclude universal receiver rules and regulations as a practical technique for spectrum management.

Every band, radio service, and application has unique features that warrant special consideration. Additionally, there are limits to a receiver's ability to reject interference, even in the case of well-designed receivers and when the interference energy is confined to frequencies outside of the allocated band for the desired radio service. This is often the case for federal systems. Relying on receiver performance alone to ensure coexistence between adjacent-band radio services is most difficult when:

- High sensitivity receivers are required to process desired signals that are very low in power (e.g., within radars, satellite navigation, radio astronomy, passive sensors).
- Adjacent-band transmitters are high-powered or can be very close to the receiver.
- Desired and adjacent-band interfering signals are near the common edge of the allocated band.
- The existing systems are difficult (e.g., expensive or inaccessible) to replace or modify and there is no obvious near-term benefit.

In many of these cases, other interference-mitigation approaches (e.g., transmitter limits, guard bands, and system approaches) may need to be considered to improve the effectiveness of the spectrum utilization.

Despite these limitations, there are a number of broad steps that NTIA can take to improve the receiver performance of federal systems.

These broad steps are the focus of the recommendations below.

Recommendations

Recommendation #1: *Implement specific mitigations on a case-by-case basis, prioritizing bands being studied for repurposing.* Consider implementation of receiver interference-mitigations, possibly including receiver performance requirements, on a case-by-case basis as bands (or adjacent bands) are studied for repurposing. This approach allows for recognition of the unique characteristics of many federal systems or operations, and the need to consider the full range of options to optimize receiver protection.

In bands being studied for repurposing, NTIA should issue guidance for agencies to consider incorporating receiver performance improvement costs into their spectrum pipeline and transition plans for Spectrum Relocation Fund (SRF) consideration as applicable. To the extent it is necessary to assess the interference immunity performance of fielded equipment, the report identifies a set of best practices in Section 4.3 including developing inventories of fielded makes/models of receivers and testing all or at least a representative subset against relevant types of interference.

Recommendation #2: *Develop a policy statement and roadmap for improving receiver performance.*

- *NTIA should issue a policy statement.* A formal NTIA statement, like the one issued by the FCC in April 2023, would pave the way for additional receiver performance improvement measures. These could include incentives to motivate the implementation of receiver performance improvement measures and mechanisms to reimburse stakeholders for costs incurred to improve receiver performance.
- *Address data collection and transparency.* Section 10.8.7 of the NTIA Manual specifies receiver characteristics that are required from Federal agencies seeking NTIA Certification of Spectrum Support for radio systems. This set of characteristics, which includes filter characteristics of various receiver front-end stages, is useful but incomplete for coexistence studies considering all of the mechanisms by which interference can degrade receiver performance (see Section 2.2 and Appendix A of this report). NTIA should consider changes to Section 10.8.7 of the NTIA Manual to collect alternative, more relevant receiver characteristics such as blocking interference levels as a function of frequency at the receiver input.

  Additionally, NTIA should collaborate with the FCC to issue guidance and best practices addressing data transparency, specifically approaches to increase transparency into physical layer data on RF performance and interference while still protecting sensitive information in the data fields or RF signature, to enable more advanced data analytics supporting efficient and effective spectrum use.
- *Perform a companion study to develop best practices for transmitter performance.* NTIA might consider a study on transmitter performance, focusing on its ability to control unwanted emissions outside of an allocated or assigned band, as a follow-on to this study on receiver performance.
- *Recommend best practices for receivers*. NTIA should recommend best practices, such as those outlined in *Best Practices for Designing Interference-Resilient RF Receiving Systems*[1], to educate and encourage federal agencies to procure receivers that are more robust and conform with applicable rules. The recommended best practices could also be used as a basis for vendors to demonstrate their level of adherence to design practices based on common guidance.

MITRE recognizes that NTIA must prioritize and/or procure more resources to implement recommendations to improve the receiver interference immunity performance of federal systems.

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[1] At the time of the writing of this report, MITRE is concurrently developing the aforementioned, for release by NTIA in 2025. We summarize the best practices detailed in that report in Appendix A.5.

Report Overview

Section 1: Introduction

Rapidly growing demand for spectrum and high-profile issues with spectrum repurposing have brought increased attention to the role of receivers within spectrum management. NTIA tasked MITRE to perform a study to inform its deliberations on whether its policies, regulations, and procedures adequately address receivers.

A rapidly growing number of radio services rely on the electromagnetic spectrum, making it an increasingly congested and practically finite national resource. Prudent and effective management of spectrum is paramount to meeting this ever-increasing demand. Federal spectrum management techniques have traditionally focused on regulating the emission characteristics of transmitters and placed less emphasis on regulating receivers.

Recently, the role of receivers in spectrum management has received increased attention due to high-profile developments, such as:

- Ligado/GPS: Ligado Networks received authorization from the Federal Communications Commission (FCC) in April 2020 to deploy a low-power terrestrial nationwide network in bands adjacent to the Global Positioning System (GPS). In September 2022, Ligado notified the FCC that it was not intending to move forward with a trial deployment of its network in order to allow additional time for discussions with NTIA to resolve concerns of interference to GPS and other systems.
- C-Band/Radio Altimeters: The auction of 5G spectrum from 3.7 to 3.98 gigahertz (GHz), near the radio altimeter band in 4.2 to 4.4 GHz, raised concerns of interference from 5G to airborne radio altimeters that are critical to many flight operations.

The developments mentioned above were highlighted in an April 2022 FCC Notice of Inquiry seeking to update the public record on the role of receivers in spectrum management and inform possible steps for how the FCC might best promote improvements in receiver performance. One year later, in April 2023, the FCC issued a policy statement addressing these topics. NTIA is currently considering whether its policies, regulations, and procedures adequately address receivers. The National Spectrum Strategy, released by the White House in November 2023, contains a goal of developing a roadmap for improving receiver immunity to harmful interference. In July 2024, the Government Accountability Office (GAO) issued a report on improving receiver performance which included a recommendation for the NTIA to identify and assess its current data sources related to federal receiver performance. To inform NTIA deliberations on these topics, MITRE was tasked to perform a study, culminating in this report, that addresses the following specific topics:

1. Existing government and non-government receiver performance requirements or specifications.
2. Information on receiver performance characteristics that manufacturers test for or collect, as well as best practices for testing including when there are a large number of legacy device models.
3. Implications of limiting receiver protection to only that spectrum allocated to the desired radio service.
4. Policy options and recommendations for improving receiver performance.

5. Information on what other countries or international organizations are doing to improve receiver performance.

The report is organized according to the mechanisms by which interference can degrade receiver performance, the established methods to specify and assess a receiver's performance, and technical and non-technical mechanisms that could mitigate receiver performance degradation. Summaries of the content provided in the report related to each of these areas are included below.

<u>Section 2: Receiver Performance Issues</u>

There are many mechanisms by which receiver performance can degrade due to interference. Achievable receiver interference performance is limited by size, weight, power, and cost (SWAP-C) constraints that vary widely across systems. Receiver interference performance issues have hindered spectrum repurposing activities; many organizations have studied these issues and offered recommendations to spectrum regulators.

Section 2 and Appendix A of the report provide a foundational technical understanding of receivers and the mechanisms by which interference may degrade their performance. This material includes a review of common receiver architectures (2.2, A.1), identification of the typical mechanisms that cause receivers to experience performance issues due to interference (2.2, A.3), as well as a discussion of recent examples of issues caused by receivers experiencing interference (2.3). Notable prior studies on receiver performance are also discussed (2.4).

<u>Section 3: Receiver Standards and Performance Requirements</u>

and

<u>Section 4: Testing and Certification</u>

Prior studies on receiver performance issues have recommended the increased use of standards as a mitigation method. There are many existing receiver standards, including those invoked in regulations and voluntary industry documents. There are common parameters amongst these standards, which should be considered for any new standards. Testing is used for demonstrating compliance to standards and can also be used, in the absence of standards, to determine the interference immunity performance of fielded equipment.

Sections 3 and 4 of the report examine receiver standards, performance requirements, and the processes and best practices by which receivers can be evaluated for their performance. The material in these sections collectively outline measures by which RF devices can be certified to meet established performance standards, thereby minimizing the risk of harmful interference in the electromagnetic spectrum. Included in this material is an identification of the ten key parameters referenced in existing standards to determine receiver interference immunity (3.1), a discussion of the existing standards in federal (3.3), international (3.4), and private industry (3.5) sectors, and an identification and discussion of the various processes used to assess receivers for conformance both against a referenced standard (4.2) and in lieu of one (4.3).

<u>Section 5: Technical Mitigations</u>

and

<u>Section 6: Non-technical Mitigations</u>

There are many potential technical and non-technical mechanisms to improve receiver performance, each with their own pros and cons. Prescriptive, regulatory approaches can ensure that receivers are built with a known degree of immunity to interference but can be costly and take a long time to implement. Less prescriptive approaches such as policy statements, "Best Practices" guides, and incentives can also be effective. A case-by-case, band-specific approach is recommended.

Section 5, Section 6, and Appendix A.4 to A.6 outline technical and non-technical strategies to enhance the resilience of receivers to interference. This material includes an examination of emerging technologies (A.6) and best practices (5.2, A.5) to improve receiver performance against interference degradation, as well as an identification of additional standards and performance requirements (5.3) that could improve receiver performance. Additionally, the material discusses several policy (6.4) and economic-based incentives (6.3) that may be leveraged to promote improved receiver performance.

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1 Introduction

1.1 Overview

The purpose of this report is to provide the National Telecommunications and Information Administration (NTIA) with technical findings and recommendations to inform its future policies regarding receiver interference immunity performance (henceforth "receiver performance").

To achieve this objective, MITRE conducted research into the technical and non-technical considerations inherent to developing receiver performance policies. The contents of this report reflect the multiple aspects of receiver performance that MITRE researched and evaluated in its study. The key research objectives, areas studied, and the associated research outcomes are summarized below.

Receiver Performance Degradation Causes and Examples

Objective: To provide a foundational technical understanding of receivers and their performance issues, including pertinent real-world examples. In pursuit of this objective, MITRE developed the following results:

- A review of common receiver architectures and an identification of the typical mechanisms that cause receivers to experience performance issues due to interference,
- A discussion of recent, notable examples of issues caused by receivers experiencing interference and the associated opportunity costs.

Specification and Assessment of Receiver Performance

Objective: To provide awareness of the established characteristics used to specify receiver performance in existing standard and regulations, as well as the methodologies suitable for evaluating whether a receiver conforms to given performance specification. Aligned with this objective, the results for this work include:

- An identification of key documents relevant to domestic receiver performance requirements and specifications, including existing Federal Communications Commission (FCC) and NTIA rules within Title 47 of the Code of Federal Regulations (47 CFR)[2], as well as a broad set of additional government and non-government receiver performance requirements, specifications, and recommendations.
- An identification and assessment of key international documents and regulatory initiatives related to receiver performance, including those from the European Union Radio Equipment Directive, the European Conference of Postal and Telecommunications Administrations (CEPT), the Electronic Communications Committee (ECC) of the CEPT, the International Telecommunication Union (ITU), and the International Electrotechnical Commission (IEC).

[2] Chapter 1 (Sections 0 – 199) of 47 CFR contain the FCC's rules. 47 CFR 300.1 incorporates by reference NTIA's Manual of Regulations and Procedures for Federal Radio Frequency Management.

- A review of the conformance testing processes currently used to evaluate receiver performance, including the parameters tested for or collected, the test procedures followed, and the purposes for which such tests are done.
- A discussion of the challenges, lessons learned, and best practices for testing key receiver performance parameters, including such cases where a large number of different model legacy devices must be considered.

Mechanisms to Improve Receiver Performance

Objective: To provide insights into technical and non-technical mechanisms that may be employed to mitigate receiver performance degradation. The results for this research include:

- A review and discussion of the opportunities and technological trends that may be useful in improving receiver performance, as well as recommendations for mechanisms to address receiver technical performance issues.
- A discussion of policy and economic-based incentives that may be leveraged to promote improved receiver performance, as well as recommendations for non-technical mechanisms to address receiver technical performance issues.

1.2 Background

Electromagnetic spectrum is a critical national resource that is required for the operation of wireless systems. All wireless and radio services depend on effective and efficient spectrum access. Spectrum must be managed to minimize interference and ensure its efficient and effective use. It is widely recognized that the demand for spectrum is growing, but its supply is practically limited. CTIA (formerly the Cellular Telecommunications and Internet Association) forecast in 2023 that data traffic on macro cellular networks would increase by over 250 percent in the next five years and over 500 percent in the next 10 years [1] [2].

The value of spectrum has increased alongside its demand. For example, the C-band auction in 2021 was the highest-grossing spectrum auction ever, resulting in auction revenue exceeding $80 billion [3]. Effective use of spectrum has become increasingly “important as industry and government continue to increase their demand for bandwidth to enable new and improved wireless communications services” [4]; additionally, radio services such precision navigation and timing services are also in increasingly high demand. Technological advancements coupled with innovation in economic and policy mechanisms can help meet this growing demand [5].

Improving receiver interference performance has been proposed as a mechanism for increasing the efficient and effective use of spectrum to help meet demand. Experts have long debated different approaches, but a clear path forward has not emerged [6] [7]. In 2022, the FCC sought public commentary on the role of receiver performance requirements in promoting more efficient usage of spectrum. This was followed by the White House’s release of its National Spectrum Strategy in November 2023, and the related Implementation Plan issued by NTIA in March 2024, which included a call for NTIA and the FCC, with input from federal agencies and the Commerce Spectrum Management Advisory Committee (CSMAC), to develop collaboratively a “roadmap” for improving receiver performance. Receivers form a foundational part of any radio service, performing the integral task of selectively filtering and processing radio-frequency energy so that desired signals may be isolated from interfering signals. As a receiver’s “performance” improves, so does its ability to more precisely select wanted signals and reject unwanted signals. Thus, a receiver's performance is also a metric of its capacity to use spectrum efficiently. In addition to promoting improved performance, prior studies have also noted the importance of gathering relevant information on fielded receivers so that potential coexistence issues due to the proposed introduction of new spectrum-dependent services can be accurately forecasted and mitigated.

The idea that requirements for receiver performance could enable more efficient utilization of spectrum is hardly new. Both the FCC and the NTIA have recognized the importance of receiver performance in meeting the growing demands for spectrum since at least 2003, when the FCC sought public commentary on incorporating receiver performance requirements in its spectrum policies through a Notice of Inquiry (NOI) [8], and the NTIA contemporaneously released a report characterizing domestic and international receiver performance as part of a broader effort to understand how receiver standards might advance spectrum management [9]. Additionally, CSMAC and the FCC's Technical/Technological Advisory Committee (TAC) have produced many white papers since that time discussing the role of receiver performance in improving spectrum efficiency [10] [11] [12] [13] [14] [15].

However, the costly and potentially catastrophic ramifications of *not* more robustly addressing receiver performance issues were manifested recently in two high-profile developments that demonstrate the criticality of receiver performance in the modern spectrum landscape. One was the inability to implement the proposal (and subsequent filing of a $39 billion lawsuit [16]) of Ligado Networks' terrestrial network because of a concern about the potential for interference to legacy Global Positioning System (GPS) receivers. The other was the concern about potential harmful interference of C-band 5G base stations to radar altimeters on civil and military aircraft. These developments, along with the demand for additional spectrum by new and existing users, have prompted regulators to explore anew potential approaches to mitigate receiver interference performance issues, including an April 2022 NOI and subsequent April 2023 FCC policy statement [17] [18].

1.3 Scope

The general focus of this report is the federal receivers that fall under the NTIA's purview. However, commercial and federal interests are necessarily intertwined in the current spectrum landscape; accordingly, many of the discussion topics in this report include whole-of-nation considerations and examples pertaining to both federal and non-federal receivers. For clarity, where possible, this report will clearly distinguish when discussions pertain to federal, non-federal, or both federal and non-federal receivers.

Receivers can experience harmful interference from many types of unwanted signals. Within this report, we focus on unwanted signals from spectrally proximate services, as did the April 2023 FCC policy statement, since:

- Adjacent-band interference has been the primary concern in recent high-profile spectrum management issues such as the Ligado/GPS and the C-band 5G to radio altimeter issues introduced in Section 1.3.
- Receiver interference immunity performance variations are typically greater for unwanted signals outside of the allocated bands than for in-band signals.

Although this report does not directly address co-channel or other in-band spectrum sharing, we note that some of the findings may apply in these situations as well.

1.4 Report Organization

This report is organized as follows:

- Section 2 provides a broad overview of receivers and their performance issues, including recent operational examples and relevant prior studies.
- Section 3 describes common receiver performance parameters and the existing domestic and international, governmental and non-government standards that define receiver performance requirements.
- Section 4 discusses how receivers may be evaluated for their conformance to performance standards, including methods to evaluate receiver performance in the absence of a standard.
- Section 5 provides an overview and evaluation of the means by which receiver performance may be improved, including emerging technologies and best practices.
- Section 6 discusses the non-technical mechanisms by which receiver performance issues may be mitigated, including economic and policy-based initiatives and incentives.
- Section 7 provides a summary and recommendations to guide future policies regarding receiver performance.
- Appendix A provides a comprehensive background to inform best practices for receiver performance, including common receiver architectures and components, interference mechanisms, interference mitigation, and emerging technologies to improve receiver performance.
- Appendix B summarizes more than 150 documents containing electromagnetic compatibility (EMC) requirements for receivers, including the publisher of the document, the required EMC characteristics, and the type of receiver to which the requirements apply.
- Appendix C contains a glossary of abbreviated terms used within this report.

2 Receiver Interference Performance Issues

2.1 Overview

As noted in the introduction, the primary objective of this report is to inform NTIA's future policies regarding receiver interference immunity performance. A logical place to start this analysis is with a discussion of why a receiver might experience degraded performance due to interference in the first place. We begin our analysis of this topic in this section: 2.2 summarizes common receiver architectures and the mechanisms through which interference can degrade the functionality of the receiver; 2.3 provides several examples where receiver susceptibility to adjacent-band interference has been problematic; and 2.4 summarizes prior studies of receiver interference performance issues.

We will discuss in 2.2 that there are multiple receiver architectures in widespread use. Some of the components that play an important role in a receiver's ability to suppress interference include antennas, filters, amplifiers, mixers, frequency synthesizers, and analog-to-digital converters. Although ideal receivers would not respond to energy arriving from directions not expected for desired signals and at frequencies outside of a desired passband, all practical receivers have imperfections that result in some response to undesired signals. Importantly, we will also note towards the end of 2.2 that there is a trade-off continuum between receiver interference immunity and size, weight, and performance; and cost (SWAP-C). Receivers can improve immunity to interference with increased SWAP-C, and it is more difficult to achieve interference robustness in equipment that is required to be small, light, low-power, or inexpensive.

Although improving receiver interference immunity may be beneficial in some circumstances to improve spectrum efficiency by allowing additional services to coexist in proximate frequencies, we will also note in our discussion that some coexistence issues may not be resolvable through receiver improvements alone. Challenging situations include when receivers must process very low-power signals (e.g., for radars, radio astronomy, or satellite navigation), when adjacent band transmitters are high-powered or can be very close to the receiver, when desired and interfering signals are both near the common edge of adjacent allocated bands, and when existing systems are difficult (e.g., expensive or inaccessible) to replace or modify.

Three examples of spectrum management issues that have arisen due to receivers being susceptible to interference from frequencies beyond their intended passbands are discussed in 2.3:

1. Interference from FM broadcasting to aviation systems – This issue, regarding interference from FM broadcast radio towers in the 88 – 108 MHz band to aviation systems operating in the 108 – 118 MHz band, first arose in the 1970's. It has been largely resolved through receiver improvements and by ensuring that new FM radio towers operating at frequencies close to 108 MHz are not sited next to airports. A new chapter of this issue opened with FCC rulemaking in 2023 that proposes to permit FM stations to broadcast digital sidebands with asymmetric power levels. This proposal is of concern to the aviation community and discussions to resolve the issue are ongoing.
2. GPS/Ligado –Ligado Networks received authorization from the FCC in April 2020 to deploy a low-power terrestrial network in bands adjacent to GPS. In September 2022, Ligado notified the FCC that it was not intending to move forward with a trial

deployment in order to allow additional time for discussions with NTIA to resolve concerns of interference to GPS and other systems.
3. C-band/radio altimeters – The auction of 5G spectrum from 3.7 – 3.98 GHz near the radio altimeter band of 4.2 – 4.4 GHz has raised concern of potential interference from 5G to airborne radio altimeters that are critical to many flight operations.

There have been many prior studies on receiver interference performance issues and proposed methods to resolve these issues; we highlight key studies related to this topic in 2.4. The FCC's TAC has emphasized the role of defining limitations on a receiver's ability to claim damages due to interference, which the TAC refers to as "harm claim thresholds." The TAC has also recommended the use of "risk-informed" interference assessments. NTIA has performed many related studies including on radar receiver interference immunity and a survey of existing receiver standards. NTIA's CSMAC has made relevant recommendations on the topic related to the use of statistical interference models, risk measures, and propagation model improvements. Europe has embarked on a regulatory solution, which is to introduce required levels of receiver interference immunity for a growing number of services and frequency bands.

2.2 Receiver Architectures and Interference Mechanisms

As detailed in Appendix A, there are several common receiver architectures in widespread use today, including superheterodyne, homodyne, and direct radio frequency (RF). Figure 2-1 shows some of the important components within a superheterodyne receiver, which will be used as an example to illustrate how interference outside a receiver's passband can degrade performance.

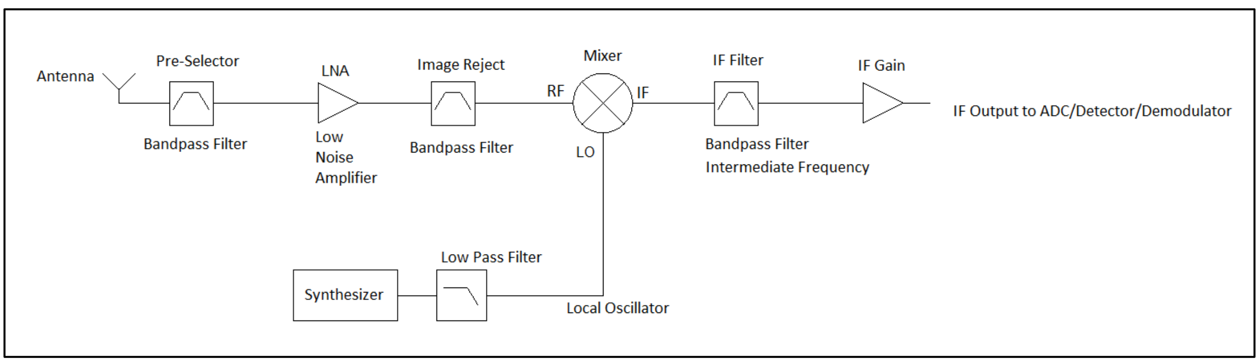

Figure 2-1: Superheterodyne Single-Conversion Receiver

In any radio receiver, the first component encountered will be the *antenna*, a transducer that converts electromagnetic fields in space (e.g., those generated by transmitters in communications systems) into currents confined to transmission lines (e.g., wires, microstrip lines, waveguides) for downstream processing. The antenna impacts interference performance of the receiver in several important ways:

- Many receiving antennas are *directional*, i.e., they will output a varying level of power as a function of the direction of the arriving electromagnetic wave even if the power in that wave is held constant. This directionality is typically specified by the antenna's *gain pattern*, which is a measure of how much power the antenna outputs as a function of the incident direction (azimuth and elevation) of the electromagnetic field as compared to a reference *isotropic* antenna that is defined to be both lossless and producing the same output power independent of the direction of the incident wave. Importantly, the gain pattern of a receiving antenna is a function of the polarization of the incident electromagnetic wave. Although an antenna may be designed to only be receptive to a certain polarization type (e.g., linear, right-hand circular, left-hand circular), a typical antenna does provide some response to incident waves with other polarization characteristics.

- The electrical behavior of antennas is frequency-dependent. The gain pattern of the antenna toward interference in an adjacent or distant frequency band may be significantly different that the antenna's gain pattern for the desired signal in the intended receiver passband. Some antenna structures are *broadband*, which means that their electrical characteristics (including gain pattern) change very slowly with frequency. Other antenna structures (e.g., microstrip patch) are *resonant*, and their electrical characteristics may change very rapidly with frequency.
- Antennas may be packaged separately from the receiver and this separate package may include low noise amplifiers (LNAs) and other components (e.g., filters). Antennas packaged with amplifiers are referred to as *active antennas*. Active antennas can *saturate* in the presence of strong interference (see discussion of saturation later in this section).

Following the antenna, receivers will typically include layers of filters and amplifiers. *Bandpass* and *lowpass* filters are the most common types used within receivers. As illustrated in Figure 2-2, ideal bandpass and lowpass filters allow signals within only a finite range of frequencies to pass through without any impact and completely suppress (attenuate) signals outside of this desired *passband*. For bandpass filters, the passband includes the range between two positive frequency values. Bandpass filters are used within receivers or active antennas to pass the desired RF signals before down-conversion and also at intermediate frequencies (IF) after down-conversion. Lowpass filters are often found after down-conversion within receivers that utilize a low or no IF, or at times even with a high IF to suppress harmonics generated within the mixers used for down-conversion.

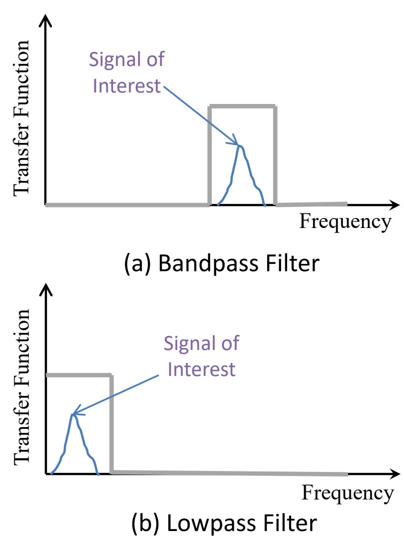

Figure 2-2: Ideal Bandpass and Lowpass Filters

Real-world filters, unfortunately, do not exhibit the ideal behavior shown in Figure 2-2. Imperfections include:

- *Insertion and return loss* – Whereas an ideal filter would not attenuate the desired signal at all, real-world filters will result in small levels of attenuation, which is referred to as insertion loss. An ideal filter would be perfectly matched in impedance with preceding receiver components and only pass energy forward. Real-world filters may not be perfectly impedance-matched and may result in some reflected energy, which is referred to as return loss.
- *Selectivity* – Whereas an ideal filter would completely suppress signals outside of their intended passband, real-world filters only provide a finite amount of signal attenuation as a function of frequency. The profile of attenuation versus frequency is referred to as selectivity. By convention, *high selectivity* refers to a filter that provides a large amount of attenuation to signals outside of the desired passband. *Low selectivity* refers to a filter where the amount of attenuation is very low or grows very slowly with change in frequency beyond the passband. In a typical receiver, the bandpass filters become more selective as the signal progresses through the front-end due to a physical characteristic of filters referred to as *quality factor* ("Q factor") that makes it easier to achieve high selectivity at lower center frequencies and smaller bandwidths. For example, in a receiver with an RF filter and two IF stages, the RF filter would typically be the least selective, the IF filter after the first mixer would be more selective, and a final IF filter after a second mixer would be the most selective.
- *Amplitude and phase variations* – Whereas an ideal filter would not distort the desired signal in any way, real-world filters do impart amplitude and phase variations that can degrade receiver performance. A filter phase response that is linear with frequency will delay the intended signal, which is of particular importance for services relying on radio ranging (e.g., radars and radionavigation). Importantly, the delay is often a function of frequency (referred to as *differential group delay*) in which case the desired signal is not only delayed but is distorted.
- *Environmental sensitivity* – The filter characteristics described above can vary significantly with temperature. Some filter types (e.g., those that convert electrical signals to acoustic waves) are additionally sensitive to vibration.

A wide variety of filter topologies and construction methods are used in receivers. As might be expected, there are typically trade-offs involved between selectivity, insertion loss, return loss amplitude/phase variations, environmental sensitivity, and size, weight, power, and cost (SWAP-C). In some very low-cost or poorly-designed receivers, one or more of the filters shown in Figure 2-1 may be omitted. Common filter types and their performance characteristics are detailed in Appendix A.

Referring back to Figure 2-1, after the antenna within a typical receiver the first bandpass filter encountered is referred to as a *pre-selector*. The pre-selector is designed to protect the following LNA from interference outside the receiver's desired passband. In some receiver designs (e.g., for some federal radars), the passband for the RF filtering may be the entire allocated band for the radio service of interest. In other designs, the RF filter passband may be just a subset of the allocated band that includes only the necessary bandwidth of the signals of interest. The latter can help alleviate some interference issues for some systems, but may require manually swapping out different sets of physical components when changing the operating frequency.

LNAs are amplifiers that are designed to increase the power of the received signal while adding as little noise as possible. An ideal amplifier would provide an output voltage that is some constant (greater than unity) K times the input voltage. The nominal power gain of the amplifier is $20 \log_{10} K$ decibels (dB). For instance, Figure 2-3 shows the input-output voltage characteristic for an ideal 34.5-dB-gain LNA. As illustrated in Figure 2-3, a typical (physically realizable) LNA will always saturate at some point, i.e., the output voltage (and power, which is proportional to voltage squared) will approach a limit. The point at which a practical LNA's output power is 1 dB less than would be expected for an ideal LNA is called the *1-dB compression point*. It may be referred to by the input power level resulting in 1-dB compression or the output level occurring at 1-dB compression.

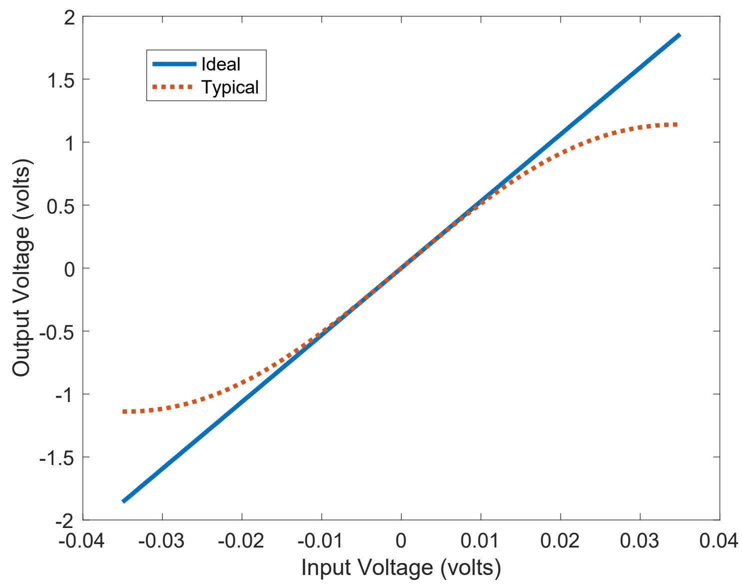

Figure 2-3: Ideal and Typical LNA Input-Output Voltage Characteristic

When receiver amplifiers saturate, the desired signal becomes distorted and performance suffers. Saturation can also result in the generation of signals within the receiver passband at the LNA output from interfering signals that are outside of the receiver passband at its input. For instance, two interfering signals at frequencies f_1 and f_2 that are just below the receiver's passband at the input to a saturated LNA can result in third-order *intermodulation products* at $2f_1 - f_2$ and $2f_2 - f_1$ at the LNA output, which may fall within the receiver passband. Several other consequences of saturated LNAs that may result in receiver performance issues in the presence of out-of-band interference, including the generation of *harmonics* and spreading of the bandwidth of noise-like signals, are discussed in Appendix A.

Practical LNAs also add noise to the received signal. The signal-to-noise ratio (SNR) at the output of the LNA is lower than the SNR at its input, and the ratio of these two SNRs (input SNR divided by output SNR) is referred to as the LNA *noise figure*. The noise figure of an LNA and its gain for the desired signal will generally degrade when the LNA enters into compression. These combined effects can substantially reduce the receiver sensitivity and are called *desensitization*.

Referring back to Figure 2-1, after the LNA and an additional (image reject) bandpass filter, the next receiver component encountered is a *mixer*. An ideal mixer would multiply the received signal against a perfect tone created within the receiver (the *local oscillator* [*LO*]) at a frequency, f_{LO}, slightly above (*high-side injection*) or slightly below (*low-side injection*) the desired RF signal's center frequency, f_{RF}. The output of an ideal mixer would be a perfect copy of the desired signal frequency translated to a convenient *intermediate frequency* (IF) for further processing and a second perfect copy of the desired signal frequency translated to the sum of its original RF frequency and the LO frequency, i.e., $f_{RF} + f_{LO}$ that is typically not utilized. The IF frequency, f_{IF}, will be at $f_{LO} - f_{RF}$ with high-side injection and $f_{RF} - f_{LO}$ with low-side injection. See Figure 3-1 and Figure 3-2 for example frequency response curves for the RF and IF stages of a radar receiver, respectively.

Mixers can contribute to receiver performance issues through several mechanisms. Note that even an ideal mixer is susceptible to interference at its *image* frequency given by $2f_{RF} - f_{LO}$ for both high-side or low-side injection. Any interference at this frequency at the mixer input will be added to the desired signal at the output IF frequency. Undesired signals at the image frequency may be suppressed by filtering preceding the mixer (as in Figure 2-1; note that the bandpass filter preceding the mixer is referred to as an *image-reject* filter) or through specially designed mixers that are built to suppress the *image response*.

Mixer imperfections result in additional interference mechanisms. These mechanisms, detailed in Appendix A, include:

- *Reciprocal mixing* – Real-world receivers' LOs are not perfect tones but may include spurious frequency components due to oscillator phase noise and discrete spurs created by the frequency synthesizer.
- *Saturation* – If the input to the mixer is too strong (e.g., because of the presence of interference), the mixer can saturate leading to effects similar to those resulting from amplifier compression discussed above.

As shown in Figure 2-1, after the mixer there are typically additional filtering and amplifier stages before *digitization* in an *analog-to-digital converter* (ADC) found in most modern receivers or other circuitry for detection or demodulation in older analog receivers. The IF filter shown in Figure 2-1 is typically much more selective than the RF filter. As discussed in Appendix A, in some receivers (e.g., dual- or triple-conversion) there are multiple IF stages, often with increasingly selective IF filtering at the end of each stage. In some receivers, the downstream amplifiers may have variable gain as part of an automatic gain control (AGC) function within the receiver to keep the desired signal output of the receiver front end close to a target power level. These gain stages and the AGC function are both susceptible to degradation due to near-band interference if the upstream filtering has not provided sufficient attenuation by this point. Such remaining near-band interference can also be aliased (i.e., the sampling rate is too slow for the upper frequencies of the band) by the ADC from the edge of the desired band to the center of the desired band resulting in additional performance issues.

An additional interference mechanism, not explicitly shown in Figure 2-1, is the fact that some electronic components within the receiver can unintentionally radiate or generate voltages/currents in response to electromagnetic radiation. The implication is that external interference can couple to the receiver through other entry points in addition to the receiver's antenna. Also, there may be *crosstalk* or signal coupling between receiver components for which no connection was intended. Crosstalk can result in some interference bypassing filters and often limits the maximum rejection possible within a receiver to out-of-band interference especially for low SWAP-C devices. Careful layout of components and shielding may be used to minimize receiver performance issues due to this interference mechanism.

A typical overall receiver response to an interfering signal of a certain type (e.g., modulation, bandwidth) as a function of its frequency is illustrated in Figure 2-4. The plot notionally shows how much interference can be tolerated at the input of the receiver as a function of frequency before receiver performance falls off beyond a specified tolerable level. Such a curve provides information for the overall *receiver selectivity*, which is defined by the ITU as a receiver's "…ability to discriminate between a wanted signal to which the receiver is tuned and unwanted signals" [19]. In Figure 2-4 the receiver's passband is the central "floor" at which it is most sensitive to interference. The passband aligns with the spectral location of the desired signal. Referring to the passband, the ITU recommends that "the bandwidth of the receiver shall be no wider than is essential for the transmission of the necessary modulation of the wanted signal without significant distortion" [19]. The receiver's filtering attenuates interfering signals beyond the receiver passband, but it is not possible to build a receiver that completely attenuates such interference, due to the interference mechanisms summarized above. As illustrated in Figure 2-4, for interference outside of their passband most receivers are most sensitive to interference that is in *adjacent bands*, i.e., those frequencies just beyond the passband where the receiver filtering has not yet been able to provide high attenuation. Even at distant frequencies, there is often a limit to the maximum tolerable interference levels that may be driven by one or more of the interference mechanisms discussed earlier in this section. For very high levels of interference at any frequency, there may also be concerns of physical damage to the receiver.

As detailed in Appendix A, there is a trade-off continuum between receiver interference immunity performance and receiver SWAP-C. Receiver designs can provide improved immunity to interference with increased SWAP-C, and it is more difficult to achieve interference robustness in equipment that is required to be small, light, low-power, or inexpensive.

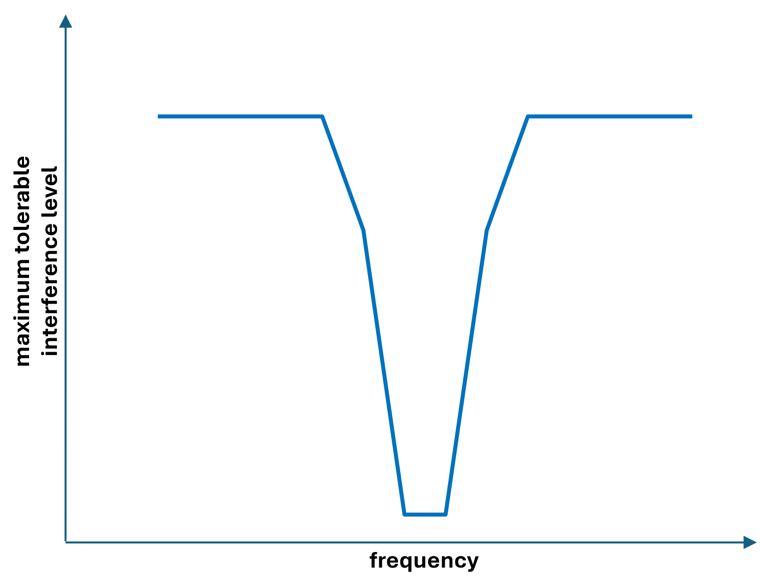

Figure 2-4: Typical Receiver Selectivity Characteristics

Whereas Figure 2-4 is notional, Section 3 of this report identifies numerous receiver standards that provide receiver selectivity requirements with similar features.

In the comments and reply comments in response to the FCC's April 2022 Notice of Inquiry on receiver performance, various views were offered on how FCC should consider receivers within future spectrum management deliberations. These views ranged from suggestions that the FCC "should provide no protection for devices that listen out of band" [20] to alternative suggestions that it is not possible for receivers to bear the entire burden of mitigating performance issues from unwanted emissions outside of their passband "particularly when intensive and high-powered spectrum uses are proposed in adjacent frequencies" [21]. The FCC's TAC has also noted that "[a]ctual receivers can only provide a finite amount of rejection of unwanted signals outside the assigned channel" due to "practical considerations, such as power consumption, size and cost" [14]. Many respondents to the FCC's April 2022 NOI noted that there is no "one size fits all" solution to considering receivers within future spectrum management matters. MITRE agrees with this view. There are many additional mitigation approaches that should be considered as coexistence issues continue to arise due to repurposing of spectrum. These approaches include:

- Limiting transmitter power in adjacent bands, requiring greater transmitter-receiver separation distances, or favoring the spectrum management philosophy that has been followed for many years of keeping like services together.
- Guard bands – There are many instances of the use of guard bands between services to allow receiver filters the span of frequencies necessary to achieve the levels of attenuation required for coexistence.
- Allocating adjacent bands to services that are not used at the same locations or at the same times.
- Continuing to limit unwanted emissions from transmitters outside of their allocated spectrum.
- Conditions that may lead to adjacent-band coexistence issues that may not be resolvable through receiver improvements alone include:
    - High sensitivity – various radio systems (e.g., radars, satellite navigation, deep-space telemetry, radio astronomy) require receivers to process desired signals that are very low in power. For these systems, the "trough" in the receiver selectivity response (see Figure 2-4) will be very low, which makes it difficult for filtering to provide much attenuation at frequencies close to the passband.
    - High-powered adjacent band services – if adjacent-band transmitters are very powerful, receiver filtering needs to provide a great deal of attenuation to avoid performance issues (e.g., the slope of the selectivity curve beyond the "trough" in Figure 2-4 is required to be very high).
    - Proximate transmitters and receivers – note that in free-space propagation conditions, every time the separation between a transmitter and a receiver is divided in two, received power increases by a factor of 4. So, for example, a 1 milliwatt (0.001 W) transmitter that is 1 meter from a receiver will result in the same received power level as a 1 kilowatt (1000 W) transmitter that is 1 km away.

- Desired and interfering signals both near the common edge of the allocated bands – this situation leaves no room for filter attenuation to ramp up from the passband to the adjacent band.
- Existing systems are difficult (e.g., expensive or inaccessible) to replace or modify.

2.3 Examples

This section provides several examples of spectrum management issues that have arisen due to receivers being susceptible to interference from frequencies beyond their intended passbands.

2.3.1 ILS (and VOR, GBAS, and VHF A/G Radio) FM Immunity

Within the United States, 88–108 MHz is allocated to the broadcasting service, specifically for frequency modulation (FM) radio broadcasting with applicable FCC rules provided in 47 CFR 73. The adjacent 108–117.975 MHz band is allocated for aeronautical radionavigation services (ARNS). This ARNS band is used by aviation navigation systems including the Instrument Landing System (ILS) localizer, Very High Frequency (VHF) Omnirange (VOR), and Ground-based Augmentation System (GBAS). The next higher band in frequency, 117.975–137 MHz, is allocated for the aeronautical mobile service (AMS) and aeronautical mobile (route) service (AM(R)S) and used for VHF air-ground (A/G) radio communications.

In the late 1970s and early 1980s, the Federal Aviation Administration (FAA) received multiple complaints of interference to ILS, VOR, and VHF A/G systems from FM broadcasting stations [22]. After considerable study in both the United States and abroad, it was determined that FM broadcasting could interfere with the aviation systems in 108–137 MHz through several mechanisms including unwanted emissions from the FM broadcast stations above 108 MHz, intermodulation products generated within the aviation receivers from FM emissions from two or more stations below 108 MHz, and aviation receiver desensitization from FM emissions from one or more stations below 108 MHz [23].

This compatibility issue was partially resolved through “FM Immunity” requirements for ILS receivers that were added to the International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPs) in 1985 [24]. Similar requirements have been put in place for VOR, VHF A/G, and GBAS receivers within standards produced by RTCA, Inc. (formerly the Radio Technical Commission for Aeronautics), and incorporated by reference in FAA Technical Standard Orders. The FAA also screens requests for new FM broadcast stations or modifications to existing stations to ensure that no safety risk would result from their operation within the United States [25]. This screening process is an example of an enforcement mechanism, which are discussed further in 6.4.4.2.

A new issue of compatibility between FM broadcast stations and aviation systems in the adjacent 108–137 MHz bands within the United States has recently arisen following the release in August 2023 of an FCC Order and Notice of Proposed Rulemaking that proposes to permit FM stations to broadcast upper and lower digital sidebands with asymmetric power levels [26]. The aviation community has expressed concerns that this regulatory change may result in FM broadcast station emissions that exceed the ability of aviation receivers to be “immune” to these signals. See, e.g., [27].

2.3.2 GPS/Ligado

In April 2020, the FCC authorized Ligado Networks to deploy a nationwide terrestrial network with base stations transmitting in the 1526–1536 MHz band and mobile devices transmitting in the 1627.5–1637.5 MHz and 1646.5–1656.5 MHz bands [28]. These bands are adjacent to the 1559–1610 MHz radionavigation satellite service (RNSS) band used by the U.S. GPS and similar foreign satellite navigation systems (e.g., Europe's Galileo, China's BeiDou, Russia's GLONASS, and several regional systems). After the FCC granted the order, Congress directed an independent review by the National Academies of Sciences, Engineering and Medicine (NASEM). This NASEM study concluded that although most fielded GPS receivers are compatible with the Ligado network, some GPS receivers will experience "significant harmful interference" and that "Iridium terminals will experience harmful interference on their downlink" due to the Ligado network [29]. In September 2022, Ligado notified the FCC that it was not intending to move forward with a trial deployment in order to allow additional time for the company's discussions with NTIA to resolve these issues [30].

As stated in its April 2020 Order, the FCC's decision to authorize Ligado's terrestrial network "drew to a close a 17-year old proceeding." The reason for the extensive amount of time from application to authorization for Ligado's network was Ligado's inability to overcome concerns of adjacent-band interference from both base stations and mobile devices in the network to GPS, other RNSS systems, and mobile satellite services (MSS). Over the course of the proceedings Ligado (and its predecessors) made many concessions to mitigate these interference concerns including reducing base station effective isotropic radiated power from an initially proposed 32 dBW (1585 W) to 9.8 dBW (9.5 W) and also eliminating an initially proposed second base station transmission band (1545–1555 MHz) that was closer in frequency to the RNSS band. Despite the concessions, federal agencies still found them inadequate to prevent harmful interference and thus still oppose the FCC April 2020 Order due to continued concerns of interference to GPS (see [31] for a compilation of studies indicating compatibility issues). In May 2020, on behalf of the executive branch, NTIA submitted both a Petition to Reconsider and a Petition to Stay to the FCC regarding the April 2020 Order [32] [33]. The Petition to Reconsider requested that the FCC "rescind its approval" of Ligado's license because it would "cause irreparable harms to federal government uses of the Global Positioning System (GPS)." Other non-federal entities filed Petitions for Reconsideration as well. On January 21, 2021, the FCC denied NTIA's Petition for Stay finding, among other things, that NTIA was unlikely to succeed on the merits. In September 2022, NASEM issued its Congressionally-mandated independent review of the FCC's order authorizing Ligado's terrestrial operations. A few days after release of the Congressionally-mandated review, Ligado Networks deferred a trial deployment its terrestrial network. In October 2023, Ligado filed a lawsuit against the U.S. Government claiming damages of "as much as $39 billion" on the basis of an unlawful taking [34]. The Department of Justice has filed for dismissal, arguing that Ligado's novel claims have no legal basis.

Figure 2-5 shows an example set of results from federal testing of GPS receivers against 10-MHz Long Term Evolution (LTE) signals on a wide range of center frequencies from 1475–1675 MHz. These results were from a test campaign that included 80 GPS receivers and was conducted within an anechoic chamber at the U.S. Army's White Sands Missile Range (WSMR) in New Mexico in April 2016 [35]. Each curve in the figure represents the measured selectivity of the most sensitive receiver within each of six classes: general aviation (GAV), general location/navigation (GLN), high precision (HPR), timing (TIM), spaceborne (SPB), and cellular

(CEL). These curves are real-world examples of the notional receiver selectivity characteristics discussed in Section 2.2. This data indicates that, even at a reduced power level of 9.8 dBW, there is still the potential for interference from proposed Ligado base station emissions in 1526 - 1536 MHz to some proximate GPS receivers.

One notable aspect of the Ligado/GPS issue, worthy of further general consideration (e.g., within the National Spectrum Strategy's planned roadmap to improve receiver performance), is that some of the most sensitive GPS receivers to emissions in the 1525–1559 MHz band are actually dual-service receivers. They are designed to receive both authorized GPS emissions in the 1559–1610 MHz RNSS band and authorized mobile satellite service (MSS) space-to-Earth emissions in the 1525–1559 MHz band. They utilize MSS downlink signals to provide corrections to GPS for high-precision applications including positioning of vehicles used for agriculture (e.g., tractors) and construction (e.g., bulldozers, graders). There are many other examples of dual- or multiple-service receivers being used today, e.g., radios that are designed to receive signals in broadcasting and meteorological service bands.

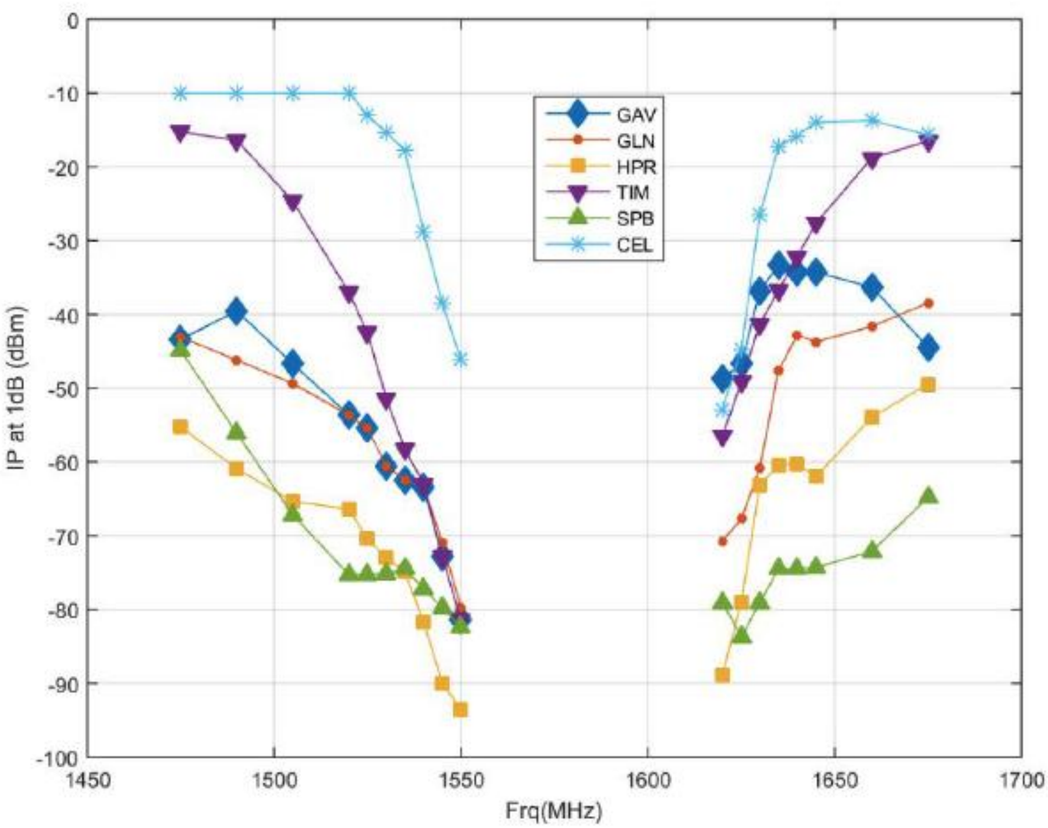

Figure 2-5: Received Interference Power (IP) of 10-MHz LTE Signals at Which GPS Receivers Experienced a One Decibel (1 dB) Loss in Signal-to-Noise Ratio

2.3.3 5G/Radar Altimeters

The FCC allocated the frequency band of 3.7 to 3.98 GHz to terrestrial fixed and mobile services in 2020 [36]. This allocation was of concern to the aviation industry, and comments were submitted during the rulemaking stating that these operations could cause potential interference to certain radar altimeters due to the increased power levels authorized for these new telecommunications systems as compared to previous systems (e.g., satellite downlinks) that resided in this frequency band. The radar altimeter's in-band frequency range is 4.2 to 4.4 GHz.

At the time the then in-service radar altimeters were designed, there was not a significant concern related to interference from other communication systems due in some cases to their lower power levels and in others to there being relatively few sites and their operating less often than a typical base station would. In-band interference from other radar altimeters was understood. During the FCC's 3.7 – 3.98 GHz band rulemaking, the aviation industry noted that some radar altimeters might not have sufficient filtering in their front end to attenuate signals outside of their primary operating band of 4.2 to 4.4 GHz.

Specifically, with the introduction of terrestrial fixed and mobile services from 3.7 to 3.98 GHz, the aviation industry concern was that interference could potentially occur under certain conditions from both primary 5G emissions (3.7 to 3.98 GHz) and unintentional (spurious) 5G emissions (4.2 to 4.4 GHz). We note that there is nothing unique about the 5G waveform that would cause interference to a radar altimeter or degrade the radar altimeter's performance. The potential interference concern was related to the then-existing level of radar altimeter robustness and the potential power level of the 5G spectrum emissions in proximity to the radar altimeter band.

Given the performance level of radar altimeters at the time, unintentional 5G emissions in the 4.2 to 4.4 GHz frequency range and the primary 5G emissions in the 3.7 to 3.98 GHz frequency range could potentially increase the noise floor of the radar altimeter and/or saturate the radar altimeter's RF receiving chain. If 5G emissions were to increase the radar altimeter's noise or saturate its front end, this could potentially decrease the radar altimeter's detection signal-noise-ratio or cause the radar to fail. The failure of a radar altimeter to report the correct altitude or no altitude at all could result in reduced safety of flight and potential loss of life.

In response to the aviation concerns, in its 2020 rulemaking the Commission adopted technical and service rules for the new terrestrial wireless services in the 3.7-3.98 GHz band and established a guard band to protect against the potential for harmful interference. The Commission also encouraged the aviation industry to take into account the evolving RF environment in the band and to take appropriate action, if necessary, to ensure protection of devices operating in the 4.2–4.4 GHz band.

Many organizations studied the potential impact of 5G emissions on radar altimeters:

- RTCA (2020): RTCA formed a multi-stakeholder group under Special Committee SC-239 in 2019, which was initially tasked with providing a predictive, quantitative evaluation of radar altimeter performance regarding potential RF interference from expected 5G emissions in the adjacent band. The resulting 2020 report did predict a "major risk" of harmful interference and also noted that changes in assumptions could affect those results [37].

- AVSI (2021): The Aerospace Vehicle Systems Institute (AVSI) measured both the sensitivity of radar altimeters to fundamental out-of-band 5G emissions as well as spurious in-band 5G emissions and published their full quantitative results in three volumes in 2021 [38]. This project was limited to black-box laboratory testing (i.e., testing a system without regard to its internal workings) of nine RAs with the intent to investigate the possibility of harmful interference from out-of-band emissions. AVSI concluded that there was "a credible risk of harmful interference."

- JI-FRAI QRT (2022): The Joint Interagency Fifth Generation (5G) Radar Altimeter Interference (JI-FRAI) Quick Reaction Test (JI-FRAI QRT) executed a phased test strategy comprised of bench testing, radio frequency over-the-air testing, and operational flight tests in a real 5G environment. These test activities brought together participants from across the federal government, the commercial aviation community, major cellular service providers, radar altimeter manufacturers, and government partners. In FY22, JI-FRAI delivered a combined test methodology summarizing best practices, lessons learned, operational considerations, resource requirements, and mitigation strategies.

- NTIA-ITS (2022): ITS measured aerial radiation patterns of MIMO transmitter arrays incorporated in four radio models produced by the three manufacturers of C-band 5G equipment deployed in the United States [39]. The ITS study found, among other things, a "low level of unwanted 5G emissions within the radar altimeter spectrum band" that "reduces the potential for a 5G-to-radar altimeter harmful interference scenario which would be due to 5G unwanted emissions on radar altimeter receiver frequencies."

- CTIA (2024): CTIA replicated AVSI's laboratory test environment and tested several RA models to assess the potential improvement achieved with custom bandpass filters designed to pass the RA's occupied channel and begin rolling off within the unused portion of the RA band. The CTIA study found that, with custom bandpass filters, all tested RAs showed no degradation from 5G signals below 4.0 GHz [40].

In 2023, C-band licensees voluntarily committed to restrict the early deployment of 5G base stations near airports. The licensees did so without stating that the restrictions were necessary to prevent harmful interference. The current specifications of telecommunications equipment fielded by the carriers are much lower in terms of the potential out of band emissions into the radio altimeter band as compared to the FCC authorized levels. These voluntary mitigations [41] are agreed to remain in place until January 2028.

The aviation industry was required by FAA to improve the bandpass filtering at the radar altimeter's RF front end by July 1, 2023. These band pass filters were developed by the radar altimeter manufacturers as well as other industry organizations. Additional standards development work is underway at RTCA to further improve the tolerance of radar altimeters to spectral emissions.

Conclusion

The radar altimeters installed on aircraft prior to the 2020 FCC Report and Order were engineered to operate in the spectrum allocation environment that prevailed at that time. The introduction of 5G systems operating in the 3.7-3.98 GHz band created the potential for a markedly different operational landscape, including the potential operation of systems in spectral proximity to aviation operations.

2.4 Prior Studies

Regulators and established groups of independent advisors and experts have been developing related technical studies in an effort to improve receiver interference immunity performance and inform future policy considerations.

The FCC TAC and CSMAC developed papers on metrics that describe and measure spectrum efficiency and utilization that can be used to optimize spectrum usage. They also advised comparison of like systems and that, for example, radar systems should not be directly compared with communication systems. The FCC TAC released papers on the role of defining limitations on a receiver's ability to claim damages due to interference from external sources and on quantitative risk analysis.

NTIA developed reports that detail the technical approach for analysis and mitigation of interference to federal radar receivers and provide a quantitative assessment for the level of interference the tested receivers can withstand before degradation. CSMAC recommended the development of guidelines for the use of statistical models and analysis for coexistence studies, the translation of spectral interference into risk measures, and improvements to propagation modeling.

The Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT) identified major and critical receiver parameters required for future coexistence studies to adequately characterize the level and impact of interference on a particular receiver. It also created receiver resiliency metrics.

GAO identified key practices that could potentially improve receiver immunity performance and recommended the establishment of measurable goals, strategies and resources to implement spectrum management principles, factors that could affect achieving goals, and current and additional information related to federal receiver performance and spectrum efficiency efforts.

These efforts are described further below.

2.4.1 FCC/TAC

In December of 2011, the FCC TAC released a white paper [11] with the goal of developing a set of metrics for describing and measuring the utilization of spectrum. With a well-defined set of metrics, one should be able to reasonably determine if a particular band's usage can be optimized, shared, or even re-allocated for a more suitable public interest.

The TAC report leveraged heavily from a 2008 NTIA CSMAC report [42] which developed initial efficiency metrics for several classes of systems including personal communications, point to point, short range devices, satellite, radars, and passive listeners. Both reports leveraged International Telecommunication Union, Radiocommunication Sector (ITU-R) SM.1046-2 [43] for a quantifiable measure of efficiency.

From ITU-R SM.1046-2, the Spectrum Utilization Efficiency, SUE, of a system can be expressed by the parameter:

$$\mathrm{SUE} = \{M, U\} = \{M, B \cdot S \cdot \mathrm{T}\} \quad (1)$$

where:

M: is the useful effect obtained with the system in question, *U*: is the spectrum utilization factor for that system,

B: is the frequency bandwidth,

S: is the geometric (geographic) space, and

T: is the time denied to other potential users.

With regards to radar systems, both papers concluded that metrics for communication systems are not appropriate for use on radars as they cannot be compared directly. Likewise, the TAC paper did not comment on passive systems, which are primarily for astronomical, space surveillance, remote sensing, and atmospheric measurement.

Both the TAC and CSMAC reports believe that efficiency metrics with a quantifiable measure are paramount to spectrum allocation decisions and both agree that radar systems and scientific or passive listening systems should not be compared directly with communication systems as the metrics are not appropriate.

The FCC TAC has also released a number of white papers that emphasize the role of defining limitations on a receiver's ability to claim damages due to interference from external sources [12] [13] [15]. These limitations are defined through extensive efforts in quantifying a statistical level of energy present at the receiver input, based on proposed transmission characteristics (type of systems, quantity of systems, radiated power, etc.) of the prospective licensee or licensees.

The concepts outlined for claiming harmful interference are independent of the receiver and therefore apply to all receivers in that designated band with that interference mask; however, multiple masks may be present for a given band and group of systems. A receiving system that does not imply sufficient tolerance to the defined statistical input level may not claim interference with the FCC.

The above-mentioned white papers from the TAC outline the metrics which could be used to evaluate efficiencies, or alternatively deficiencies, in spectrum allocations along with a proposed methodology to introduce regulations for receivers. What ties both propositions together is another concept explored by the TAC which reinforces the value of quantifiable metrics when used in allocation decisions – quantitative risk analysis.

In 2015, the TAC released a white paper [14] which proposed the use of risk analysis when assessing the harm which may occur when spectrum services are adjusted. The "risk-informed interference assessment is the systematic, quantitative analysis of interference hazards caused by the interaction between radio systems. Such an assessment has three major steps:

- "Make an inventory of all significant harmful interference hazard modes.
- "Define a consequence metric to characterize the severity of hazards.
- "Assess the likelihood and consequence of each hazard mode." [14]

The use of quantitative risk analysis may require slow and steady indoctrination over many years. Determining likelihoods and consequences of hazard modes may be difficult or impossible due to insufficient data. The recommendation by the TAC was for the FCC to introduce quantitative risk assessments over time by developing agency staff through lectures on risk management, courses within the agency's curriculum, authoring papers utilizing quantitative risk analysis, and provide guidelines on unquestionable risks.

2.4.2 NTIA/CSMAC

The NTIA has released reports that detail the technical approach for analysis and mitigation of interference to federal radar receivers [44] [45]. Both reports provide a quantitative assessment for the level of interference the tested receivers can withstand before degradation.

Notable results from Report TR-06-444 were summarized in five major findings:

- Radars are vulnerable to the effects of communication signal interference.
- Radars perform robustly in the presence of interference from other radars.
- Low-level interference effects in radar receivers are insidious.
- Low-level interference can cause loss of radar targets at any range.
- Radar interference waveforms and test reporting should be standardized.

NTIA Report 03-404 [9] details existing federal and industry standards and provides options and recommendations for a follow-up effort. A key observation of the report is that regulatory approaches to promoting or ensuring adequate receiver performance can generally be grouped into three approaches: regulatory mandated standards, voluntary standards, and reliance on "insightful manufacturers specifications and designs". As an example of the last approach, they cite the addition of discrete codes in garage door opener receiver signals to mitigate the unexpected behaviors caused to these receivers by in-band and out-of-band interference. The suggested follow-up effort in this report included the examination of and trade-offs for regulatory approaches on receiver standards such as mandated standards, voluntary (industry-led) standards, and more robust manufacturer designs through the dissemination of detailed information on the RF environment.

CSMAC, which advises the Assistant Secretary for Communications and Information at NTIA, released the Final Report of its Subcommittee on Electromagnetic Compatibility Improvements [46]. Several key recommendations from this CSMAC report should be noted:

- "**RECOMMENDATION 2: Statistical Models/Analysis.** The CSMAC recommends that NTIA, in collaboration with the FCC and federal and non-federal user/stakeholder communities, develop guidelines for the use of statistical models/analysis for coexistence studies[.]
- "**RECOMMENDATION 5: Risk Measures.** The CSMAC recommends that NTIA translate interference in the radiofrequency realm into risk measures. A risk measure could be defined as the tolerance for interference that a particular system could manage. Risk measures could be used to model the statistical likelihood of harmful interference and based on the government-determined tolerance for risk[.]
- "**RECOMMENDATION 6: Propagation Model Improvements.** The CSMAC recommends that NTIA engage in measurements of the RF environment to improve and inform propagation modeling to enable coexistence analysis between aeronautical radar and commercial wireless services[.]
- "**RECOMMENDATION 7: Propagation Model Working Group.** The CSMAC recommends that NTIA should establish a working group that includes NTIA, FCC, and any interested federal agencies and industry stakeholders to tune and validate propagation modeling[.]"

Receiver sensitivity value can be incorporated in the recommended assessments.

2.4.3 ECC/CEPT

The Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT) has produced a number of documents relevant to receiver interference resiliency.

ECC Recommendation 24(01), approved 10 May 2024, establishes a framework for continuous future improvement of receiver interference resiliency in many spectral and operational domains. Specific annexes deal with broadcasting, fixed, land-mobile, short-range, and wireless access services.

ECC Report 310 [47] identifies major receiver parameters that would be required for future coexistence studies. The most critical of those parameters are identified as:

- Co-channel Protection Ratio
- Adjacent Channel Selectivity
- Receiver Blocking

Values of these critical parameters, as well as other major parameters, are necessary information for adequately characterizing the level and impact of interference on any particular receiver.

Technical analyses for future coexistence studies can use the methodologies outlined in ECC Report 356 [48], approved 10 May 2024, to determine the “Receiver Resilience” metric (MRR). The MRR’s intended use is to derive blocking and selectivity levels given the four parameters noted below. It should be noted that the MRR calculation does not characterize the impact of interference on a particular receiver.

- Noise floor (N) of the receiver.
- Maximum acceptable receiver desensitization (M) at given frequency offset.
- Interference leakage power ratio (ILR) of the interfering signal at given frequency offset
- Receiver selectivity (FOS) at given frequency offset.

ECC Report 127 [49] aimed to identify specific examples of negative consequences in frequency management due to poor receiver performance. It further aimed to estimate the net benefit that regulatory frameworks would have imposed had they been in place. Some notable conclusions were:

- Historically, the extent of technical benefit or disadvantage has not been quantified.
- Receiver parameters are a crucial element of coexistence calculations and therefore also are crucial to spectrum management.
- Carefully chosen values for receiver parameters should be available for compatibility studies.
- Field surveys are necessary in many cases to determine the actual performance of receivers.

Notable recommendations of the report were:

- Identify the set of receiver parameters that could be introduced in standards on a case-by-case basis in Harmonized Standards and/or in regulations.
- Where absolutely necessary for spectrum management purposes, introduce a limited number of receiver parameter minimum values in relevant Harmonized Standards and/or regulations.
- Where necessary for spectrum management purposes, the European Telecommunications Standards Institute (ETSI) should introduce specific receiver parameter values in relevant Harmonized Standards.

2.4.4 GAO

In July 2024, the Government Accountability Office (GAO) released GAO-24-106325 Report to Congressional Committees titled "Spectrum Management - Key Practices Could Help Address Challenges to Improving Receiver Performance" [50]. GAO was asked to review issues related to receiver performance with the goal of identifying key practices that could potentially improve receiver performance given the ever-increasing demand for frequency spectrum and the increasing potential for receivers to be subjected to in-band and out-of-band interference. The goal with identifying these key practices and making receivers more resilient to interference is to facilitate future reallocation of spectrum necessary to support the increasing demands of wireless services for more bandwidth.

Since the FCC and NTIA allocate spectrum for non-federal and federal use, respectively, the GAO report focused on preparing recommendations to the FCC and NTIA to support their spectrum management efforts. Two particularly relevant sections of the report include the section discussing stakeholder identified challenges related to improving receiver performance and the section discussing NTIA's information collection and certification processes.

In support of the report, GAO interviewed stakeholders and experts who identified challenges to improving receiver performance in five topic areas: 1) the rapidly evolving spectrum environment, 2) information and data sharing limitations, 3) technical tradeoffs and physical limitations, 4) cost and 5) disagreements and varied perceptions among stakeholders. A summary of these topic areas is presented here:

1) The Rapidly Evolving Spectrum Environment

   The design of incumbent receivers is typically based on a set of requirements for the specific system in which the receiver will be used. These requirements are often focused on optimizing the performance of the system and do not necessarily take into consideration the impact other systems may have on the system's receiver performance. This was less of a problem many years ago, when the RF spectrum was less congested, however, with spectrum reallocation and increasing frequency usage, receivers may be subjected to increased interference. The fact that receiver designers may not be aware of how spectrum will be allocated in the future is a challenge for designing receivers intended for long-term use.

2) Information and Data Sharing Limitations

   One of the challenges noted by federal agencies is the lack of information provided by carriers and original equipment manufacturers (OEM) on system performance properties, which are often considered proprietary. This lack of information makes it difficult to perform interference assessment studies and ultimately makes it difficult to develop interference mitigation strategies.

3) Technical Tradeoffs and Physical Limitations

   In many instances, retrofitting or upgrading a receiver to mitigate interference may be a significant technical challenge or not possible due to constraints related to accessibility, weight, size, power and sensitivity.

4) Cost

   Cost can be a significant factor and challenge in the design, development and manufacture of new receivers as well as in retrofitting existing receivers to mitigate interference. One of the major questions is who pay for this cost?

5) Disagreements and Varied Perceptions among Stakeholders

   The GAO report noted that stakeholders they interviewed informed them that disagreements and different perceptions regarding spectrum use among stakeholders present a challenge to improving receiver performance.

In the report, GAO discusses how NTIA manages federal receiver performance by ensuring that receivers meet specified performance standards through the NTIA certification process. The report states: *"NTIA considers the performance of federal receivers by mandating performance standards for certain receivers and collecting information through its process to authorize spectrum use. However, NTIA has not fully aligned its activities to broader spectrum efficiency efforts, including spectrum management goals shared with FCC."*

The report provides additional details on the NTIA certification process and the efforts NTIA undertakes to help ensure federal system receivers are resilient to interference, particularly from commercial wireless systems operating at frequencies near those of federal systems.

In the section discussing the NTIA, GAO also discusses the National Spectrum Strategy in that it acknowledges that a holistic approach is required for services to coexist, and that coexistence is dependent upon receiver characteristics and transmitter operations. Additional information on the National Spectrum Strategy will be provided in later sections of this report.

In concluding the report, GAO presented four recommendations, three to the FCC and one to NTIA:

- The Chair of FCC should define measurable goals related to implementing the spectrum management principles outlined in FCC's April 2023 policy statement.
- The Chair of FCC should identify strategies and resources necessary to achieve goals related to implementing the spectrum management principles outlined in FCC's April 2023 policy statement.
- The Chair of FCC should identify internal and external factors that could affect FCC achieving goals related to implementing the spectrum management principles outlined in its April 2023 policy statement. These factors should inform FCC's efforts to develop strategies for achieving its goals.

The NTIA Administrator should assess current information and evidence sources related to federal receiver performance and identify and collect additional information as appropriate. Such information and evidence should align with and address broader spectrum efficiency efforts including objectives outlined in the National Spectrum Strategy and FCC and NTIA’s MOU.

3 Receiver Performance Standards and Regulations

3.1 Overview

Whereas in Section 2 and its corollary sections in Appendix A we were interested in *why* a receiver's performance might degrade in the face of interference, in this and the following section we now turn to the question of *how to quantify and evaluate* a receiver's interference immunity performance. Specifically, in this section we discuss how receiver interference immunity performance can be specified, in terms of both performance characteristics and the standards that reference them, while in Section 4 we discuss how a receiver can be assessed for compliance against a specified level or performance.

We begin our discussion of receiver specification in 3.2, where we identify ten key parameters that determine receiver interference resiliency: sensitivity, co-channel protection ratio, and selectivity; blocking and overload thresholds; spurious-response and intermodulation rejection; limits on spurious emissions; frequency stability; and discrimination against undesired pulsed waveforms. As we further reference throughout this section, well over 100 standards, regulations, and reports developed in the U.S. and Europe specify those 10 parameters for the receivers of a wide variety of RF systems. Most of those standards also include system transmitter specifications. Few stipulate values for every possible receiver parameter. The most widely specified receiver parameters, which are also the most important for coexistence of RF systems in adjacent bands, are selectivity and blocking threshold.

We discuss the most important and widely followed U.S. standards and regulations governing receiver interference resiliency in 3.3, including: 47 CFR (the repository of FCC rules for civil non-governmental RF systems); the NTIA Manual, for federal agencies; MIL-STD 461 and MIL-STD-188, for DoD systems; and FAA Order 6050.32B, for aviation communications and navigation systems. International organizations publishing such standards and regulations are detailed in 3.4 and include ITU-R, ICAO (for aviation), ECC, and ETSI. The last of those, ETSI, is by far the most prolific publisher of RF receiver-related standards; Appendix B of this report lists 75 of them.

A final point to consider in this section is that <u>the existence of receiver standards does not preclude spectrum management issues</u>. As we discuss in 3.6, there are multiple considerations that dictate the effectiveness of standards. To be maximally effective: a standard must be recognized by regulatory authorities; it must be tailored to the kinds of interference likely to occur in the domain of interest; all parties must agree on minimum allowable transmitter-to-receiver distance and applicable propagation and antenna models; and interference-aggregation effects must be considered and appropriate safety margins established.

3.2 Performance Characteristics

Most standards and specifications for radio-frequency (RF) systems include mandatory provisions for various receiver performance characteristics. The resiliency of an RF receiver to potential RF interference (RFI) in its electromagnetic environment depends largely on the values (if any) stipulated for each of the following parameters. Each of these parameters has an impact on the receiver's ability to share spectrum with nearby RF systems.

- Sensitivity

- Co-channel protection ratio
- Selectivity
- Blocking threshold
- Overload threshold
- Spurious-response rejection
- Intermodulation rejection
- Spurious-emission limit
- Frequency stability
- Pulsed waveform discrimination

3.2.1 Sensitivity

The sensitivity of a receiver is the minimum power level (usually expressed in dBm) of the desired signal, entering the receiver at its tuned frequency, that enables satisfactory receiver performance. The sensitivities of nearly all receivers are substantially negative values, (e.g., –100 dBm). Somewhat confusingly, the more "sensitive" a receiver is, the lower (more negative) is its sensitivity value in dBm. Partly to eliminate such confusion, this parameter is sometimes called the "minimum detectable signal level," especially for radar receivers.

High sensitivity (i.e., a strongly negative value in dBm) is often considered a desirable attribute, since highly sensitive receivers detect desired signals very well. But that high sensitivity also causes them to detect weak undesired signals, thus increasing their vulnerability to interference. Preserving the performance of highly sensitive receivers demands greater restrictions to interference (e.g., less spectrum reuse) as compared to the restrictions needed to protect less sensitive receivers.

3.2.2 Co-channel Protection Ratio

A receiver's co-channel protection ratio (CCPR) is the minimum ratio (expressed in decibels) by which the desired signal's received power level must exceed that of a co-channel undesired signal to enable satisfactory receiver performance. Typically, a receiver's CCPR is dependent on the modulation scheme and duty factor of the interfering co-channel signal. For example, the receiver could have one CCPR value for pulsed interference, and a different CCPR value for continuous-wave RFI. If the interference is pulsed, its peak power could be much higher than its average power, so it is important for a standard to stipulate whether the CCPR refers to peak or average powers.

3.2.3 Selectivity

Receiver selectivity is arguably the most important receiver performance issue affecting the mutual EMC of RF systems operating on different frequencies or in different bands. Selectivity is the amount (expressed in decibels) by which the receiver attenuates off-frequency undesired signals, as a function of the frequency offset of the undesired signal from the tuned frequency of the receiver. Like CCPR, it may depend not only on the characteristics of the receiver, but also on those of the interfering signal and the received desired signal strength. Some standards separately stipulate the selectivity of the RF and IF stages of the receiver. Figure 3-1 and Figure 3-2 show empirical selectivity curves for these respective stages in a radar receiver. For small frequency offsets, selectivity is often called adjacent-channel rejection.

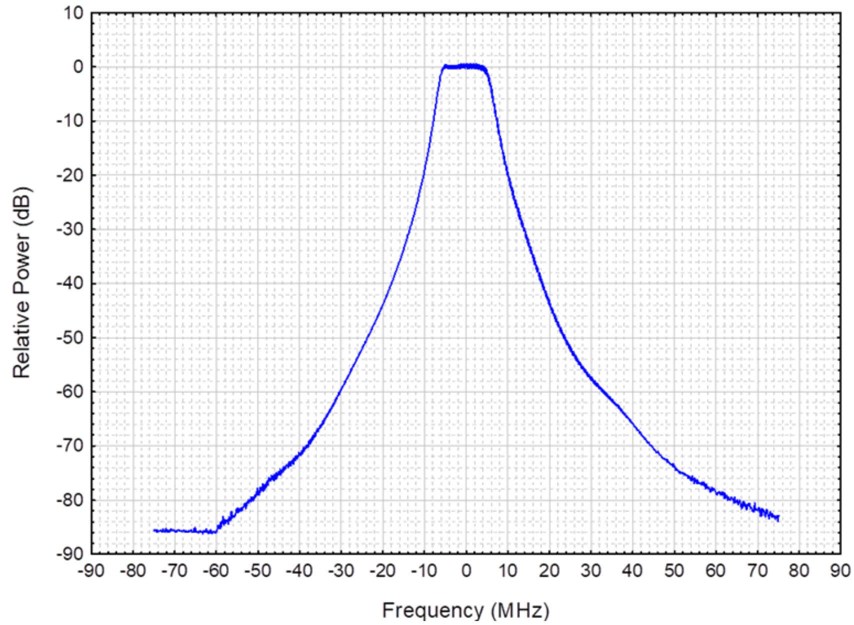

Figure 3-1: Example of a Measured Radar RF Filter Response

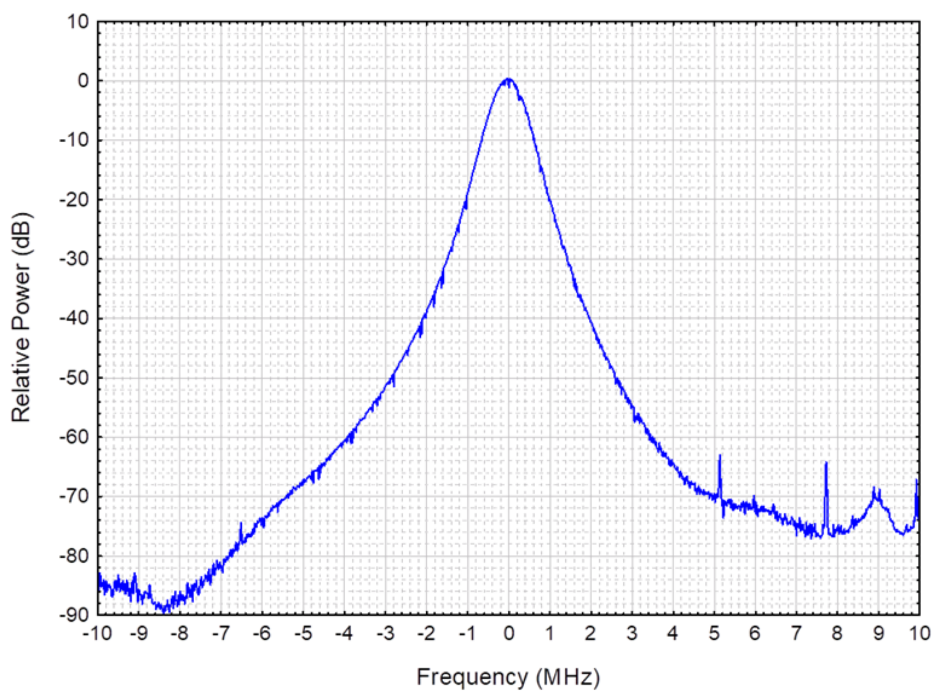

Figure 3-2: Example of a Measured Radar IF Selectivity Curve

When all systems in a channelized band have similar architectures, the overall spectral efficiency of the band (i.e., the number of users that can coexist in the band) can be greatly enhanced by minimizing the 3-, 20-, and 60-dB bandwidths of their IF selectivity curve, while ensuring that their frequency stabilities are adequate. An example of this is the 117.975–136 MHz band for

VHF voice air/ground radio communications. Improvements over the last several decades in the IF selectivities of radios in that band have enabled reductions in channel widths from the original 200 kHz, to 100 kHz, to 50 kHz, to the present 25 kHz, yielding an eightfold increase in the number of available channels within the U.S. and a large (though not necessarily identical) increase in the supportable number of users. A final reduction to 8.33 kHz has been implemented in en route airspace within Europe.

3.2.4 Blocking Threshold

The blocking threshold of a receiver is the maximum ratio, expressed in decibels, by which the strength of an off-channel undesired signal can exceed that of the desired signal at the receiver input without significantly degrading receiver performance. This parameter is sometimes called the off-channel (or adjacent-channel) protection ratio. It is applicable when neither the desired nor the undesired signal is strong enough to drive any of the receiver stages into its nonlinear operating region, in which output ceases to be proportional to input.

3.2.5 Overload Threshold

A receiver's overload threshold is the input signal power level (desired or undesired), in dBm, above which a receiver stage enters gain compression (i.e., becomes nonlinear), thus distorting the signal and degrading receiver performance. The amount by which the overload threshold exceeds receiver sensitivity is called the receiver's dynamic range. Often the threshold is defined as the "LNA 1-dB compression point," which is the received input power level at which the output of the amplifier is 1 dB below what it would have been if the amplifier were still in its linear operating region. Figure 3-3 shows an example from NTIA Report 13-490 in which the overload threshold (at the input to the LNA) is –4 dBm.

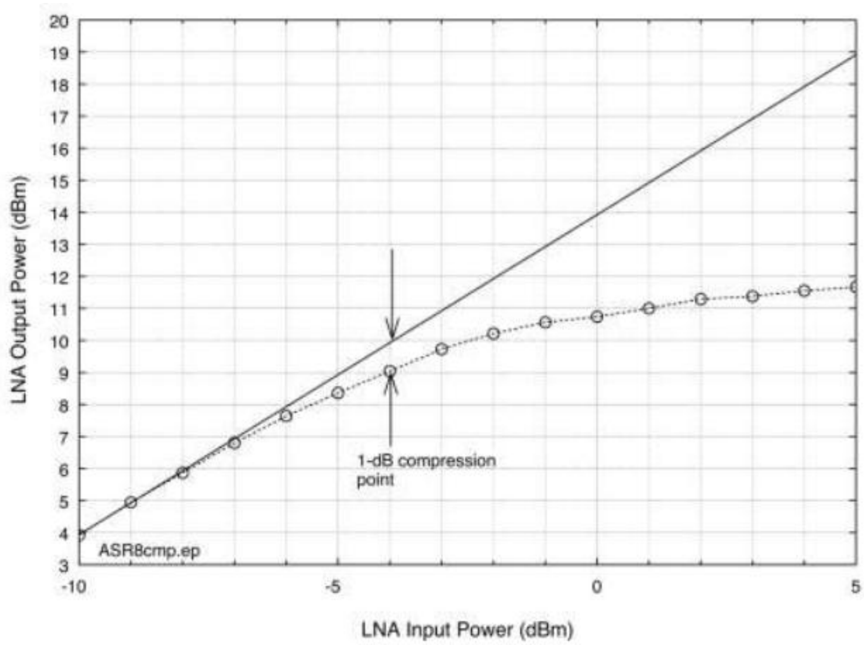

Figure 3-3: Example of Gain-Compression Curve

Note: The definitions of "blocking" and "overloading," and the distinction between the two terms, that are used in this report have been taken from ECC Report 310 [47]. See the illustration on page 25 of that report.

3.2.6 Spurious-Response Attenuation

Spurious-response attenuation is the maximum ratio by which a receiver's desired-signal response exceeds that of the strongest spurious response caused by nonlinear mixing of undesired signals and local-oscillator outputs, thereby causing interference. This form of interference is a vulnerability of superheterodyne receivers. The purpose of heterodyning is to convert the desired incoming RF signal, centered on the carrier frequency f_{RF}, to an IF signal centered on a constant frequency f_{IF}, to simplify subsequent processing. The receiver does this by mixing the RF signal with the output of the receiver's LO at frequency f_{LO} to generate a large number of second-, third-, and higher-order intermodulation products. The receiver's IF bandpass filter attenuates all but the two second-order products at the "beat" frequencies $f_{RF} – f_{LO}$ and $f_{LO} – f_{RF}$, respectively.

An image response is a special case of a superheterodyne receiver's spurious responses, and potentially the most important one because the IF bandpass filter provides no protection against it. The receiver is designed so that one of the second-order products ($f_{RF} – f_{LO}$ or $f_{LO} – f_{RF}$) is the intermediate frequency f_{IF} to which an incoming signal at the frequency f_{RF} is to be converted. However, the other second-order product makes the receiver vulnerable to an undesired signal at the "image frequency" f_{IMG} that is $2f_{IF}$ above (or below) the desired frequency f_{DES} (and on the other side of f_{LO} from f_{DES}). For example, if $f_{IF} = f_{DES} – f_{LO}$, then it will also be true that $f_{IF} = f_{LO} – f_{IMG}$, which means that the image frequency f_{IMG} will be $2f_{IF}$ below desired frequency f_{DES}, and the receiver will be vulnerable to any undesired signal that happens to arrive at that image frequency. (See the example in Figure 3-4.) Designers of superheterodyne receivers must take care to ensure that for every possible value of the desired frequency, the corresponding image-frequency response will be well attenuated.

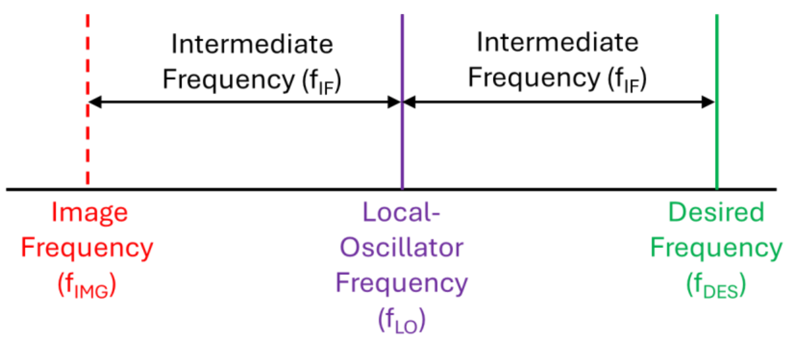

Figure 3-4: Example of Desired, Local-Oscillator, Intermediate, and Image Frequencies

3.2.7 Intermodulation Rejection

Intermodulation (IM) rejection is the minimum amount (in dB) by which the received strength of two undesired RF signals can exceed the sensitivity of the receiver without their intermodulation products (IMPs), formed in the receiver's mixer(s), unacceptably degrading the performance of the receiver. An example of third-order IMPs generated by two intermodulating input signals appears in Figure 3-5.

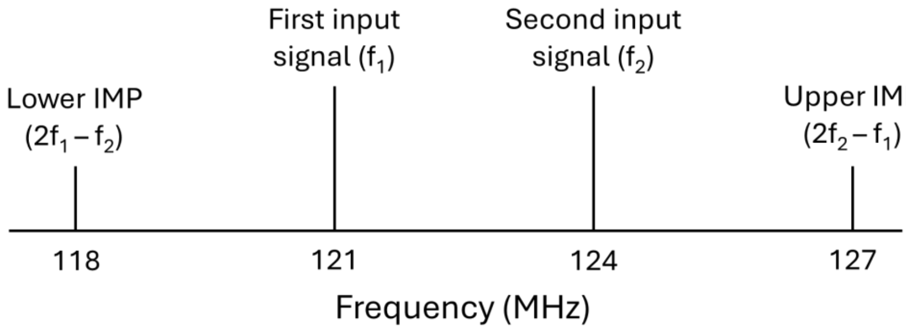

Figure 3-5: Example of Intermodulation Products

3.2.8 Spurious-Emission Limit

The local oscillator(s) of a receiver generate sinusoidal waveforms that may be unintentionally radiated as spurious emissions. Many receiver standards stipulate the maximum undesired power (in dBm) of such emissions that the receiver may create at any frequency or combination of frequencies.

3.2.9 Frequency Stability

The frequency stability of a receiver should be consistent with that of the transmitter whose signal it is intended to receive, with an allowance for worst-case Doppler shift between the two radios. This requirement, however, is seldom explicitly stated in receiver standards.

3.2.10 Pulsed Waveform Discrimination

Some pulsed-radar receivers are able to use signal processing to discriminate against undesired pulsed signals by suppressing asynchronous and/or incoherent pulse trains. (This desirable feature is not always explicitly stipulated in radar standardization documents.) To help ensure that pulse trains of neighboring radars are asynchronous, some radars have adjustable or selectable pulse repetition rates (PRRs).

3.3 U.S. Government Standards and Regulations

Office of Management and Budget (OMB) Circular A-119, in accordance with Section 12(d) of Public Law 104-113 (the National Technology Transfer and Advancement Act of 1995) directs agencies to use voluntary consensus standards in lieu of government-unique standards except where that would be inconsistent with law or otherwise impractical. It also provides guidance for agencies participating in voluntary consensus standards bodies and describes procedures for satisfying the reporting requirements in the Act. The policies in the Circular are intended to reduce to a minimum the reliance by agencies on government-unique standards.

U.S. government agencies that issue standards for and regulations governing RF equipment include NTIA, FCC, FAA, National Oceanic and Atmospheric Administration (NOAA), and DoD.

3.3.1 NTIA

Most of the NTIA documents referenced in Appendix B are extracts from the NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management. Those have been incorporated by reference within 47 CFR in accordance with 47 CFR 300.1. They are sections of the Manual with receiver performance standards applicable to federal government systems, and are summarized in Appendix A to NTIA's response to the FCC's April 2022 Notice of Inquiry (See: https://www.fcc.gov/ecfs/search/search-filings/filing/1062896294033). The following requirements are quantified in that appendix:

- Selectivity, intermodulation, and spurious-response rules for federal VHF land-mobile radios near the Mexican border.
- Selectivity of federal high-frequency (2–29.7 MHz) radios.
- Selectivity, spurious-response, and noise-figure rules for federal Ultrahigh Frequency (UHF) and Superhigh Frequency (SHF) fixed point-to-point radio links.
- Adjacent-channel, spurious-response, and intermodulation rejection requirements for federal fixed, mobile, and portable VHF and UHF radios.
- Adjacent-channel, spurious-response, and intermodulation rejection requirements for federal fixed and mobile narrowband VHF and UHF radios.
- Adjacent-channel, spurious-response, and intermodulation rejection requirements for federal fixed and mobile digital 6.25-kHz-channel VHF and UHF radios.
- Selectivity, spurious-response, and frequency-stability requirements for receivers of federal Criteria A, B, and C radars.
- Selectivity, spurious-response, frequency-stability, and asynchronous-pulse-suppression requirements for receivers of federal fixed 2.7–2.9 GHz Criteria D radars.
- Selectivity, spurious-response, and incoherent-pulse-suppression requirements for receivers of federal 449-MHz Criteria E wind-profiler radars (WPRs).

The NTIA radar selectivity requirements noted above, which are part of NTIA's Radar Spectrum Engineering Criteria (RSEC), are mostly expressed as limits on the ratio of each radar's 3-dB RF bandwidth to its 3-dB IF bandwidth, and of its 3-dB IF bandwidth to its 3-dB emission bandwidth. The exception is for WPRs, whose 3- and 60-dB receiver bandwidths NTIA says must be "commensurate" with the corresponding emission bandwidths. NTIA has updated the RSEC receiver selectivity requirements using the sound method of examining actual Federal receiver performance data and incrementally requiring higher selectivity for new system procurements based upon the level of performance achieved by the majority of fielded equipment.

The NTIA Manual additionally includes antenna standards (within Section 5.3.3.3), that are intended to minimize interference in certain bands by ensuring appropriate antenna directivity.

Two other NTIA documents are test reports on radar susceptibility to RFI. NTIA Report 13-490 presents detailed measured selectivity curves and gain-compression curves for various radars that use the 2.7–2.9 GHz band. Those radars are ASR-8, -9, and -11 airport surveillance radars, and WSR-88D (NEXRAD) weather radars. NTIA Report TR-06-444 presents measured blocking thresholds for a wide variety of radars (long- and short-range air search, fixed and airborne meteorological, and maritime) exposed to various types of interfering signals.

An unnumbered "Cellular Device Test Report" on NTIA's website reports results of 2011–2012 testing of the vulnerability of GPS receivers to the transmissions of cellular telephones, including LightSquared (since renamed Ligado) devices.

3.3.2 FCC

The FCC's technical requirements for RF emitters and receivers are contained in Title 47 of the Code of Federal Regulations. Appendix B summarizes the 47 CFR entries most pertinent to receiver EMC requirements, covering a wide range of service domains from aviation, maritime, and the Citizen's Broadband Radio Service, to cable television. Characteristics often regulated by these entries include sensitivity, blocking thresholds, and intermodulation rejection ratios.

The FCC rules additionally include antenna requirements (e.g., within 47 CFR 101.115 for fixed microwave systems), that are intended to minimize interference in certain bands by ensuring appropriate antenna directivity

3.3.3 FAA

The FAA's most important single source of information on receiver EMC parameters is its Spectrum Management Regulations and Procedures Manual, FAA Order 6050.32B [25]. That document contains considerable information on the sensitivity, CCPR, selectivity, and adjacent-channel rejection of various aviation communications, navigation, and surveillance systems managed by the FAA. Those systems include the VHF/UHF air/ground radio system for air traffic services, ILS, VOR, Distance Measuring Equipment (DME), and many others.

The FAA has also issued many Technical Standard Orders (TSOs), each governing the use and spectrum management of a specific RF system developed for aviation. Those TSOs are not listed in Appendix B, but they often refer to EMC characteristics provided in technical documents, developed by industry groups such as RTCA, that are referenced in that appendix.

One unnumbered FAA document is also listed in Appendix B. Published in 2012, it addresses the question of LightSquared (now Ligado) compatibility with GPS.

3.3.4 NOAA

NOAA has published the receiver characteristics, including receiver selectivity and dynamic range, of its WSR-88D (NEXRAD) weather radars publicly on its website [51].

NOAA also recommends, but does not require, that users of its Weather Radio broadcasts choose receivers developed following CTA 2009-B-2010, Performance Specification for Public Alert Receivers [52] [53], a standard developed by the Consumer Technology Association in conjunction with the National Weather Service.

3.3.5 DoD

Two main standards are used by the DoD for implementing regulations on receivers, MIL-STD-461 [54] and MIL-STD-188 [55] [56]. MIL-STD-461, initially released in 1967, specifies the requirements and verification methods for electromagnetic interference and EMC in all active DoD platforms [57].

MIL-STD-188 is a series of technical standards that define the interoperability and performance objectives for all DoD tactical communication systems including radios in the Medium Frequency, High Frequency, and satellite Earth Terminals in the SHF bands.

MIL-STD-188-141 establishes both technical requirements and design objectives to "a level of performance … that is considered necessary to satisfy the requirements of the majority of users" [58]. Guidance and design objectives are provided for most of the key performance criteria outlined in Section 3.2. This Interface Standard could be considered an example of a well implemented set of requirements for the tactical radio subgroup of receivers.

3.4 International Regulations and Standards

International bodies that establish regulations, standards, and methodologies for compatibility and coexistence of RF systems include the ITU Radiocommunication Sector (ITU-R), ICAO, ECC/CEPT, the International Electrotechnical Committee (IEC), and IEC's International Special Committee on Radio Interference (CISPR).

3.4.1 ITU-R

ITU-R, a specialized agency of the United Nations, is the leading international spectrum organization and the publisher of the worldwide Radio Regulations that are updated after each World Radiocommunication Conference (WRC), as well as a large number of spectrum-related reports and recommendations. It has traditionally focused on regulating interference mainly by stipulating the transmitter EMC characteristics such as power flux densities, with relatively little attention paid to receiver parameters. A major exception is Recommendation ITU-R SM.332-4, "Selectivity of receivers," published in 1978. That document recommends that "the bandwidth of the *receiver* [italics added] shall be no wider than is essential for the transmission of the necessary modulation of the wanted signal without significant distortion". It also says that in determining that bandwidth, account must be taken of CCPR, blocking, spurious responses, and intermodulation, which should be considered in computing "effective selectivity." It gives specific advice for dealing with amplitude-, frequency-, and phase-modulated signals, but not the more modern modulation types and multiple-access schemes that have become increasingly common since 1978.

Nine other ITU-R documents are referenced in Appendix B. One is Recommendation ITU-R M.2013, "Non-ICAO 1-GHz ARNS systems," published in 2012, which among other things shows the great variation in selectivity among various classes of tactical air navigation system receivers. Another is Recommendation ITU-R Rec. M.2059, which discusses technical characteristics of different kinds of 4.2–4.4 GHz radar altimeters, including sensitivity, selectivity, blocking, and overloading. The remaining seven documents are band studies that address the sensitivity and selectivity, and (sometimes) blocking and spurious-response characteristics of radars and navigational equipment operating in particular frequency bands. Most of those band studies consider selectivity only to the 3-dB point, although one study (Report ITU-R M.2205) shows the selectivity of some 960–1164 MHz equipment out to their 60- or 70-dB points.

3.4.2 ICAO

ICAO is another agency of the United Nations. It has published a multi-volume set of International Standards and Recommended Practices (SARPS), "Aeronautical

Telecommunications," as Annex 10 to the International Convention on International Civil Aviation. Among many other things, Annex 10 defines EMC standards for receivers of many types of aeronautical navigation and communications systems. The systems include ILS, VOR, DME, and VHF air/ground radio. The specified receiver EMC characteristics include sensitivity, CCPR, selectivity, blocking, overload, intermodulation, and receiver spurious emissions. However, Annex 10 does not specify every one of those receiver characteristics for all the RF systems it covers.

3.4.3 ECC

Prior work by ECC on the subject of receiver resiliency is summarized in Section 2.4.3 of this report.

3.4.4 International Electrotechnical Commission (IEC)

IEC is a not-for-profit, non-governmental organization that publishes consensus-based international standards for electrotechnology (i.e., electrical and electronic products, systems, and services). Publications serve as a basis for national standardization and as references when drafting international contracts.

3.4.4.1 International Special Committee on Radio Interference (CISPR)

CISPR is a part of the IEC that sets standards for controlling electromagnetic interference in electrical and electronic devices. It comprises six subcommittees, of which one (subcommittee I) deals with EMC of information technology equipment, multimedia equipment, and receivers. One of its receiver-related standards (published in 2020) is CISPR/TR 29, on "Television broadcast receivers and associated equipment, their immunity characteristics, and methods of objective picture assessment."

3.5 Industry Standards

EMC-related industry standards and guidelines are published by several organizations, including the Alliance for Telecommunications Industry Solutions (ATIS), the Third-Generation (3G) Partnership Project (3GPP), the European Telecommunications Standards Institute (ETSI), RTCA, the Radio Technical Commission for Maritime Services (RTCM), the Telecommunications Industry Association (TIA), and the Advanced Television Standards Committee (ATSC).

3.5.1 ATIS

ATIS is a U.S.-based standards organization that develops technical and operational standards and solutions for the information and communications technology (ICT) industry. It has more than 160 member companies, including telecommunications service providers and equipment manufacturers, and vendors. Its many committees also deal with topics such as AI-enabled networking, distributed ledger technology, non-terrestrial networks, cybersecurity, network reliability, and system interoperability.

ATIS is one of seven organizations that cooperate to develop standards for 3GPP. All of the 3GPP standards can be purchased directly from ATIS, but the ATIS website advises that each of those standards can (and ordinarily should) be downloaded for free from 3GPP with the same technical content and no significant difference except for the title page. (The same 3GPP standards can also be downloaded under similar conditions from ETSI.)

3.5.2 3GPP

3GPP is an association of seven standards organizations (two of which are ATIS and ETSI) that develop standards for 3G, Fourth-Generation (4G), and Fifth-Generation (5G) mobile broadband communications. Many of those standards include specifications for (among other things) EMC-related receiver performance, including requirements for important EMC-related receiver parameters such as sensitivity, in-channel selectivity, adjacent-channel selectivity, in-band blocking, out-of-band blocking, spurious-response limits, intermodulation rejection, and spurious-emission limits. However, few if any 3GPP standards deal solely with receivers; transmitter specifications and overall system considerations are generally included as well. But our focus here is on the portions of those standards that are related to receiver resiliency to RFI.

3GPP's standards for 3G and beyond are grouped into eighteen series numbered 21 through 38, of which 38 is the most recent. The standards in series 36 and 38 may be considered reasonably indicative of the current state of the art in 4G and 5G cellular radio technology. Series 36 deals with LTE (Evolved Universal Terrestrial Radio Access (E-UTRA)), LTE-Advanced, and LTE-Advanced Pro radio technology. Series 38 covers radio technology beyond LTE, most notably 5G New Radio (NR).

3.5.2.1 5G Standards

Dozens of Series 38 3GPP technical specifications (TSs) describe 5G requirements in detail. Key standards that address EMC-related 5G receiver requirements are:

- TS 38.101-1 V18.7.0 (2024-09), Group Radio Access Network (RAN), NR, User Equipment (UE) radio transmission and reception, Part 1: Range 1 Standalone
- TS 38.101-4 V18.5.0 (2024-09), NR, UE Radio Transmission and Reception; Part 4: Performance Requirements
- TS 38.104 V18.7.0 (2024-09), Group RAN, NR Base Station (BS) radio transmission and reception
- TS 38.106 V18.6.0 (2024-09), Group RAN, NR, NR repeater radio transmission and reception
- TS 38.141-2 V18.7.0 (2024-09), NR, Base Station Conformance Testing, Part 2: Radiated Conformance Testing
- TS 38.521-1,2,3 V18.4.0 (2024-09) NR, User Equipment (UE) Conformance Specification, Radio Transmission and Reception, Parts 1, 2, and 3: Ranges 1, 2, and 3 Standalone

3.5.2.1.1 TS 38.101-1 (NR UE)

TS 38.101-1 defines 5G NR UE requirements for receiver sensitivity, selectivity, blocking thresholds, intermodulation rejection, spurious-response attenuation, and spurious-emission limits.

Sensitivity: This standard specifies reference sensitivity power level as the minimum mean desired-signal power applied to each of the UE antenna ports for all UE categories, at which the throughput shall be at least 95% of the required value for the specified reference measurement channel. The sensitivity value depends on a wide variety of UE parameters, including the operating band, subcarrier spacing (SCS), channel width, network configuration (supplemental downlink (SDL) or other), duplex mode (FDD or time-division duplex (TDD)), use or nonuse of transmitter diversity, number of receiver antenna ports, whether or not the mode of operation is vehicle-to-everything (V2X), and whether or not carrier aggregation (CA) is used (and if so, whether the CA is intraband contiguous, intraband noncontiguous, or interband).

Selectivity: The standard also specifies required adjacent-channel selectivity (the ratio of filter-attenuation values to signals on undesired and desired frequencies) as a function of the receiver's operating-band limits, channel bandwidth, SCS, interference power and bandwidth, CA type used, and mode of operation (e.g., V2X or air-to-ground (ATG)).

Blocking: TS 38.101-1 specifies in-band and out-of-band blocking thresholds. The blocking threshold, i.e., the maximum allowable undesired power level, is the receiver's reference sensitivity plus an amount that depends on the receiver's operating-band limits, its channel bandwidth, the interferer's channel bandwidth, and frequency offset. If a CW interfering signal is not more than 15 MHz outside the UE receive band, the potential problem is considered in-band blocking; otherwise, it is out-of-band blocking and different threshold values apply. The blocking thresholds also depend on whether CA is used, and if so, which type; whether uplink (UL) multiple-input, multiple-output (MIMO) antennas are employed; and whether the UE is being used for V2X or ATG operation.

Spurious responses: The document specifies spurious-response limits as dependent on several factors, including the receiver's reference sensitivity, band limits, channel bandwidth, and types of CA and MIMO (if any); and whether the UE is used for V2X

Intermodulation: TS 38.101-1 specifies required intermodulation rejection for various sets of receiver parameters in situations involving wideband IM (where two modulated NR signals mx to produce an IM product (IMP)), and/or use of the NR for V2X, ATG, or certain other modes of operation.

Spurious emissions: TS 38.101-1 specifies receiver spurious-emission limits for various situations, including cases involving inter-band CA or ATG.

3.5.2.1.2 TS 38.101-4 (NR UE EMC)

TS 38.101-4 specifies additional performance requirements for 5G NR UEs operating in both FR1 (sub-6 GHz) and FR2 (millimeter-wave (MMW)) bands. It complements TS 38.101-1 by adding performance benchmarks for higher bandwidths and coexistence scenarios under network loading conditions.

EMC Thresholds: This standard defines spurious emission and receiver blocking thresholds, which are especially critical in high-frequency bands to ensure the device does not interfere with nearby channels and can reject interference effectively.

Blocking Requirements: TS 38.101-4 expands on blocking and adjacent-channel performance to ensure devices can operate efficiently without degradation in dense urban and rural deployment scenarios.

3.5.2.1.3 TS 38.104 (NR BS)

TS 38-104 separately specifies two types of receiver EMC requirements for 5G NR BSs: conducted characteristics and radiated (over-the-air (OTA)) characteristics. In general, the kinds of parameters to be measured are the same for both types, but are measured at different test points.

Sensitivity: This standard specifies reference sensitivity power level as a function of BS type (wide-area, medium-range, local-area, and home), BS channel bandwidth, and SCS.

Selectivity: The standard specifies in-channel selectivity (ICS) as a measure of the receiver's ability to receive a wanted signal at its assigned resource-block locations in the presence of an interfering signal received at a larger power spectral density in the same channel. Maximum acceptable values of received undesired-signal power are stipulated as a function of BS type, E-UTRA channel bandwidth, and interfering-signal bandwidth. The standard also specifies adjacent-channel selectivity as a function of the same variables, as well as frequency offset.

Blocking thresholds: The document specifies thresholds for in-band and out-of-band blocking as a function of BS type, mean desired-signal power, interfering-signal type and bandwidth, and whether or not the BS is collocated with other BSs using other frequency bands.

Other parameters: TS 38.104 specifies spurious-emission limits as a function of operating frequency range and measurement bandwidth. It specifies receiver IM rejection for each of the four BS types, the type of interfering signal, and the power levels of the desired and interfering signals.

3.5.2.1.4 TS 38.106 (NR Repeater)

TS 38.106 specifies conducted and radiated (OTA) receiver EMC characteristics for repeaters, including reference sensitivity levels, adjacent-channel rejection ratios, blocking characteristics, maximum input power levels, receiver intermodulation, and receiver spurious emissions.

3.5.2.1.5 TS 38.141-2 (NR BS Radiated Conformance Testing)

TS 38.141-2 covers the radiated testing requirements for 5G NR base stations operating in FR1 and FR2. Radiated testing is critical for MMW frequencies, where beamforming and directional antennas are used.

Radiated EMC Testing: Specifies how to test radiated emissions, spurious emissions, and blocking under radiated conditions. This includes ensuring the base station's antennas and beamforming units meet EMC requirements.

OTA Requirements: Defines OTA testing standards for assessing performance and interference resilience in real-world conditions, especially for 5G base stations with massive MIMO and beamforming capabilities.

3.5.2.1.6 TS 38.521-1,2,3 (NR UE Conformance)

TS 38.521 Parts 1, 2, and 3 define the conformance requirements for 5G NR UEs operating in various bands and scenarios. Part 1 addresses conformance for FR1 devices, covering conducted RF testing for emission and interference limits. Part 2 covers FR2 devices, specifically addressing conducted tests in mmWave bands. Part 3 focuses on radiated testing, including spurious emissions, receiver blocking, and adjacent channel selectivity in FR1 and FR2. It specifies limits for adjacent channel leakage, spurious emissions, and blocking to ensure that devices will perform effectively in complex RF environments.

3.5.2.2 LTE Standards

Key LTE-related standards in Series 36 include:

- TS 36.101, E-UTRA UE radio transmission and reception. In many ways this is the E-UTRA counterpart of TS 38.101-1. It defines E-UTRA UE requirements for receiver sensitivity, selectivity, blocking thresholds, intermodulation rejection, spurious-response attenuation, and spurious-emission limits. Separate sets of required values are specified for many different combinations of UE operating band, channel width, duplex type, carrier aggregation, mode of operation, and other independent variables.
- TS 36.102, E-UTRA UE radio transmission and reception for satellite access. This document addresses the same types of EMC-related receiver parameters as TS 36.101, but in situations where satellite access is a consideration.
- TS 36.104, E-UTRA BS radio transmission and reception. This standard specifies E-UTRA base-station receiver parameters similar to those treated for UEs in TW 36.101.
- TS 36.106, E-UTRA frequency-division duplex (FDD) repeater radio transmission and reception (59 pages). This document addresses selectivity, intermodulation-rejection, and spurious-emission requirements for the receivers of E-UTRA FDD repeaters.
- TS 36.108, E-UTRA Satellite Access Node radio transmission and reception (67 pages). This defines sensitivity, selectivity, blocking, intermodulation-rejection, and spurious-emission requirements for E-UTRA satellite access nodes.

3.5.3 ETSI

ETSI is a prolific publisher of publicly available standards that include requirements for EMC-related RF receiver parameters. This may result in part from the European Parliament's 2014 issuance of Directive 2014/53/EU on the harmonization of radio equipment within the European Union [59]. That mandate, referred to as the Radio Equipment Directive (RED), placed new emphasis on the need for receiver EMC in Clause 11, which said that "Although receivers do not themselves cause harmful interference, reception capabilities are an increasingly important factor in ensuring the efficient use of radio spectrum by way of an increased resilience of receivers against harmful interference and unwanted signals."

A catalog of ETSI standards for RF systems is available at https://www.etsi.org/standards-search#Wireless%20Systems. Several dozens of those standards include EMC requirements for receivers within those systems. These ETSI standards, most of which are subtitled "Harmonized Standard for access to radio spectrum," constitute nearly half of all the standards referenced Appendix B of this report. A breakdown of RF device types addressed by the referenced ETSI standards appears in Table 3-1.

Table 3-1: RF System Types Covered in ETSI Standards Referenced in Appendix B

RF System Type	Number of Standards
Broadband Networks	6
Broadcasting	6
Fixed Communications	7
Miscellaneous	11

Mobile, Cellular	11
Mobile, Noncellular	11
Navigation	4
Radar	8
Satellite Communications	5
Ultrawideband	5

Each of the 74 referenced ETSI standards discusses, or specifies required values of, at least one of the EMC-related receiver parameters identified in Section 3.2 of this report. Table 3-2 shows how many ETSI documents address each parameter.

Table 3-2: Receiver Parameters Addressed in ETSI Standards Listed in Appendix B

Receiver EMC Parameter	Listed ETSI Documents Addressing the Parameter
Sensitivity	47
CCPR	13
Selectivity	54
Blocking Threshold	60
Overload Threshold	22
Spurious-Response Attenuation	19
Intermodulation Rejection	27
Receiver Spurious Emission Limit	47

3.5.3.1 ETSI Selectivity Requirements

Fifty-four of the 75 ETSI standards address receiver selectivity. Fifty-three of those stipulate receiver selectivity requirements for specific classes of systems. However, the ETSI treatment of that critically important parameter varies greatly from system to system.

- Thirty-six of the ETSI standards specify minimum required attenuation only for the first adjacent channels (i.e., the two channels immediately above and below the desired channel).
- Two of the standards specify attenuation requirements for the first and second adjacent channels above and below the desired channel.
- Six standards specify attenuation requirements for the first, second, and third adjacent channels above and below the desired channel.
- Two standards (one for 1030/1090-MHz surface multilateration equipment, and the other for secondary surveillance radar interrogators) stipulate “stairstep” curves of required attenuations versus frequency offset without regard to channelization.

Seven of the ETSI standards, all of which are for primary radars, mandate detailed selectivity masks for the radar receivers. The radar types concerned are:

- 2.7–2.9 GHz meteorological radars

- 2.7–3.1 GHz primary air-traffic-control (ATC) radars
- 5.25–5.85 MHz meteorological radars
- 8.5–10 GHz primary ATC radars
- 8.5–10 GHz coastal and harbor radars
- 9.3–9.5 GHz meteorological radars

An unusual feature of those seven ETSI radar-receiver masks is that none of them stipulate any receiver selectivity requirements within (B_{-40} / 2) MHz of the radar's tuned frequency, where B_{-40} is the 40-dB emission bandwidth of the radar transmitter. For example, EN 303 347-1, the ETSI standard for 2.7–2.9 GHz meteorological radars, stipulates the receiver mask shown in Table 3-3 and Figure 3-6 (on condition that the peak received undesired-signal power does not exceed –30 dBm).

Table 3-3: ETSI Receiver Mask for 2.7–2.9 GHz Meteorological Radars

Absolute Value (MHz) of Undesired Carrier's Frequency Offset (Δf) from Radar's Carrier Frequency	Maximum Allowable Value (dB) of Received Signal Relative to Value at Radar Carrier Frequency	Mask Slope (dB / decade)
0 to $0.5B_{-40}$	Unspecified	Unspecified
$0.5B_{-40}$	–40	–∞
$0.5B_{-40}$ to $5B_{-40}$	–40 to –70	–30
$5B_{-40}$ to $10.8B_{-40}$	–70 to –90	–60
> $10.8B_{-40}$	–90	0

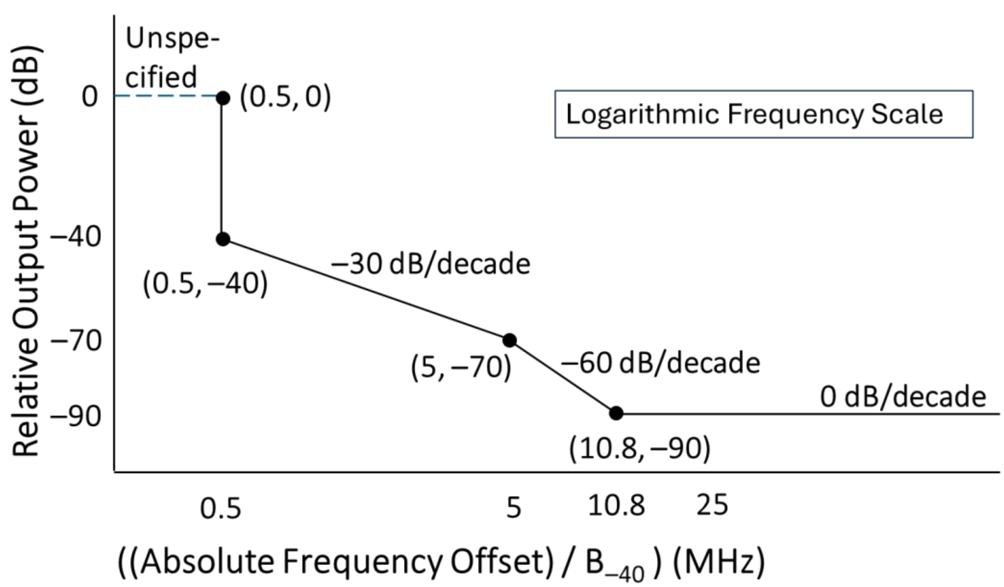

Figure 3-6: ETSI Receiver Mask for 2.7–2.9 GHz Meteorological Radars

As the above figure and table show, the ETSI standard mandates a “selectivity floor” of 90 dB for 2.7–2.9 GHz meteorological radars. But if the peak undesired-signal power entering the receiver exceeds –30 dBm, the mask changes as discussed in the standard.

Another example is taken from EN 303 364-2, the ETSI standard for 2.7–3.1 GHz primary ATC radars, which stipulates for those radars the much simpler (and considerably less stringent) receiver selectivity curve shown in Figure 3-7. Here, the relative output power of the interfering signal is allowed to bottom out at –60 dB instead of the –90 dB mandated for the meteorological radars of Figure 3-7. ETSI gives no reason for the difference.

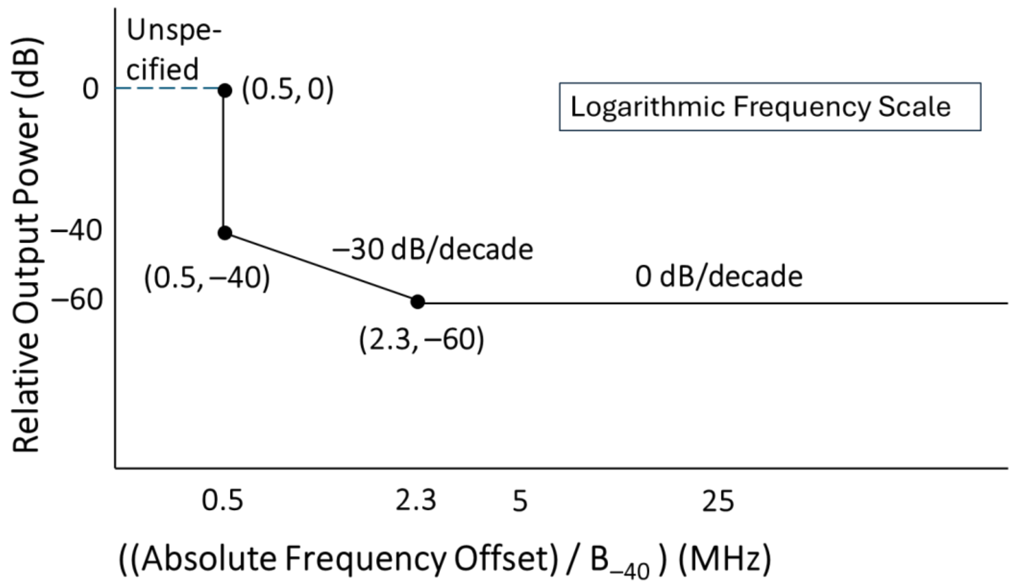

Figure 3-7: ETSI Receiver Mask for 2.7–3.1 GHz ATC Radars

In short, the ETSI standards address the crucial parameter of receiver selectivity much more thoroughly for the seven primary radar systems and the two 1030/1090-MHz systems than for any other system classes. Selectivity of the other system classes is considered only to the first adjacent channels and (sometimes) out to the second and/or third adjacent channels.

3.5.4 RTCA

RTCA develops and maintains standards for electronic systems used in aviation for communications, navigation, and surveillance (CNS). In Appendix B we have identified 14 RTCA products that are relevant to the resiliency of CNS receivers to interference. Two are especially relevant. One is DO-229F, dated 2020, which describes the expected interference environment and specifies the in-band and out-of-band frequency selectivity of airborne receivers of the GPS Satellite-Based Augmentation System. Another is DO-253C, published in 2008, which specifies CCPRs, adjacent-channel rejection values, and out-of-band interference rejection factors for airborne receivers of the GPS Local Area Augmentation System.

Some RTCA standards are jointly published with EUROCAE, a similar standards organization chartered by the European Union.

3.5.5 RTCM

RTCM publishes globally accepted standards for maritime navigation and communications equipment, land and maritime distress alerting services, distress alerting devices, and differential global navigation satellite systems (DGNSS). Their publications include RTCM 11701.0 (Standard for Installed Maritime VHF Radiotelephone Equipment Operating in High Level Electromagnetic Environments) and RTCM 13500.1 (Radio Layer for Real-Time DGNSS Applications).

3.5.6 Telecommunications Industry Association

The Telecommunications Industry Association (TIA), in conjunction with the Electronic Industries Association (EIA), publishes recommended standards designed to serve the public interest through eliminating misunderstandings between manufacturers and purchasers, facilitating interchangeability and improvement of products, and assisting purchasers in selecting and obtaining with minimum delay, the proper products for their particular needs. TIA is accredited by the American National Standards Institute (ANSI) as a standards developing organization. Adherence to their standards, which is very widespread, is entirely voluntary. The receiver standards adopted by NTIA for land mobile systems are based on TIA/EIA standards. Annex M of the NTIA Manual also references the TIA standards for a limited set of receiver measurement methods.

TIA is the publisher of TIA-603-E, "Land Mobile FM or PM [phase-modulated] Communications Equipment Measurement and Performance Standards," a substantial part of which specifies receiver sensitivity, adjacent-channel rejection, selectivity, spurious-response rejection, IM rejection, and spurious-emission limits. The equipment specified is private (dispatch) land-mobile radios operating at frequencies of one gigahertz or less.

3.5.7 Advanced Television Standards Committee

The Advanced Television Standards Committee develops technical performance standards for digital television. In 2010 it issued document A/74:2010, a set of guidelines for designing digital television receivers with regard to sensitivity, CCPR, selectivity, spurious responses ("taboo channels"), IM rejection, and maximum spurious output power,

3.6 Effectiveness of Standards and Regulations

Unfortunately, the existence of receiver standards and regulations does not preclude spectrum management issues. For example, in the GPS/Ligado issue (see Section 2.3.2) the FCC conditionally authorized a terrestrial 4G network in January 2011 [60] that was later determined to have transmission characteristics that would have resulted in massive levels of interference to aviation GPS receivers built to RTCA standard DO-229 first published in 1996 [61]. The FAA has invoked DO-229 in avionics certification guidance since 1998, and harmonized aviation receiver interference requirements have been included in international standards maintained by the ICAO since 2001. Whereas the FCC's 2011 conditional approval of this terrestrial network would have permitted 32 dBW (~1.6 kW) base stations operating in the 1526–1536 MHz and 1545–1555 MHz bands just below the GPS Link 1 (L1) center frequency of 1575.42 MHz, to mitigate concerns of interference from this terrestrial network to aeronautical and other GPS receivers, the FCC later provided final authorization of the network in April 2020 [28] limiting base station operation to just the lower 1526–1536 MHz band and with a maximum radiated power limit of only 9.8 dBW (~10 W).

For receiver standards to be maximally effective to avoid receiver performance issues, the following circumstances are required:

- Regulatory authorities must recognize the standard either formally or at least to the extent that they agree to utilize the standard in establishing coexistence requirements between services. This could further be realized by incorporating standards documents by reference within regulations, although this solution can present legal issues. See, e.g., https://docs.fcc.gov/public/attachments/FCC-23-14A1.pdf.
- The standard must include requirements relevant to the applicable interference characteristics. It is not practical for a standard to include requirements for receiver performance in the presence of a multitude of types of interference. So, often, standards will only include requirements for receiver performance in the presence of a simple interference type (e.g., continuous wave) or an expected interference type (e.g., 4G/LTE with a specified bandwidth). It happens quite frequently that the expected adjacent-band interference characteristics evolve with time and the interference characteristic that a standard includes requirements to address no longer applies. For instance, as discussed in Section 2.3.1, the issue of FM broadcasting interference to aeronautical systems was addressed years ago through the development of standards requiring receivers to be able to meet performance requirements in the presence of FM broadcasting signals. As noted in Section 2.3.1, the FM broadcast signals are evolving and the aviation community is now concerned that proposed new signal characteristics may not be compatible with receivers built to existing standards.
- All the receivers operating within an allocated band for which protection is to be afforded must be built to one or more standards. Many bands are shared by different classes of receivers, some of which may be built to standards and others not. For example, many receivers are fielded today to process GPS and other satellite navigation signals in the 1559–1610 MHz RNSS band. Only a relatively small subset of these receivers are used on board aircraft and built to aviation standards such as those developed by RTCA domestically (and invoked by the FAA) and ICAO internationally. The remaining receivers are used for many different applications including recreational use (running, bicycling, hiking), navigation/tracking of other vehicles (ships, automobiles, spacecraft), surveying, machine control, precision timing, military, and scientific. Many of these other receivers are not built to any standard. Protection of the certified aviation receivers would not necessarily protect all of the other classes of receivers within this band.
- Transmitter-to-receiver coupling scenarios must be established and agreed upon by all parties including:
    - The minimum distance between transmitters and receivers. This parameter is often a topic of dispute between parties especially when mobile services are involved. How close to a cell tower should a drone be expected to operate? How close can a mobile device get to a transmitter or receiver in the same automobile? These are difficult questions to answer definitively and often best answered on a band-by-band, service-by-service basis.

- An appropriate propagation model. The choice of propagation model is also a frequent subject of debate. For maximum protection of receivers, the free-space propagation model is often favored. Although for some scenarios, less-than-free-space propagation losses can occur (e.g., due to constructive interference of multiple paths followed by the transmitted signal due to a reflective surface) and may be more appropriate for protecting extremely critical receivers. Advocates of new services often note that transmitted signals are likely to be attenuated by human bodies, buildings, foliage, terrain, etc., and thus propagation models that predict far greater attenuation than free-space path loss are more appropriate.
- The antenna gain of the transmitter toward the receiver. This assumption is also more difficult to establish for mobile services and considering new technologies such as the multiple-input multiple-output (MIMO) adaptive antennas used for 4G/5G cellular and other services.
- Aggregation effects, which may need to be considered when a receiver may simultaneously receive unwanted emissions from multiple transmitters.
- Safety margins, which are often warranted for the protection of some critical radio services such as aeronautical navigation (see, e.g., [62]).

4 Testing and Certification

4.1 Overview

In the last section, we discussed how receivers can be specified for a given level of performance. In this section, we discuss how– given a performance specification– receivers can be assessed for their *conformance* to that specification. Conformance testing of receivers is an important aspect of effective spectrum management; the extent to which a receiver can consume spectrum efficiently is ultimately measured by its realized performance, not its specification. The material in this section will highlight that conformance testing procedures are not standardized in either federal or non-federal domains. NTIA's spectrum certification process (4.2.1), for example, requires detailed assessments of receiver characteristics at various stages of system development, while the FAA (4.2.3.1) and DoD (4.2.3.2) have their own certification processes that include specific receiver performance requirements. In private industry (4.2.4), independent certification bodies like IEEE ICAP, GCF, and PTCRB may help ensure that receivers conform to industry standards through defining rigorous testing protocols. In situations where no defined standards exist (4.3), a methodical approach wherein representative transmitters and receivers are selected for EMC analysis may instead be necessary.

In our discussion of the FCC’s Equipment Authorization procedure (4.2.2), we note that type acceptance rules for transmitters have a dynamic range of 50 to 60 dB, which likely was sufficient for analysis historically, but may now be inadequate for EMC analysis and frequency-dependent rejection (FDR) calculations. The collective material of 4.2 also highlights how modular and varied conformance testing procedures are across the federal and non-federal sectors. This overall lack of uniformity may be necessary for certain services like mobile broadband where technology is constantly changing and a prescriptive approach might hinder innovation. However, it can lead to inconsistencies in how receiver performance is assessed, tracked, and managed, making efficient and effective spectrum management at the federal level difficult to coordinate.

Lastly, our discussion of the conformance testing steps that could be followed in situations where no standards exist emphasizes how, ideally, effective interference testing would require varying multiple system parameters (e.g., interference power, frequency, modulation characteristics) for each receiver under test, while also considering the test equipment’s operational context (i.e., distance to transmitters, firmware version, usage requirements, etc.). The comprehensiveness and costliness of such testing likely precludes its feasibility, and instead necessitates the use of representative testing. This, in turn, likely introduces imprecision and inefficiency into the spectrum management process.

4.2 Conformance Testing

4.2.1 NTIA

In order for a federal agency to operate a telecommunication system (i.e., a system intended to transfer information using the radio spectrum), the NTIA must first grant the system a certification of spectrum support. The NTIA outlines the procedures by which telecommunication systems will be reviewed for certification in Chapter 10 of its Manual of Regulations for Federal Radiofrequency Spectrum Management [63].

It is perhaps notable that Chapter 10 of the NTIA Manual begins by stating that all telecommunication systems to be used by federal agencies must take “all reasonable measures” to ensure that they “neither cause *nor receive* harmful interference” (emphasis ours) [64]. This statement roughly suggests that a system’s transmitter and receiver characteristics are of equal importance in the certification process.

The four stages of development at which a system can be reviewed in pursuit of certification are outlined in Section 10.2.5. At each of these stages, the Spectrum Planning Subcommittee (SPS), on behalf of the Interdepartment Radio Advisory Committee (IRAC) for the Deputy Associate Administrator, Office of Spectrum Management (OSM) of NTIA, develops recommendations regarding certification for the system under review. Section 10.4.1 describes the intent, outcomes, and applicable systems of each review stage. We summarize that information in Table 4-1.

A point of emphasis here is that not all equipment arrives for certification in the order of the outlined stages of development. For example, federal agencies may purchase commercial off-the-shelf equipment for which the FCC granted equipment authorization; these systems must meet the NTIA standard but would not enter certification at Stage 1.

Table 4-1: Stages of Review for NTIA Certification of Spectrum Support

Stage	Applicable Systems	Intent	Outcomes
1. Conceptual	• Systems or subsystems that have a major impact on spectrum usage as defined by the user agencies, IRAC, or NTIA • Especially applicable to those that use new technological concepts or use existing technology in significant new ways	To provide guidance on the feasibility of obtaining certification of spectrum support at subsequent stages	Guidance will indicate any modifications, including more suitable frequency bands, necessary to ensure conformance with the National Table of Frequency Allocations and the provisions of Chapter 5
2. Experimental	• Prerequisite for NTIA authorization of radiation in support of experimentation for systems that are subject to these procedures • May be requested for test equipment, modified operational equipment, or initial design models	To provide guidance for ensuring certification of spectrum support at subsequent stages	Determination of which of several frequency bands or which of several proposed equipment configurations should be selected for continued investigation
3. Developmental	• Prerequisite for NTIA authorization of radiation in support of experimentation for systems that are subject to these procedures	To provide guidelines for ensuring certification of spectrum support at Stage 4	Testing of proposed operational hardware and potential equipment configurations
4. Operational	• Stage 4 is a prerequisite for NTIA authorization of radiation from a station with an operational station class (i.e., other than experimental) for systems that are subject to these procedures • Tracking, telemetry, and telecommand operations for major satellite networks, prior to the launch of the spacecraft		Restrictions on the operation of the system or subsystem as may be necessary to prevent harmful interference

During each of these review stages, the SPS can give consideration as to whether EMC testing should be performed and evaluated for a given prototypical system. Otherwise, the major considerations with respect to how a system will avoid creating or receiving harmful interference involve: 1) an assessment of whether a systems stated transmitter or receiver characteristics comply with the "prevailing spectrum management policy, allocations, regulations, and technical standards (Federal, National, and International)"; and 2) the predicted degree of EMC between the proposed system and the electromagnetic environment in which it will operate [64]. The manner in which EMC predictions are to be obtained are outlined in Section 10.6.2; as systems progress in operational maturity, so do the requirements for EMC analyses. For example, while

Stage 1 analyses may rely on gross estimates, measured data from experimentation is required for Stage 3 analyses.

Sections 10.8.6 and 10.8.7 enumerate the specific transmitter and receiver characteristics data required for certification of spectrum support, respectively, that federal agencies must provide for any telecommunications system for which certification is sought. The receiver characteristics listed in 10.8.7 are shown in Table 4-2.

Table 4-2: Required Receiver Characteristics Data for Federal Telecommunications Systems as Listed in 10.8.7 of NTIA Manual

Receiver Characteristics Data
a. The receiver nomenclature/name model number and manufacturer
b. The frequency stability
c. The spurious rejection level
d. The image rejection level
e. The frequency range through which the receiver is capable of being tuned
f. The emission designators identifying the types of emission for which this receiver is designed
g. For each frequency band, the RF bandwidths at the -3, -20, -60 dB levels
h. For each emission designator, the IF bandwidths at the -3, -20, -60 dB levels for the narrowest IF amplifier
i. For each emission designator, the receiver sensitivity and the criteria used to determine performance

We note that some of these receiver characteristics are not well-defined for some receiver technologies (e.g., direct-RF) and furthermore are not sufficient to fully characterize all aspects of receivers that are relevant to determining their interference immunity (e.g., amplifier, mixer, and AGC compression levels). It would be beneficial to consider changes to Section 10.8.7 of the NTIA Manual to use alternative data fields such as blocking interference levels as a function of frequency.

4.2.2 FCC Equipment Authorization

RF devices must be properly authorized under 47 CFR part 2 prior to being marketed or imported into the United States. The Office of Engineering and Technology administers the equipment authorization program, which consists of the steps described in Table 4-3.

Table 4-3: FCC Equipment Authorization Steps

Step	Description
• **Determine FCC Rules That Apply**	Determine if the device is a Radio Frequency device subject to the FCC rules. Determine all applicable technical and administrative rules that apply.
• **Equipment Authorization Procedures**	Determine the type of equipment authorization that applies to the device.
• **Compliance Testing**	Perform the required tests to ensure the device complies with the applicable technical requirements.
• **Approval**	After the testing is complete, if the device is determined to be in compliance, finalize the approval process based on the applicable approval procedure.
• **Label/Manual/Record Retention**	Label the product and provide the required customer information. Maintain all documentation and ensure that the manufactured products are in compliance.
• **Manufacture/Import/Market**	Follow the FCC importation requirements when importing or marketing products.
• **Modifications to Approved Products**	Changes to your product design may require additional approval. KDB Publication 178919 gives general guidance when making changes to a previously approved product.

These requirements are intended to minimize the potential for harmful interference. As mentioned in the overview of Section 4, the FCC type acceptance rules for transmitters have a dynamic range of 50 to 60 dB for out-of-band emissions, which is likely unsatisfactory for EMC analysis and frequency dependent rejection (FDR) calculations. The latter is of particular relevance to the this report as NTIA uses FDR for its sharing studies as a key component in interference analysis. A brief description of FDR follows, while a detailed description of how to compute FDR can be found in Recommendation ITU-R SM.337-6 [65]:

- *Frequency Dependent Rejection*– is a calculation of the amount of transmitter energy that is rejected by a victim receiver due to the IF filtering in the radar receiver. This FDR attenuation is composed of two parts: on-tune rejection (OTR) and off-frequency rejection (OFR). The OTR is the rejection provided by a receiver's 3 dB bandwidth to a co-tuned transmitter's 3 dB bandwidth and the OFR is calculated by using the receiver's IF selectivity and the transmitters emission spectra. The radar receiver IF selectively and 3 dB bandwidth data for the federal systems is obtained from the agencies.

Note that the current FCC Equipment Authorization process includes manufacturer compliance reports with screen shots of emission spectra. This data is sufficient to show compliance with FCC rules, and is not intended to support extracting the data for further analysis; a SME consulted for this report suggested that compliance reports could also be outputted as ASCII text files of power versus frequency in the wider dynamic range in order to support additional analysis.

4.2.3 Other Federal Examples

4.2.3.1 FAA

The Federal Aviation Administration defines certification steps for all avionics equipment in FAA Order 8110.4C [66]. This "type certification" process contains five broad steps: conceptual design, requirements definition, compliance planning, implementation, and post-certification.

However, not all steps are necessary if the equipment in question was developed under a known Technical Standard Order (TSO). As described in Section 3.3.3, FAA TSOs often invoke, by reference, avionics standards developed by industry groups like the RTCA. A number of FAA TSOs contain receiver performance requirements, including interference masks and selectivity requirements.

The process for obtaining TSO authorization (TSOA) is described in 14 CFR Part O. In general, the certification process may be expedited significantly if a TSOA can be acquired—since TSOs describe the testing requirements to prove compliance, applicants need only state their system complies with the TSO in order to be certified [67].

4.2.3.2 DoD

As described in Section 3.3.5, only a few standards related to receiver performance characteristics are applicable to all DoD systems. Processes to assess receiver conformance across the DoD are also similarly modularized according to the receiver use cases and the programs under which they operate. Pre-acquisition verification testing performed by vendors or third parties may be sufficient in some circumstances. However, many programs include their own certification branches specifically to verify conformance. For example, the Space Systems Command of the U.S. Space Force conducts its own certification of GPS receivers as part of its larger GPS Certification Branch.

Although receiver conformance testing procedures are not broadly defined across the DoD, a singular certification process does exist for all radio-frequency systems within DoD: the Joint Frequency Allocation-to-Equipment, or "JF-12" process. In fact, spectrum certification (i.e., the process by which spectrum dependent systems acquire frequency allocations) is predicated on the JF-12. The JF-12 is a multi-step process that begins with the completion of a Department of Defense Form 1494 (DD1494).

The DD1494 requires 21 identifying characteristics for any system receivers, including many of the receiver performance characteristics listed in Section 3.1. Additionally, the DD1494 does require that any testing reports or corresponding data used to derive the entered performance characteristics be included with the completed form. However, the DD1494 (and, moreover, the JF-12) is not a means to specify *how* receiver compliance is to be tested; rather, the DD1494/JF-12 is merely a process to create an entry of record for the performance metrics a system is alleged to have met.

4.2.4 Certifying Conformance with Industry Standards

Conformance assessment is a methodology, accepted within a given industry, of verifying that a device conforms to a standard. Such assessment consists of inspection, testing, certification, and registration. One category of conformance assessment is RF compliance assessment, which seeks to ensure that RF electronic devices and systems (including receivers) operate within established regulatory limits and conform to industry and/or governmental standards.

An equipment manufacturer may elect to have conformance testing of its products (or prototypes of those products) performed by an outside organization rather than in-house for any of the following reasons:

- The inability of the manufacturer's in-house testing facilities or personnel to perform all required testing (e.g., lack of an anechoic chamber large enough to test a particular antenna).
- The ability of an outside organization to do the testing more efficiently and cheaply than the manufacturer.
- The existence of an outside testing organization that is well-known and prestigious enough for its seal of approval to mean more to customers than a manufacturer's internal seal of approval.
- A contractual requirement to have the testing, or parts of it, done by an independent organization.
- A customer's desire to do its own testing.
- In some cases, a need to obtain certification before the manufacturer can mark its equipment with trademarked logos or advertise its products as being compliant.

Various industry groups are in place to help ensure conformity with industry standards. Some that include receiver performance requirements within their purview are:

- The Institute of Electrical and Electronics Engineers (IEEE) Conformity Assessment Program (ICAP), which ensures conformance with IEEE standards. ICAP partners with leading test laboratories to develop conformity assessment programs based on IEEE standards.
- The Global Certification Forum (GCF), in which 175 manufacturers participate. This forum certifies that equipment is compliant with various standards, including those of 3GPP. Its members include terminal manufacturers, mobile network operators, vendors of test equipment, and Recognized Test Organizations (RTOs). RTOs have demonstrated to the GCF their qualifications to assess cellphones and wireless devices against GCF's certification criteria. Conformance and Field Trial RTOs are also capable of ensuring quality compliance for such devices in live networks.
- PTCRB (formerly the PCS Type Certification Review Board), which provides a framework in which wireless devices can be certified. It operates certification programs for smartphones, tablets, Internet of Things devices, and laptop computers. The certifications are based on standards and test cases developed by 3GPP, the Open Mobile Alliance, the FCC, and/or foreign government agencies having jurisdiction in such matters. The foreign agencies include the Telecom Engineering Centre (TEC) in India; the Korea Communications Commission (KCC), which is modeled after the U.S. FCC; and the European Commission, which oversees implementation of the European Radio Equipment Directive.

A test case is an executable script written to verify proper device performance in a particular realistic scenario. Bodies such as GCF and PTCRB define sets of test cases that devices and chipsets must execute successfully to become certified.

There are three principal types of test cases for 5G devices:

- Protocol testing, which verifies the device's proper execution of protocols such as 5G or C-V2X. Both standalone and non-standalone modes may need to be considered.
- RF testing, which verifies device performance in all required frequency ranges and compliance with specifications for blocking, spurious emissions, and other crucial electromagnetic compatibility and performance parameters.
- Radio resource management testing, which confirms that the device can remain reliably connected to a network not only in stationary situations but also in mobile scenarios involving intercellular handovers.

Test cases are validated by organizations such as ICAP, GCF, PTCRB, TEC, KCC, or the European Commission, but there is also a role for unvalidated test cases. Unvalidated test cases enable testing of customizations that exceed the baseline requirements imposed by regulatory bodies in order to maximize equipment performance, user experience, and (potentially) electromagnetic compatibility of transmitters and receivers.

4.3 Determining Receiver Interference Performance in Absence of Standards

In the absence of standards, there is often the need to determine receiver interference performance characteristics for various purposes; e.g., studying potential coexistence issues if neighboring bands are repurposed. The following steps may be followed:

- Identify makes and models of receivers that are operating in the band or are being developed or procured to operate in the band of interest. Equipment inventories should additionally include information on:
  - Antenna makes/models that the receivers are paired with (for receivers that utilize separately packaged antennas) and the cable lengths/types that are used to connect the receiver and antenna. Note that receiver interference performance issues due to strong adjacent-band or out-of-band interference are influenced by these components.
  - The firmware version, for modern digital receivers that are software controlled.
  - The location of the receiver for fixed services, or the range of locations for transportable or mobile devices.
  - Operational usage of the device. Is it used all the time? Are there safety, national security, or other special considerations? If the antenna orientation may change with time (physically or electronically) what are the relevant characteristics and constraints.
- Ideally, all makes/models and receiver equipment configurations (including antenna pairings) will be tested against relevant types of interference at frequencies that the interference may be centered on. Frequently, it is not practical to perform such

comprehensive testing. To limit testing to adhere to labor and schedule constraints it may be necessary to:

  - Identify representative or bounding receiver/antenna configurations by establishing equipment classes and selecting one or more receiver within each class. Makes/models that are fielded in greater number, associated with more critical missions, or known to be more susceptible to interference should be prioritized. For example, within the 5G/radio altimeter issue discussed in Section 2.3.3, in an RTCA study, radio altimeters were categorized by the type of aircraft they were installed on: commercial transport, general aviation (including business and regional), and rotary wing (helicopters). For a DoD study, equipment for testing was prioritized by numbers of fielded systems.

- Prudent considerations for testing include:
  - Sharing and seeking feedback from stakeholders on a test plan before initiating testing can maximize the chances that the test results will be satisfactory, especially by spectrum regulators.
  - Varying interfering signal characteristics – If testing reveals significant coexistence issues, proposals for new services in neighboring bands may be modified. With automated testing, it is far less expensive to test against parametrically varied interference parameters in one test event than to have to return to a facility to conduct an additional test event. Test plans should consider varying the following interference characteristics:
    - Interference power – Periods of zero interference are typically included in testing to establish nominal receiver performance. This period should be followed by steps in interference power to the maximum levels that are capable for the test equipment without causing damage to the receivers.
    - Interference frequency – The center frequency of the interfering signal may be varied if there is the likelihood that it may be adjusted in later proposals.
    - Modulation characteristics – For instance, if 5G is being considered in the neighboring band, various configurations permitted by the relevant 5G standards for the modulated signal characteristics might be tested (e.g., bandwidth).
  - Varying desired signal characteristics – If the desired service is also new, or for other reasons can practicably adapt to certain changes in signal characteristics, alternative configurations as identified above for the interfering signal may be considered.
  - Filtering – Highly selective (e.g., cavity) filters are often required when emulating the interfering signal using test equipment to ensure that unwanted emissions of the emulated transmission within the receiver's desired band are controlled to proposed levels. Even if the proposed levels in the receiver's desired band are the dominant interference mechanism, it is prudent also to test with lower in-band (to the receiver under test) emissions in case this is later proposed to be the solution to ensure coexistence. Record and replay – In some cases, it may be more effective to record and replay an interfering signal rather than emulate it. This

method can be cost effective particularly if the interfering signal is complicated, proprietary, or not readily generated by existing test equipment. Care must be taken to ensure that the replayed signal is a faithful reproduction of the recorded signal. For instance, that the test equipment does not introduce out-of-band emissions at levels not consistent with the true interfering signals.

5 Technical Mitigations

5.1 Overview

In this section, we focus on *technical* strategies to improve interference immunity in receivers; we supplement this discussion with further technical considerations in A.4 to A.6. In Section 6, we turn our attention to *non-technical* mechanisms to improve receiver interference immunity performance.

As we will discuss in 5.2 and A.6, a number of emerging technologies show promise for their potential to enhance receiver performance and mitigate interference issues. These technologies include: the utilization of more capable adaptive array antennas, continued progress toward the implementation and performance improvement of low SWAP-C filters at a wide range of frequencies; the development of LNAs and mixers with improved linearity; and continued advancements in the sample rates and depth of ADCs, which allows increased dependence on digital filtering within receivers.

We also discuss in 5.2 and A.5 how best practices might be leveraged to improve receiver performance. Examples of the best practices we consider in this discussion include: the use of antennas that maximize gain toward the transmitter of the desired signal(s) and that minimize gain toward transmitters of unwanted emissions; the use sufficient filtering to protect the receiver from unwanted emissions beyond the receiver's passband; ensuring that components operate in a linear region for the target level of receiver interference immunity; the utilization of forward error correction encoding of data to increase receiver tolerance to interference; considering use of methods for spectrum sharing to coordinate use and avoid harmful interference as needed (e.g. ORAN-based sharing with 5G networks, leveraging AI); and considering use of interference cancellation/excision methods.

An important finding detailed in our discussion is the potential trade-offs involved with receiver component selection, including performance and SWAP-C considerations; i.e., while the emerging technologies we present can significantly improve receiver interference immunity performance, they also present challenges due to SWAP-C constraints. Additionally, the increased demand for receiver designs that process multiple bands or operate with wider bandwidths increases these challenges.

Lastly, in 5.3 we discuss the potential for leveraging additional receiver standards and performance requirements towards improving receiver performance, but note that this approach at the federal level may have multiple downsides, including: the challenges to quickly transition legacy equipment in the field; challenges to access (for replacement) receivers that may be in spacecraft or embedded in complex systems; and costs implicated in these efforts.

5.2 Encourage Best Practices and Use of Emerging Technologies

Appendix A provides an overview of receiver architectures, components, and interference mechanisms. Appendix A also provides a set of best practices to minimize the likelihood of receiver performance issues when operating in the presence of interference. These best practices include:

- As practicable, use antennas that maximize gain toward the transmitter of the desired signal(s) and that minimize gain toward transmitters of unwanted emissions. This is straightforward for fixed point-to-point antenna systems, which can be narrow beam and pointed at the transmitters. It is more complex for mobile systems that include mobile transmitters, receivers, or both, in which case adaptive beamforming is needed. Adaptive beamforming is typically implemented digitally through array antennas, as explained in Appendix section A.2.1.2. In summary, the receiver beam adapts to track the transmitter that matters at each moment, while simultaneously detecting and nulling the directions where unwanted signals are coming from. Implementations of array antennas are common in cellular systems with large sets of antenna elements used at base stations to increase throughput using spatial multiplexing, and with a much smaller number of elements at the mobile user equipment (UEs) due to SWAP factors - typically 2x2 or 4x4 configurations - with beamforming mostly used to mitigate effects of multipath and interference.
- Use sufficient filtering to protect the receiver from unwanted emissions beyond the receiver's passband. Filtering requirements of various receiver architectures and applications will be different. Radio-astronomy receivers, Doppler radar receivers, and land-mobile radio receivers will have different receive filtering requirements. The size, weight, cost to manufacture, reliability, and performance repeatability are all considerations. The impulse response and steady state response of the filter need to be considered based on the receiver application. Effects to receiver performance in terms of insertion loss, group delay, pass-band ripple, noise figure, and impact to minimum sensitivity versus the trade-off in overall filter selectivity should also be considered.
- Ensure that components such as amplifiers, mixers, and digitizers (automatic gain control and ADCs) operate in a linear region for the target level of receiver interference immunity.
- When designing new systems, utilize modern methods to increase interference tolerance such as forward error correction encoding of data.
- Consider methods for spectrum sharing to coordinate use and avoid harmful interference as needed. For example, for compatibility with 5G mobile networks Open Radio Access Network (ORAN) capabilities have been proposed using artificial intelligence (AI) techniques based on near-real-time metrics to help optimize coexistence.
- As practicable, consider use of interference cancellation/excision methods.

One countervailing technology development was noted by several receiver manufacturer SMEs that were interviewed by MITRE – many federal and non-federal customers are requiring that new receiver designs process additional bands or operate with wider bandwidths for improved performance. Both of these requirements make it more difficult to improve receiver immunity to adjacent-band or out-of-band interference while adhering to applicable SWAP-C constraints.

Appendix A details the trade-offs involved with receiver component selection including performance and SWAP-C.

Appendix A also identifies some emerging technologies that when utilized can significantly improve receiver interference immunity performance. These emerging technologies include:

- More capable adaptive array antennas.
- Continued progress toward the implementation and performance improvement of low SWAP-C filters at a wide range of frequencies. Research in this area is largely motivated by the growing number of bands utilized by 5G mobile devices. Some 5G mobile devices require over 100 bandpass filters. These are largely bulk acoustic wave (BAW) devices, but some additional technologies are used for the higher 5G frequency bands (e.g., Frequency Range 2 [FR2]).
- Development of LNAs and mixers with improved linearity.
- Continued advancements in the sample rates and depth of ADCs, which allows increased dependence on digital filtering within receivers to suppress interference.

The 2023 National Spectrum Strategy states that the "Federal Government will encourage private entities to improve receivers' immunity to harmful interference and develop and offer dual-use technologies and services that are responsive to both commercial and unique Federal requirements" [68]. The National Spectrum Strategy Implementation Plan [69] includes an activity (Outcome 3.1(c)) for NTIA and FCC, with help from the federal agencies and CSMAC, to develop a "roadmap for improving receiver immunity to harmful interference." This activity is scheduled to be conducted between October 2025 and July 2026.

5.3 Additional Standards and Performance Requirements

More prescriptive approaches might be considered by NTIA, including the development of additional standards and performance requirements within its rules and regulations. This approach would ensure that an additional number of federal receivers would be built to a known degree of immunity to interference. There are numerous downsides, however, to this approach:

- Improving interference immunity often requires increasing receiver SWAP-C to an extent that may be problematic for some applications (see Section 2 and Appendix A).
- In bands with many fielded receivers, it is unreasonable to expect that this legacy equipment could be modified or replaced quickly[3]. A feasible transition time may be lengthy.
- Some receivers (e.g., those on spacecraft or embedded in complex systems) may not be accessible to replace or modify, which may further increase the necessary transition time.
- Federal agencies may incur significant costs as a result of regulatory changes.

The European Union is currently gaining experience with a more prescriptive approach to regulating receivers with their Radio Equipment Directive (RED). There is not yet conclusive evidence that this mandate is improving spectrum efficiency with the new receiver requirements. Receiver vendor SMEs interviewed by MITRE have expressed the view that the RED mandate currently only requires receiver interference performance that is consistent with the low-end of fielded equipment. Receiver manufacturers and users applied significant political pressure in the development of the RED receiver standards to avoid the downsides listed above associated with

[3] A pertinent example is GPS receivers, where there are an estimated 3 billion globally, with 900 million in the US alone. [98]

imposing additional receiver regulations. Furthermore, these SMEs indicated that satisfying the RED mandate requires costly testing and compliance documentation that is increasing their costs to produce equipment, which in turn is increasing receiver sales prices for consumers. There are concerns that future revisions of these standards will require new receiver designs.

MITRE recommends that additional receiver standards and performance requirements be considered by U.S. regulators only on a case-by-case basis as bands (or neighboring bands) are studied for repurposing, and that all other interference mitigation approaches in these circumstances be also considered (e.g., transmitter limits, guard bands, system approaches). For instance, the National Spectrum Strategy identifies specific bands for repurposing studies. It would be prudent to inventory receivers within these bands and investigate their interference performance as early as possible using the approaches outlined throughout this report. As NTIA has done for their RSEC receiver selectivity requirements, it would be prudent to ensure that any proposed receiver standards can be practically achieved as demonstrated by the availability of equipment that meets the targeted level of interference performance while also satisfying all other performance requirements and SWAP-C constraints.

Some subject matter experts that MITRE interviewed for this study noted that, for some neighboring bands, unwanted emissions from transmitters that fall within the allocated band for a receiver was the dominant cause of coexistence issues. In such cases, consistent with the FCC’s April 2023 Policy Statement, modification of regulatory limits on the transmitters should be considered. NTIA might consider a study on transmitter performance, focusing on their ability to control unwanted emissions outside of their allocated band, as a follow-on to this study on receiver performance.

6 Non-Technical Mitigations

6.1 Overview

This section continues our discussion of mechanisms to improve receiver interference immunity performance that we began in Section 5. Here, we turn our attention to *non-technical* mitigations to receiver interference performance issues. After identifying non-technical challenges and opportunities, our discussion will highlight several non-technical mechanisms – specifically incentives, policies, and standards – that could be implemented to address challenges, leverage opportunities, and provide motivation, guidance, requirements, and/or specifications to support receiver interference performance improvements. These mechanisms could also help address the burden of additional costs requirements for effectively increasing spectrum utilization to enable more users and/or usage which, in turn, is expected to generate greater national economic benefits.

As we discuss in 6.3, incentives are one type of non-technical mechanism that could provide motivation to improve receiver immunity performance. For example, parties (e.g., federal agencies or commercial entities) could be reimbursed for their receiver improvement costs. A decentralized approach could also enable parties to negotiate solutions amongst themselves.

A second non-technical mitigation strategy is the use of policy, which we discuss in 6.4. For example, as we discuss in 6.4.1, an interference limits policy could describe the environment in which a receiver must operate without necessarily specifying receiver performance, while a harm claim threshold could provide ceilings on in-band and out-of-band interfering signals. Other types of policies we discuss include: a rule-making process (6.4.2) that would establish specific rules for certain bands; policies that provide cost reimbursement for mandatory receiver immunity performance improvements (6.4.3); and data transparency and enforcement policies that could support receiver performance improvements (6.4.4).

A final type of non-technical mitigation strategy could be the use of standards developed by industry alliances and working groups. As we discuss in 6.5, standards could be used to define acceptable parameter and performance bounds for classes/services of receivers.

However, as noted in throughout this report, there is complexity in ensuring that both transmitters and receivers do not cause or receive harmful interference and also uncertainty in the dynamic and continuously changing spectrum environment. Each band is unique with its particular mix of physics, incumbents, and use cases that shape current and future interference dynamics of in-band and out-of-band emissions.

Therefore, while the technical and non-technical mechanisms to improve receiver performance that we discuss here, in 5, and in Appendix A are promising, it is worth noting here that there is no quick and easy "one size fits all" solution to optimizing receiver interference immunity performance. However, there are steps that can be taken on a case-by-case basis to improve receiver interference performance. This includes acknowledging that both transmitters and receivers impact the efficiency of spectrum use. Specific steps should be taken to improve receiver interference immunity performance as opportunities arise, such as through new acquisitions and/or repurposing activities when appropriate and on a case-by-case basis as bands (or neighboring bands) are studied. Also, guidance and best practices to address data transparency and the protection of sensitive data are needed to further advance dynamic spectrum access and management.

6.2 Considerations

6.2.1 Challenges

Non-technical challenges to improving the performance of receivers include the costs associated with receiver upgrades, the designation of any parties responsible for upgrades, and the planning, implementation, and evaluation of the upgrading process itself.

A primary challenge to improving receivers is the direct and indirect costs associated with implementing any receiver performance mechanisms. Direct costs will be incurred at each stage of a receiver upgrading process including the design, fabrication, implementation, and testing and certification steps. Indirect costs associated with the receiver improvement process could be both monetary and non-monetary. For example, indirect monetary costs could include the opportunity costs of lost revenues if services must be halted while receivers are upgraded as well as any costs associated with mitigating disruptions to services. Examples of non-monetary indirect costs to improving receiver performance would include any increased risks to missions, incumbents, and safety-of-life services during an upgrading process.

It can be challenging to accurately estimate required costs and to justify them, such as through projections of increased spectrum efficiency and/or higher expected auction revenue. The spectrum environment is dynamic and continuously changing, which adds uncertainty as to the costs, benefits, and solutions as well as their applicable time period and impact on future spectrum use and equipment decisions. Each band represents a unique case and multiple stakeholder organizations are often involved which further adds to the complexity.

Another non-technical challenge associated with mitigating receiver performance issues is deciding which party will bear the costs of implementing receiver improvement measures, as outlined above. The stakeholder bearing responsibility for these costs may not be the one to receive its expected benefits. Potential responsible parties could include the government, vendors, and/or any direct beneficiaries to improved receiver performance (e.g., service providers whose entry into a band is enabled by improved receiver performance in a nearby band).[4]

Lastly, a receiver-upgrading process is challenging to plan, implement, and evaluate. For example, any discussion of how receivers should be upgraded must first begin with a definition of which performance level is sufficient. Moreover, any non-technical mitigation that designates a prescribed receiver performance criterion must also designate the receivers to which the policy will apply. Prescribed standards may apply to new receivers as well as receivers already in operation, or they may apply to new receivers only ("grandfathering"). Other factors to consider are timeline for upgrades, the implementation method, and the party that will determine and regulate the improvement mechanisms.

[4] Federal agencies must have requirements as well as available funding to justify additional costs. There will be differences based on whether the decision to improve receiver interference immunity performance is made proactively or retroactively. During the acquisition lifecycle, a federal agency can specify receiver and transmitter standards that must be met for its system within its contract with the vendor. Past experiences have shown that the manufacturer may not be aware of contractually- required transmitter and receiver standards until after the contract value has been set; it may not want to incur additional costs to meet the standards or it may want to charge additional money.

6.2.2 Opportunities

In juxtaposition to the challenges inherent to mitigating receiver performance issues, a number of opportunities make improving receiver performance beneficial to society. In particular, improved receiver performance allows for greater and more efficient and effective wireless communications. As a critical national resource—growing in demand yet practically limited in supply—increased efficient and effective use essentially enables spectrum to support more users and/or usage. Therefore, mitigating receiver performance as part of spectrum management improves spectrum management and optimization of spectrum resources. This, in turn, leads to economic and societal benefits such as higher gross domestic product (GDP), greater economic growth, increased jobs, and improved ability to balance spectrum requirements across national security, economic, and other national interests.

6.3 Incentives

In this section we identify incentives that could motivate the implementation of receiver performance improvement measures. These include both market- and non-market-based mechanisms to reimburse stakeholders for costs incurred to improve receiver performance. Incentive options described in this section include reimbursement via the Spectrum Relocation Fund or a subsidy and leveraging a decentralized approach. For each incentive, a description is provided and its challenges and opportunities highlighted.

6.3.1 Reimbursement

This section covers two reimbursement options; the first is applicable to federal agencies and the second to commercial industry.

6.3.1.1 Spectrum Relocation Fund

The Spectrum Relocation Fund (SRF), administered by Office of Management and Budget (OMB) in consultation with NTIA, provides a mechanism for federal agencies to be reimbursed for some of their costs to repurpose spectrum; funded from auction proceeds, the SRF reimburses federal agencies to repurpose their federal use spectrum and make it available for non-federal use. Remaining funds are deposited in a general fund of the Treasury [70]. Federal agencies could include receiver performance improvement costs in their transition plans. The SRF pertains to eligible federal agencies for relocation or sharing costs for the use of eligible frequencies by non-federal users. SRF funding is only applicable to federal agencies, which may limit its overall effectiveness. Further, there are limitations in how much funding an agency can receive, based on expected revenue from auction of the spectrum as well as approval of the plans and costs by the Technical Panel, which is comprised of representatives from OMB, NTIA, and FCC.

MITRE recommends that NTIA consider issuing guidance and best practices for agencies to consider incorporating receiver performance improvement costs into their spectrum pipeline and/or transition plans.[5]

6.3.1.2 Subsidy

A subsidy could be granted to incentivize receiver performance improvements.[6] In this case, if receiver performance requirements were made voluntary, the federal government could pay a subsidy directly to vendors to compensate them for upgrade costs. An example that provides precedence for this approach is the receiver box subsidy program that took place during the digital television transition. Under that program, households could request up to two $40 coupons for converter boxes.

Paying vendors directly to compensate for upgrade costs could incentivize them to adopt receivers that are better at mitigating harmful interference. This incentive may appeal to vendors as it would provide them with the required funding to make receiver performance updates. Further, assuming that improvement mechanisms and performance targets were defined appropriately, paying vendors directly could also help enable increased compliance with the defined performance targets. The government could also use a subsidy to encourage development of dual-use technologies and services that address both federal agency and commercial requirements.

A challenge to compensating vendors directly is that it is difficult to determine an appropriate reimbursement amount. Moreover, vendors' incentive to maximize profit could limit the efficiency of outcomes. Additionally, the effectiveness of reimbursing vendors is predicated on how well improvement mechanisms and performance targets are defined. Lastly, providing compensation to vendors would require financing, which could be difficult and contentious to garner.

6.3.2 Decentralized Approach

A decentralized approach is where impacted parties negotiate solutions (i.e., receiver performance targets and/or any accompanying compensation or reimbursement) among themselves. In many cases, the providers of services adjoined in space and frequency may be best placed to negotiate to a solution. If the operating entitlements they hold are clear enough—and transaction costs low enough—these parties should presumably be able to resolve issues bilaterally.

An advantage of the decentralized approach is that it would require minimal costs and involvement from the regulatory authority. Additionally, a decentralized approach puts decision-making responsibility on groups that have industry-specific knowledge and an inherent stake in good performance within their spectrum domain.

[5] On March 12, 2024, the NTIA released the National Spectrum Strategy Implementation Plan, a follow-on document providing implementation details for their November 13, 2023, National Spectrum Strategy. The implementation plan outlines that, under 47 U.S.C. §928(g) (the "Spectrum Pipeline Act"), federal agencies may receive funding from the Spectrum Relocation Fund to conduct studies on bands identified for potential repurposing, but only once they have submitted a study plan ("pipeline plan").

[6] A subsidy is a direct or indirect payment or economic benefit provided by a government to a firm or party to promote a public objective that would not otherwise be obtained in a free market. It is a government expenditure, funded through taxation and appropriations.

However, coordination and harmony between parties in a truly decentralized setting is likely difficult to achieve. Therefore, a decentralized approach would most likely still require the involvement of a regulatory authority like the NTIA to facilitate negotiations, set minimum performance standards, and help arbitrate claims of significant interference. Moreover, even with the involvement of a regulatory authority, negotiations between impacted parties could still involve drawn-out arbitration processes and legal fees, and these challenges would likely scale with the number of parties involved in a dispute. Further, there is no guarantee that any solution that is reached at the end of this process would be optimal for the impacted parties or the wider market.

The MITRE team recommends further consideration of the decentralized approach, potentially as a longer-term solution with potential tie-ins with the Incumbent Informing Capability[7] (IIC) and in conjunction with other incentives and/or policy.

6.4 Policy

This section examines policy options for directing receiver performance improvement. Policy options described in this section include interference limits policy, rule-making process, reimbursement, data transparency, and enforcement mechanisms.

6.4.1 Interference Limits Policy and Harm Claim Thresholds

Interference limits policy includes approaches to describe the environment in which a receiver must operate without necessarily specifying receiver performance. For example, harm claim thresholds [10] [11], which are a type of interference limits policy, are ceilings on in-band and out-of-band interfering signals that must be exceeded before a radio system can claim that it is experiencing harmful interference. Under such a policy, operators, manufacturers, and industry groups develop specifications for receiver performance, given expectations about interfering signal levels.

A harm claim threshold could be represented as a graph of values of spectral field-strength density, in decibels referred to one microvolt per meter per megahertz (dBμV/m/MHz), that the signals radiated by a given class of transmitters would not be allowed to exceed in more than a given percentage of times and locations of interest, within a given frequency band. For example, within the transmitters' allocated frequency band their radiated signals might be allowed to exceed 60 dBμV/m/MHz in 50% of all times and locations, 80 dBμV/m/MHz in 10% of all times and locations, and 100 dBμV/m/MHz in 1% of times and locations. In the immediately adjacent frequency bands, the limits would be higher, perhaps 75, 95, and 115 dBμV/m/MHz respectively. Still higher limits might be allowed in more-remote frequency bands.

As indicated earlier in the paper, each spectrum sharing situation requires a unique analysis to gain the maximum amount of efficiency and effectiveness. In this situation, the concept may need to evaluate the duration of gaps between interfering signals. In some situations, a smaller undesired-signal duty factor with many short messages could cause more interference than an equal or even higher duty factor resulting from longer messages with longer gaps, because

[7] NTIA developed the concept of an IIC as a mechanism by which non-federal users in a shared spectrum band could be "more reliably" informed when incumbent federal systems were operating in close proximity—and thus in need of protection— in a 2020 white paper by DiFrancisco, Drocella, Ransom, and Cooper [97]. The IIC is proposed as a concept to more broadly enable spectrum sharing in the mid-band and other portions of spectrum principally used by federal incumbents.

desired-signal packets could squeeze through the longer gaps but be blocked by unfavorably spaced shorter messages.

An advantage of such a policy is that it provides operators with greater flexibility on how to deal with interference levels. For instance, developers of a new receiving system could improve receiver selectivity, move away from the frequency boundary where necessary, or accept the risk that their service will suffer occasional interference given their choice of receiver design. Another benefit of interference limits policies is that the regulator would not need to intervene as often to resolve inter-service interference disputes.

Several challenges must be overcome before implementing an interference limits policy. Besides selecting appropriate numerical values for the various parameters that define a harm claim threshold, the difficulties include:

- Deciding how near the "locations of interest" can be to any transmitter. Field strength rises very sharply when the receiver gets very close to a transmitting antenna. In cases where all the transmitters or all the receivers are fixed and not too numerous, this problem can be solved by stipulating a minimum allowable transmitter-to-receiver distance; but if transmitters and receivers are all mobile, that approach would generally be impracticable.
- The very considerable expense of measuring field strength at a meaningful number of points throughout the area of interest (or the volume of interest, if the receivers are not all at the same height above ground) at a sufficient number of times of interest.
- The complex issues involved if prediction rather than measurement is to be used, including the time-varying geographical distribution of transmitters, the probabilistic nature of propagation loss (especially including clutter and multipath effects), and the variable orientations of transmitting-antenna beams.

Such problems will be exacerbated when there are multiple types of transmitters, especially if they are owned by multiple entities, which may make it difficult to determine which party is responsible for the interference.

Additionally, harm claim thresholds may not be applicable for crucial safety-of-life systems, like radio altimeters, which may require very high levels of interference-free availability. However, this would likely depend on when a harm claim threshold was established: if established first, a receiver that rejects out-of-band interference poorly should not be approved for use in a safety-of-life service; here, the threshold would define the limit to the interference a neighboring device may contribute.

A final consideration for the viability of harm claim thresholds is that allowing for some levels of interference may still have associated negative mission-impact risks that would be unacceptable for critical missions.

6.4.2 Rulemaking Process

In the rulemaking process, the regulator may mandate specific performance standards and improvement mechanisms. This would require developing specific rules for certain bands. Traditionally, for RF transmitters, these rules might define how the spectrum can be used in terms of power, band, location, and equipment. For receivers, parameters that might be regulated would include those that control how resilient a receiver in a given band, for a given service and/or location, is to out-of-band emissions; e.g., a receiver's sensitivity, blocking threshold, or other parameters outlined in Section 3.1.

The regulator may choose to incorporate industry standards in rules, or may base performance values on industry standards, manufacturers' technical filings and specification sheets, and standard reference works. It is important that industry groups are involved in the rule-making process to ensure that minimum standards are feasible and appropriate. Some examples of policy that incorporates industry standards are the FAA aviation receiver standards, and the FCC's use of American Society for Testing and Materials standards in the Dedicated Short-Range Communications (DSRC) service (47 CFR § 90.379).[8]

An advantage to mandating specific rules is that it provides the regulator with greater control over improvement mechanisms. Moreover, standardized rules provide greater transparency and ensure there is less uncertainty in the processes being followed.

However, imposing mandatory rules will involve much more engagement from the regulator. Likewise, formal rules could take longer to develop and require more time and costs to verify compliance. Additionally, mandating rules could limit flexibility in improvement mechanisms, which may cause pushback from industry groups. These rules may be particularly costly and difficult for small players to conform to, since they may have fewer resources to employ toward upgrade procedures. There is also risk that the mandated rules could be overly stringent.

As a result, rulemaking for every band and receiver is not practical. The focus should be on bands with new and/or changed allocations or licenses, such as new spectrum bands designated for commercial use, or bands of particular interest. The receivers to be considered could be limited to new receivers or only existing receivers in nearby bands of interest.

6.4.3 Reimbursement

Policy options for reimbursement include use of the Spectrum Relocation Fund, appropriations to federal agencies, and payment to commercial vendors for costs to improve receiver performance.

6.4.3.1 Spectrum Relocation Fund

If standards are mandatory, there could be a formal policy where a broadened and repurposed SRF is used to reimburse agencies for costs incurred to improve receiver performance. The benefits and challenges to this approach are similar to those outlined in Section 6.3.1.1.

6.4.3.2 Appropriations

Congress could provide appropriations to federal agencies to make receiver modifications and updates. An advantage to using additional appropriations for funding is that it will be provided to stakeholders that have sector-specific knowledge. Additionally, these agencies can use the appropriations to provide vendors with the necessary funding to make required performance updates. And, assuming that improvement mechanisms and performance targets are defined appropriately, the funding can help ensure that receivers will be compliant.

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[8] The FCC initially supported DSRC standard, by allocating spectrum for its use for road safety and intelligent transportation systems. However, in 2020 the FCC announced a decision to reduce the amount of spectrum and allow the remaining portion to be used either by DSRC or by Cellular Vehicle-to-Everything (C-V2X) technologies, moving to a technology-neutral stance.

A significant challenge with using appropriations to fund receiver upgrades is that it requires Congressional approval. This may be difficult depending on the political climate and other priorities of the government.

In summary, appropriations are a reasonable policy option and should be considered primary to funding from pipeline and/or transition plans.

6.4.3.3 Subsidy

If requirements are mandatory, then there could be a formal policy where the government pays a subsidy directly to vendors to compensate them for receiver performance improvement costs. The benefits and challenges to this approach are similar to those outlined in Section 6.3.1.2.

6.4.4 Supporting Policy

This section covers policy options for data transparency and enforcement to support receiver performance improvement.

6.4.4.1 Data Transparency

Availability of accurate operating system performance data, interference metrics, and electromagnetic environmental impact data is foundational to conducting receiver interference immunity performance analysis and recommending and implementing solutions. Manufacturers of receivers could be required to make interference data publicly available. This information may include details on meeting standards for testing or characterizing resilience. This data would make it easier for users to make informed purchasing decisions. Likewise, if receiver performance data were made publicly available, it may increase the competitiveness of the market by acting as an incentive to improve performance standards. Moreover, sharing data involves little cost, assuming the data is already internally available, once the mechanism by which it is shared is determined.

A challenge with making data publicly available is to determine how to handle classified, proprietary, and other sensitive data. This may involve discussion between the regulator and agencies on how to define sensitive data. Likewise, the regulator would need to determine the mechanism by which data would be shared. For example, the regulator must consider factors such as: Would the data be part of a certification process? What data must be included? How will the data be shared (e.g., database, packaging)? Also, it is worth noting that publicly available data alone will not solve any issues with receiver performance. Rather, sharing data will need to be combined with other incentive or policy options.

In summary, it would be useful to increase data transparency, while protecting sensitive data, but this would not directly address receiver performance issues.

6.4.4.2 Enforcement

If requirements are mandatory, enforcement mechanisms must be considered.

New requirements will necessitate new procedures for testing and certifying compliance. This will involve testing and certification costs that will vary depending on whether manufacturers can self-certify that a device will not suffer from harmful interference or if the regulator mandates specific receiver performance requirements. Refer to Section 0 for current processes followed by manufacturers, regulators, and federal agencies.

Additionally, if violations to formal requirements are found, the regulator must consider appropriate responses, including actions and penalties for noncompliance. These could include warnings, fines, not authorizing the device, and pulling the product from the market.

6.5 Standards

Standards define acceptable parameters and performance bounds for classes/services of receivers that are developed by industry alliances and working groups.

An advantage to standards is that those developed for a given class of receivers will represent the technical consensus of SMEs knowledgeable about the receiver class and use case. Moreover, compliance with such standards should ensure spectrum coexistence among devices.

However, the overall effectiveness of standards to ensure improved receiver performance and heightened efficiency in spectrum usage is unclear and dependent on interests of the standards working group. Moreover, standards likely necessitate some defined minimum performance level from a regulatory authority.

In summary, the standards process provides an actionable means for defining improved receiver performance and has been used with success in many industries for similar technologies.

7 Summary, Key Findings, and Recommendations

7.1 Summary and Key Findings

The purpose of this report is to provide findings and recommendations to inform future NTIA policies pertaining to receiver performance. Receivers perform a crucial task in radio services, the criticality of which is growing apace with the nation's demand for spectrum. The contents of this report reflect the multitude of perspectives that could contribute to the development of receiver performance policies: technical and non-technical, historic and emergent, domestic and international. The major report components and key findings are summarized below, followed by our recommendations in 7.1.4.

7.1.1 Receiver Performance Degradation due to Interference

The review of receiver interference performance issues in Section 2 and Appendix A of the report focuses on common receiver architectures and the mechanisms through which interference can degrade receiver functionality. These sections collectively discuss the roles of various components such as antennas, filters, and amplifiers, highlighting how their characteristics —like directional sensitivity, frequency dependency, insertion loss, selectivity, and saturation—can impact overall performance. The discussion extends to mixers and other downstream components, underscoring the complexity of achieving optimal receiver performance amidst interference. Importantly, although receivers are generally designed to be receptive to desired signals within allocated bands or assigned channels, as noted by the FCC's Technological Advisory Committee (TAC) "[a]ctual receivers can only provide a finite amount of rejection of unwanted signals outside the assigned channel" due to "practical considerations, such as power consumption, size, and cost." MITRE agrees with this view, and the report details the trade-off continuum between receiver interference performance and receiver size, weight, and power, and cost (SWAP-C). Although increasing receiver performance may be helpful in some situations, other traditional spectrum management approaches (e.g., transmitter power limits on both wanted and unwanted signals, guard bands, allocating adjacent bands to like services) may be necessary in others. Conditions that may lead to adjacent-band coexistence issues that may not be resolvable through receiver improvements alone include services requiring high sensitivity receivers, high-powered adjacent-band services, proximate transmitters and receivers, and desired and interfering signals both near a common band edge.

Real-world examples of receiver performance issues in Section 2.3 illustrate the practical challenges of spectrum management due to receiver susceptibility to interference. Aviation navigation systems, such as the Instrument Landing System (ILS), have historically faced interference from FM broadcasting stations, necessitating the implementation of "FM Immunity" requirements. Another significant example is the ongoing controversy surrounding Ligado Networks' terrestrial network, which, despite numerous concessions, has raised concerns regarding potential interference risks to GPS systems. The deployment of 5G commercial mobile broadband networks has also raised concerns about potential interference with radar altimeters, leading to extensive testing to determine whether any risk exists and regulatory measures to ensure aviation safety. Prior studies by organizations like the FCC, NTIA, and international bodies have extensively explored various aspects of receiver interference performance. These studies assess receiver performance issues and identify a wide range of potential solutions from protection criteria that place limits on transmitters to defining limitations on receivers' ability to claim damages due to interference and the use of statistical models and risk measures for coexistence analysis. These prior studies also highlight the need for improved propagation modeling and the establishment of guidelines for receiver parameters in future coexistence studies. The prevailing view is to balance the burden of mitigating interference between transmitters and receivers, thereby ensuring effective spectrum management and minimizing performance issues.

The NTIA has released reports detailing the technical approach for analyzing and mitigating interference to federal radar receivers, providing quantitative assessments of the level of interference the tested receivers can withstand before degradation. Internationally, Europe's Electronic Communications Committee (ECC) has issued reports identifying important receiver parameters required for future coexistence studies. These parameters are crucial for adequately characterizing the level and impact of interference on receivers. The ECC has also introduced a "Receiver Resilience" metric, and issued reports highlighting specific examples of negative consequences of poor receiver performance and recommending receiver parameters that could be introduced in standards or regulations. It is important to note that ECC reports individually focus on specific receivers operating within one radio service and band. They do not attempt to provide general solutions applicable to all services and bands. It can be summarized that effectively managing receivers can provide positive impact across numerous situations, however, each situation requires a specific evaluation and performance recommendation.

7.1.2 Specification and Assessment of Receiver Performance

An examination of receiver standards, performance requirements, and the processes and best practices by which receivers can be evaluated for their performance is provided in Sections 3 and 4 of the report. This material collectively outlines measures by which RF devices can be certified to meet established performance standards and thereby minimize the risk of harmful interference in the electromagnetic spectrum.

The detailed steps involved in conformance testing, such as those described for NTIA and FCC equipment authorization, highlight the importance of comprehensive evaluation at various stages of a device's lifecycle. These steps include assessing transmitter and receiver characteristics, performing electromagnetic compatibility (EMC) analyses, and ensuring that devices meet specific performance metrics. The involvement of independent certification bodies and industry groups further enhances the credibility and reliability of the testing process, providing an additional layer of assurance that devices will perform as expected in real-world environments. This approach to testing and certification not only protects existing services but also facilitates the introduction of new technologies, fostering innovation while maintaining a stable and interference-free electromagnetic environment.

The testing and certification of receivers is necessary because it ensures that RF devices meet established performance standards, thereby minimizing the risk of harmful interference in the electromagnetic spectrum. The processes outlined by federal regulatory agencies like the NTIA and FCC, as well as independent certification bodies, provide a structured approach to evaluate and verify that receivers can operate effectively within their designated frequency bands without causing or experiencing interference. This is particularly important as the demand for wireless communication continues to grow, leading to more crowded and complex spectrum usage. By adhering to these rigorous testing and certification procedures, manufacturers can ensure that their devices are compliant with regulatory requirements, which in turn helps maintain the integrity and reliability of critical communication systems, including those used in aviation, defense, and public safety.

7.1.3 Mechanisms to Improve Receiver Performance

The examination of technical mitigations in Section 5 and Appendix A for receiver performance issues outlines practical strategies and emerging technologies that can significantly enhance the resilience of receivers to interference. By encouraging best practices such as using directional antennas, sufficient filtering, and ensuring linear operation of components, the likelihood of receiver performance issues in the presence of interference can be minimized. These practices are essential for maintaining the integrity and reliability of communication systems. Additionally, the adoption of modern methods like forward error correction and interference cancellation can further improve interference tolerance, making it possible for different RF systems to coexist more harmoniously.

Receiver examination on emerging technologies such as adaptive array antennas, low SWAP-C filters, and advanced LNAs and mixers highlights the potential for significant improvements in receiver performance. These advancements can help address the challenges posed by the increasing number of bands utilized by modern communication systems like 5G. The National Spectrum Strategy's emphasis on encouraging private entities to improve receiver immunity to harmful interference underscores the importance of these technical mitigations. By developing a roadmap for improving receiver immunity and considering additional standards and performance requirements, NTIA and FCC can help promote the development of receivers that are better equipped to handle interference, thereby enhancing spectrum efficiency and enabling the introduction of new technologies. This proactive approach not only protects existing services but also fosters innovation, ensuring that the spectrum can support a wide range of applications and services in the future.

Non-technical mitigations in Section 6 discuss potential incentives and new policy ideas to improve receiver performance. The information on non-technical mitigations for receiver interference performance issues is crucial because it addresses the economic, policy, and regulatory aspects that are essential for implementing effective solutions. Non-technical challenges such as the costs associated with receiver upgrades, the designation of responsible parties, and the planning and evaluation of the upgrading process are significant hurdles that need to be overcome. These challenges include both direct costs, like design and testing, and indirect costs, such as service disruptions and increased risks to key missions. Additionally, deciding which parties—whether government, vendors, or service providers—should bear these costs is a complex issue that requires careful consideration. Addressing these challenges is vital for ensuring that any technical improvements to receivers are feasible and sustainable in the long term.

There are benefits to improving receiver performance, when feasible. Enhanced receiver performance can lead to more efficient and effective use of the radio frequency spectrum, a critical national resource that is in high demand but limited in supply. This improved efficiency can support more users and applications, leading to economic and societal benefits such as higher gross domestic product (GDP), economic growth, and job creation, and better balancing of spectrum requirements across national security, economic, and other interests. Incentive mechanisms can motivate stakeholders to adopt better-performing receivers, while policy options can provide a framework for sustainable improvements. By addressing both the challenges and opportunities, non-technical mitigations play a fundamental role in optimizing spectrum management and ensuring the reliable operation of fundamental communication systems.

7.1.4 Key Findings

The complexity and diversity of the environments in which receivers operate preclude universal receiver rules and regulations as a practical technique for spectrum management.

Every band, radio service, and application has unique features that warrant special consideration. Additionally, there are limits to a receiver's ability to reject interference, even in the case of well-designed receivers and when the interference energy is confined to frequencies outside of the allocated band for the desired radio service. This is often the case for federal systems. Relying on receiver performance alone to ensure coexistence between adjacent-band radio services is most difficult when:

- High sensitivity receivers are required to process desired signals that are very low in power (e.g., within radars, satellite navigation, radio astronomy, passive sensors).
- Adjacent-band transmitters are high-powered or can be very close to the receiver.
- Desired and adjacent-band interfering signals are both near the common edge of the allocated band.
- The existing systems are difficult (e.g., expensive or inaccessible) to replace or modify and there is no obvious near-term benefit.

In many of these cases, other interference-mitigation approaches (e.g., transmitter limits, guard bands, and system approaches) may need to be considered.

Despite these limitations, there are a number of broad steps that NTIA can take to improve the receiver performance of federal systems.

These broad steps are the focus of the recommendations below.

7.2 Recommendations

MITRE recommends that NTIA take the following actions:

Recommendation #1: *Implement specific mitigations on a case-by-case basis, prioritizing bands being studied for repurposing.* Consider implementation of receiver interference-mitigations on a case-by-case basis as bands (or neighboring bands) are studied for repurposing. This approach allows for recognition of the unique characteristics of many federal systems and the need to consider the full range of options to optimize receiver protection.

In bands being studied for repurposing, NTIA should issue guidance for agencies to consider incorporating receiver performance improvement costs into their spectrum pipeline and transition plans for SRF funding consideration as applicable. To the extent it is necessary to assess the interference immunity performance of fielded equipment, the report identifies a set of best practices in Section 4.3 including developing inventories of fielded makes/models of receivers and testing all or at least a representative subset against relevant types of interference.

Recommendation #2: *Develop a policy statement and roadmap for improving receiver performance.*

- *NTIA should issue a policy statement.* A formal NTIA statement, like the one issued by the FCC in April 2023, would pave the way for additional receiver performance improvement measures. These could include incentives to motivate the implementation of receiver performance improvement measures and mechanisms to reimburse stakeholders for costs incurred to improve receiver performance.
- *Address data collection and transparency.* Section 10.8.7 of the NTIA Manual specifies receiver characteristics that are required from Federal agencies seeking NTIA Certification of Spectrum Support for radio systems. This set of characteristics, which includes filter characteristics of various receiver front-end stages, is useful but incomplete for coexistence studies considering all of the mechanisms by which interference can degrade receiver performance (see Section 2.2 and Appendix A of this report). NTIA should consider changes to Section 10.8.7 of the NTIA Manual to collect alternative, more relevant receiver characteristics such as blocking interference levels as a function of frequency at the receiver input.

  Additionally, NTIA should collaborate with the FCC to issue guidance and best practices addressing data transparency, specifically approaches to increase transparency into physical layer data on RF performance and interference while still protecting sensitive information in the data fields or RF signature, to enable more advanced data analytics supporting efficient and effective spectrum use.
- *Perform a companion study to develop best practices for transmitter performance.* Some subject matter experts that MITRE interviewed for this study noted that, for some neighboring bands, unwanted emissions from transmitters that fall within the allocated band for a receiver was the dominant cause of coexistence issues. In such cases, consistent with the FCC's April 2023 Policy Statement, modification of regulatory limits on the transmitters should be considered. NTIA might consider a study on transmitter performance, focusing on their ability to control unwanted emissions outside of their allocated band, as a follow-on to this study on receiver performance.

- *Recommend best practices for receivers*. For this report, MITRE interviewed multiple receiver vendors and found that they are generally well aware of methods that could be used to make their receivers more resistant to interference. However, as summarized within this report, there are SWAP-C implications of such design changes, and receiver vendors need to carefully balance performance and SWAP-C. Furthermore, receiver vendors noted that occasionally customers provided receiver specifications that did not include adherence to 47 CFR requirements such as NTIA's updated radar spectrum engineering criteria (RSEC). NTIA should recommend best practices, such as those outlined in *Best Practices for Designing Interference-Resilient RF Receiving Systems* (see A.5 for a summary), to educate and encourage federal agencies to procure receivers that are more robust and conform with applicable 47 CFR rules. The best practices could also be used as a basis for vendors to demonstrate their level of adherence to design practices based on common guidance.

MITRE recognizes that NTIA must prioritize and/or procure more resources to implement recommendations to improve the receiver interference immunity performance of federal systems.

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Appendix A Receiver Architectures and Interference Mechanisms

A.1 Common Receiver Architectures

A.1.1 Single-Conversion Superheterodyne Receiver

A block diagram of the single-conversion superheterodyne receiver is shown below. The concept is to down-convert the incoming RF signal to a common IF frequency. The RF bandwidth of the pre-selector and image reject filter may be quite large in comparison with the IF filter bandwidth. The IF filter will typically have a bandwidth consistent with the modulation bandwidth of the desired signal. With the IF bandwidth set in accordance with the expected modulation it helps band limit the noise entering the baseband processing and demodulation sections of the receiver. Down-converting to a fixed IF frequency typically allows the IF filter to have sharp selectivity. SAW filters are often employed in the IF sections [71] [72].

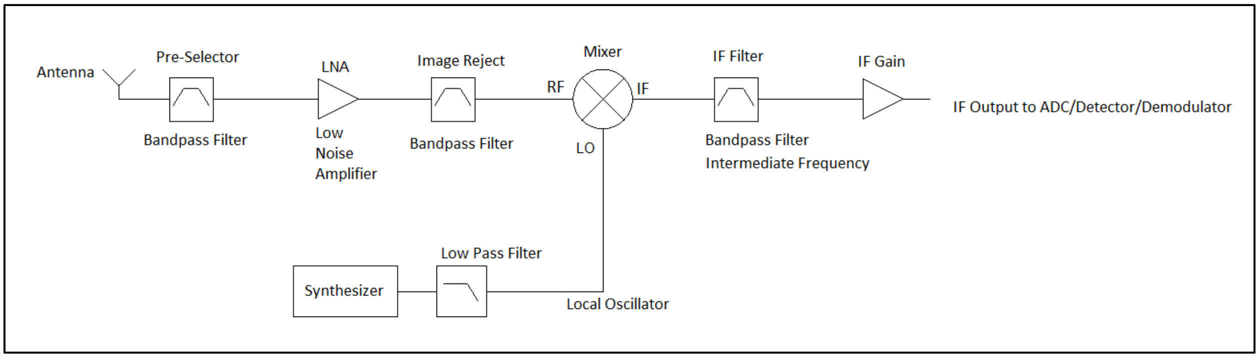

Figure A-1: Single-Conversion Superheterodyne Block Diagram

A.1.2 Dual Conversion Superheterodyne Receiver

A dual-conversion superheterodyne architecture is shown below. Triple conversion receivers are also possible. The need to use dual or triple conversion is governed by the frequency plan and the required selectivity of the system [71] [72].

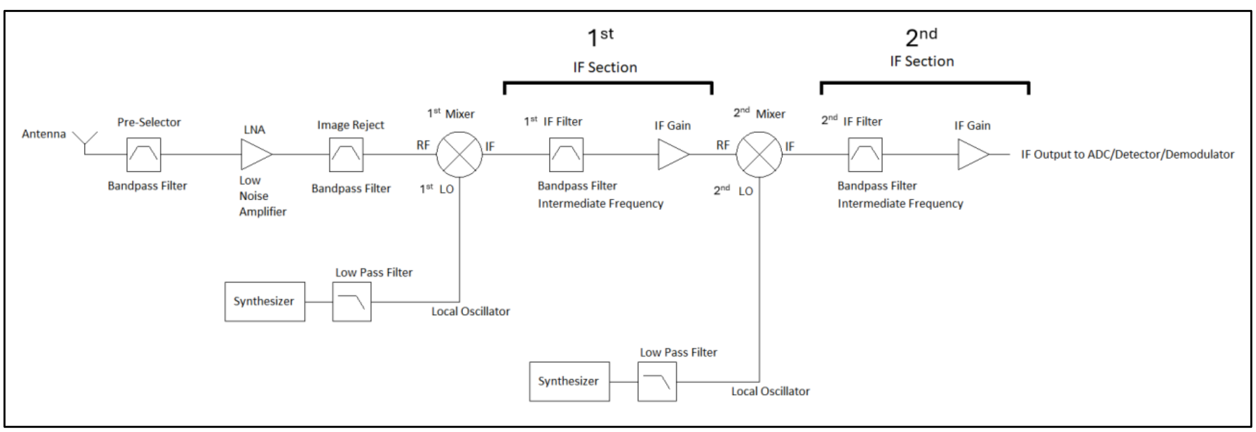

Figure A-2: Dual Conversion Superheterodyne Block Diagram

A.1.3 Direct-Conversion (Zero-IF) Receiver

A direct-conversion receiver block diagram is shown below. The incoming RF signal is split into two paths. Each RF path is then mixed with the in-phase and quadrature phase of the local oscillator. The resulting IF paths are then low-pass filtered. The LO frequency is set to match the incoming RF frequency. The resulting I and Q paths contain the baseband signal of interest [73].

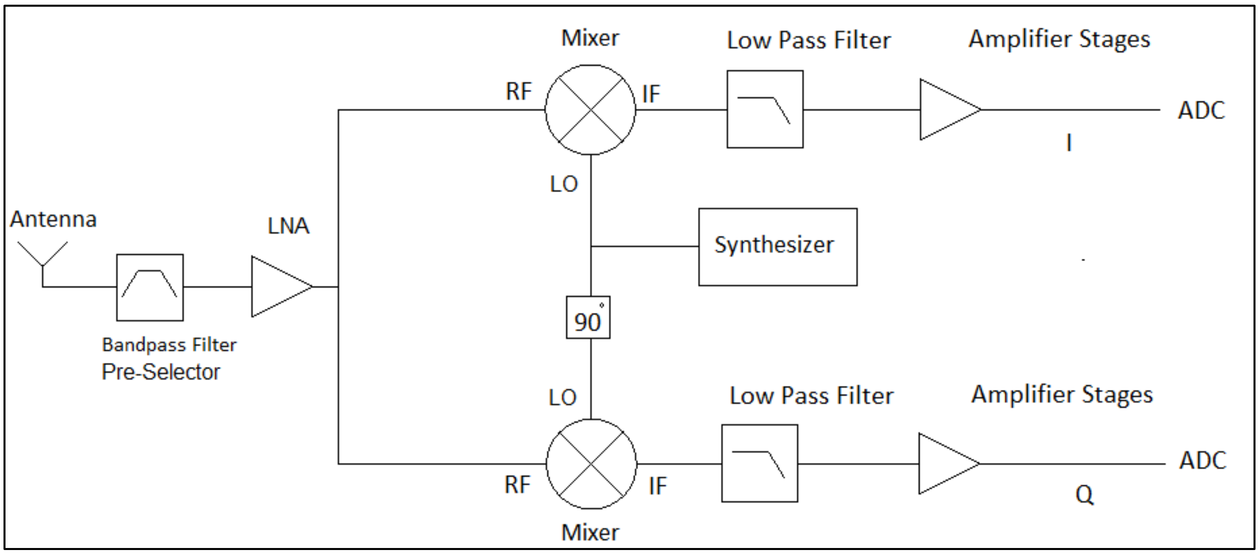

Figure A-3: Direct Conversion Receiver Block Diagram

An example of the Direct Conversion architecture can be found in the block diagram of the Analog Devices AD9361 transceiver.

A.1.4 Direct RF Receiver

Technology advances in ADC design in recent years have led to the development of direct RF sampling receivers. These receivers require no mixing or down-conversion. The incoming RF is directly sampled by the ADC. Direct sampling of L (1 – 2 GHz) and S (2 – 4 GHz) bands is now possible [74]. Although direct RF sampling receivers can provide very wide bandwidths, they have many associated implementation issues including some related to interference immunity. An overview of tradeoffs of direct RF sampling vs more traditional receiver architectures is provided in [75].

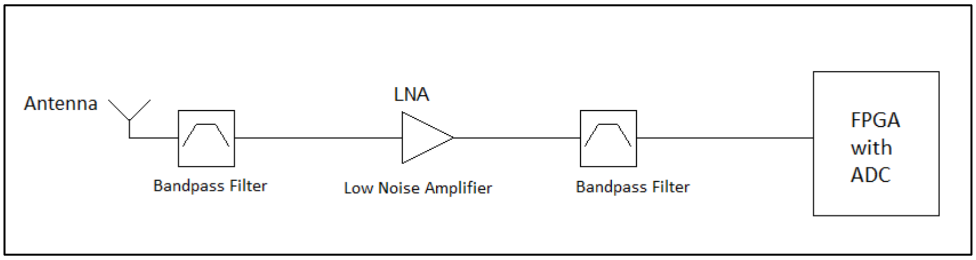

Figure A-4: Direct RF Sampling Receiver Block Diagram

A.1.5 Summary of Common Receiver Architectures

- Heterodyne – The heterodyne architectures involve at least one mixing stage and in some cases two to three mixing stages to translate the incoming RF signal down to an IF, which is passed to the baseband processor. These architectures require significant frequency planning to ensure spurious signals will not mix into the desired passband. Heterodyne architectures are generally complicated, but they do have the ability to provide high selectivity and high linearity. The number of components involved in the design of heterodyne receivers can also drive up the cost, size, weight, and power consumption [71].
- Homodyne (direct conversion, zero-IF, direct-IF) – The homodyne receiver directly converts the incoming RF signal to baseband. This is achieved by splitting the path of the RF signal and mixing it with a local oscillator and the quadrature phase component of the local oscillator. The local oscillator is tuned to the same frequency as the incoming RF signal. Consequently the I and Q resulting channels contain the baseband spectrum. As RF is converted directly to baseband, the terms zero-IF or direct conversion are often used to describe the receive architecture [73] .

  The homodyne receiver does not require image rejection filters. In general it is a simpler/lower cost design than heterodyne receivers. Depending on the bandwidth of the captured signal, the overall sampling speed of analog to digital converters is less demanding [73].
- Direct sampling – Advances in analog to digital converter technologies have enabled the development of direct sampling receivers. No mixing is required. The receiver typically employs bandpass filtering for the band of interest and a low noise amplifier. The inherent RF signal is then sampled at a high data rate. The direct sampling of L-band and S-band signals is currently achievable.

A.2 Receiver Components

A.2.1 Antennas

In any wireless RF communication, radar or sensor system, the antenna is the first component in the receiving system's RF chain. The antenna is the system component that transduces the incident electromagnetic field into an RF voltage and current (and power) in the receiving system. All antennas are passive, in that the transduction function is passive and requires no direct current (DC) power to the antenna. Any DC power supplied to an antenna is to power a separate active device such as a low noise amplifier.

The antenna is impedance-matched to the receiving system within a specified Voltage Standing Wave Ratio (VSWR), which can be translated into a frequency-dependent mismatch loss that determines how much power is delivered to the receiving system. From the receiving system's perspective, the antenna is the first bandpass filter in the system, but only plays a modest role in rejecting OOB emissions and associated interference.

Typically, antennas are specified for a maximum in-band VSWR of 2:1 to 3:1, depending on the application. Some applications, such as cellular base-station antennas, may have VSWR requirements as low as 1.2:1. The 2:1 and 3:1 VSWRs translate to mismatch loss values of 0.5 dB and 1.25 dB, respectively. While not always the case, generally, the antenna's equivalent bandpass filter response falls off faster at lower frequencies than it does at higher frequencies and the antenna correspondingly rejects interference better at lower frequencies than at higher frequencies. A typical antenna VSWR plot is shown in Figure A-5.

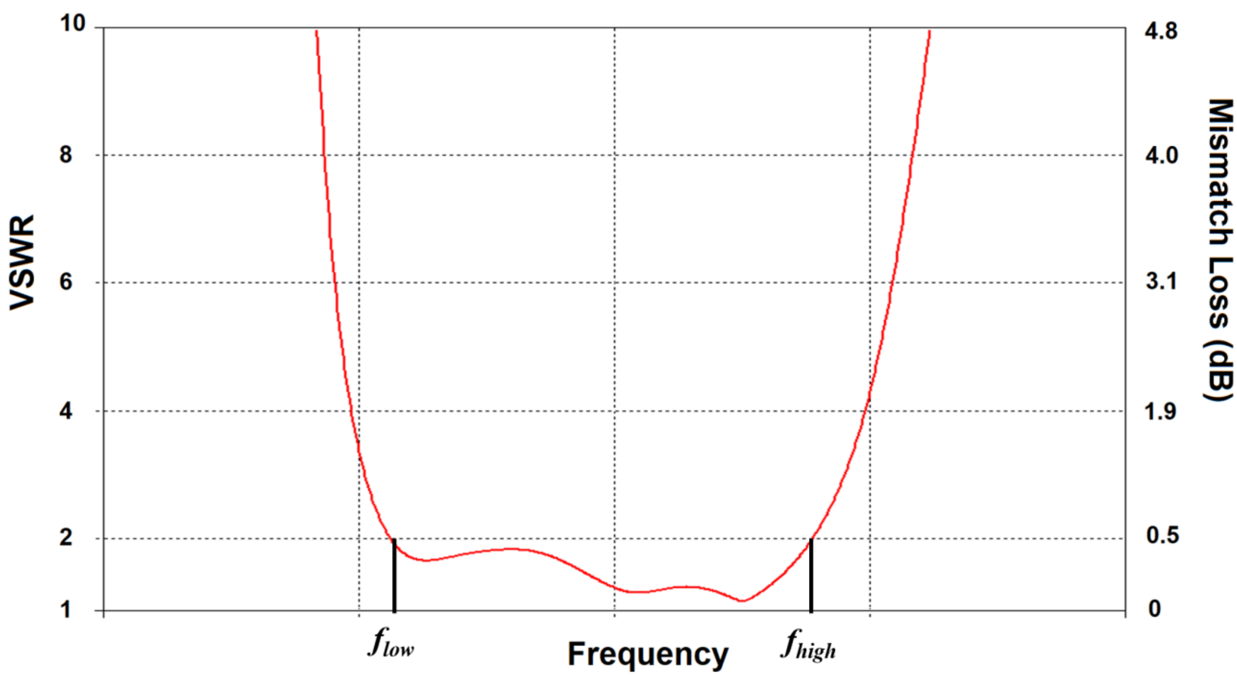

Figure A-5: Typical VSWR for a Receiving Antenna

From Figure A-5, we see that an antenna VSWR of 10:1 translates to a mismatch loss of 4.8 dB. To provide 10 dB of OOB interference rejection, the antenna VSWR must be 38:1. To provide 20 dB of OOB interference rejection, the antenna VSWR must be 400:1, which is atypical of most antennas in frequency ranges within reasonable proximity of the receiving system's operating band. While antennas do provide some level of OOB interference rejection, because of the high values of VSWR necessary to provide 10 dB to 20 dB of rejection, the antenna is not considered a significant bandpass filter and other mechanisms of frequency dependent rejection are implemented within the receiving system.

If the antenna is connected to the receiver by means of a hollow metallic waveguide, as is common at microwave frequencies in larger devices such as radars, the phenomenon of waveguide cutoff could be used to provide nearly absolute protection against relatively low-frequency OOB interference. Standard rectangular waveguides are sized so that their cutoff frequencies are about 80% of their normal operating range. For example, a radar tunable from

8.2 to 12.4 GHz could use WR-90 waveguide, whose cutoff frequency is 6.56 GHz, and so the radar would be essentially immune to antenna-coupled interference from any signals below that cutoff frequency.

To be more effective as a mechanism to mitigate in-band and OOB interference, the antenna can be designed to exhibit a directional radiation pattern, or an active or adaptive antenna can be used to null out interference from specific directions. These technologies are discussed in the following subsections.

A.2.1.1 Directional Antennas

While all antenna radiation patterns are technically directional, antennas and their associated radiation patterns are generally classified as omnidirectional and directional. An omnidirectional antenna's radiation pattern is typical of dipole-like or monopole-like antennas and exhibits constant gain in one plane, typically the horizontal or azimuth plane as shown in Figure A-6. The directional antenna's radiation pattern is more focused and generally has a significant increase in gain in one direction. A typical directional antenna radiation pattern is presented in Figure A-7. Note that antenna gain is not like that of an active amplifier; rather, antenna gain is passive and is a measure of how focused the antenna beam pattern is relative to a hypothetical, isotropic antenna that has a uniform radiation pattern in all directions. However, while passive in nature, an increase in antenna gain by X dB will increase the received power by X dB.

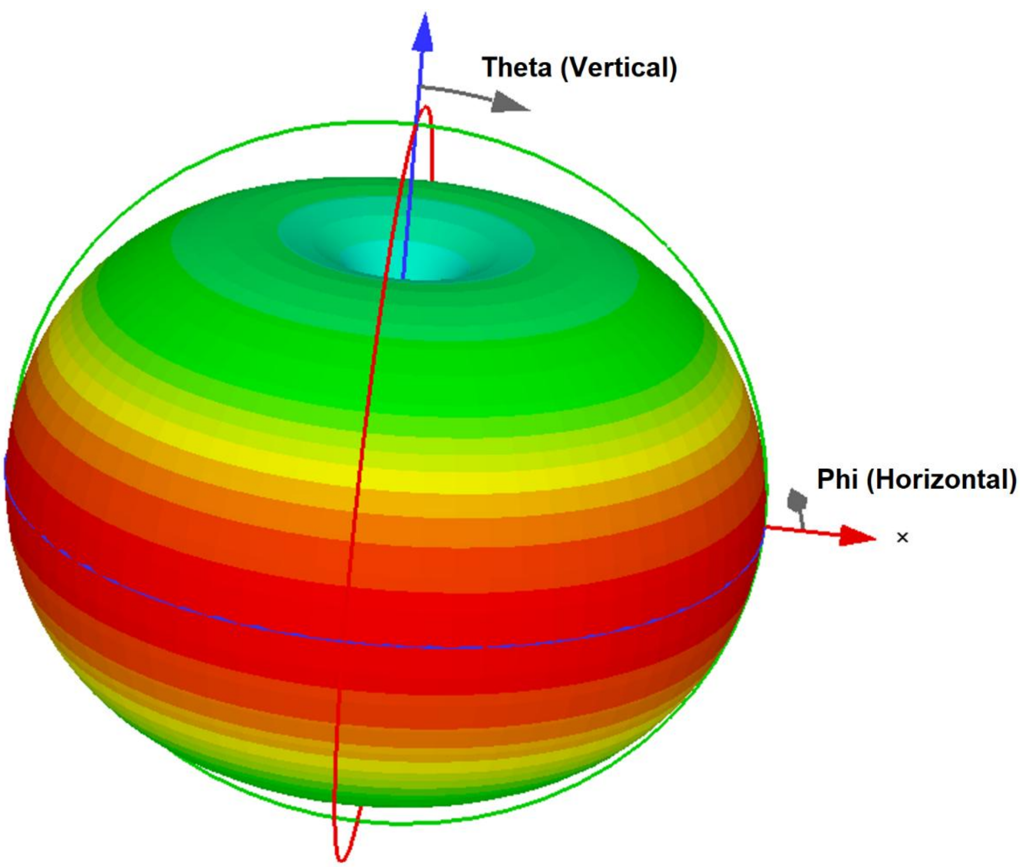

Figure A-6: Typical Radiation Pattern of an Omnidirectional Antenna

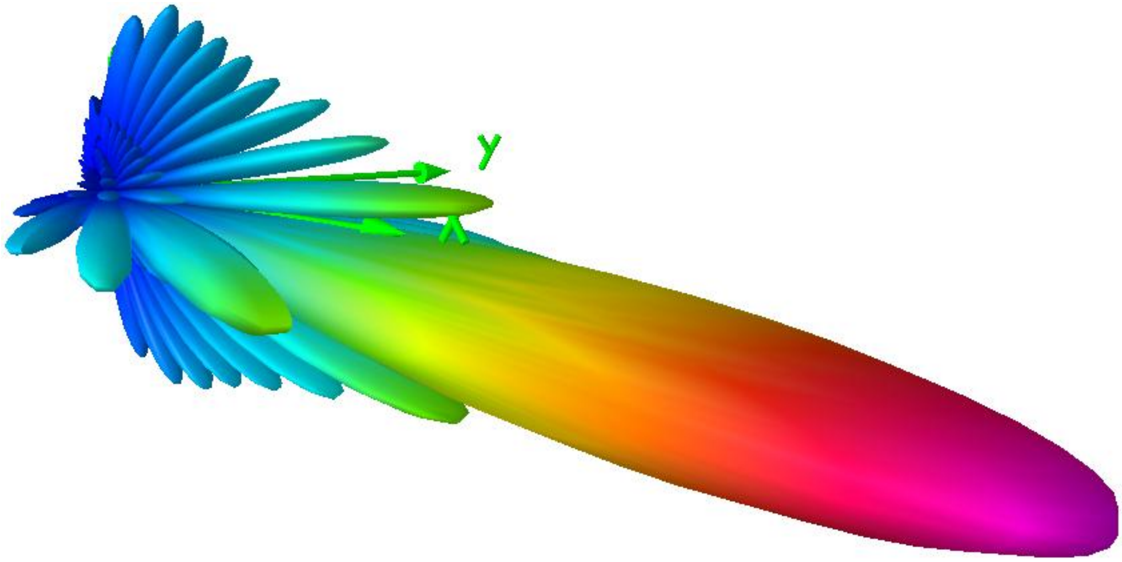

Figure A-7: Typical Radiation Pattern of a Directional Antenna

Omnidirectional antennas, having a radiation pattern that receives signals from 360° in azimuth, are highly susceptible to in-band and OOB interference. Fixed beam directional antennas (i.e. non-adaptive antennas), having a highly focused radiation pattern, are less susceptible to interference in angular regions outside their main beam. They are, however, still susceptible to in-band and OOB interference from transmitters within their main beam. Note that regions within the directional radiation pattern with high side lobes may still be significantly susceptible to interference. The constraint of using a fixed beam directional antenna is that it must be pointed toward the desired transmitter, which therefore limits the antenna's use to point-to-point communication systems.

A.2.1.2 Adaptive Antennas

Adaptive antennas are a special class of antennas that can adapt their radiation or beam pattern to a set of desired characteristics and capabilities that include, but are not limited to:

- The capability to form a directional beam pattern that can point to any direction within a defined angular range
- The capability to form multiple, simultaneous directional beams that can point in different directions
- The capability to form multiple, simultaneous nulls that can point in different directions to mitigate noise, multipath, and interference
- The capability to implement real-time tracking of radar targets or multiple users in a communication system
- The capability to implement real-time angle-of-arrival determination for geolocation purposes

Adaptive antennas are known in the industry by many names including phased arrays, electronically scanned arrays, beamforming arrays, smart antennas, adaptive arrays, digital beamforming arrays, and more recently MIMO antennas.

Receiving adaptive arrays typically comprise many directional, passive antennas or "elements" where the element received signals are combined in either the analog or digital domains using different amplitudes and phases to form a single receive beam in a specific direction or multiple receive beams in many directions. The amplitude and phase weighting can also be adjusted to form nulls in one or several directions to mitigate interference from these directions. An adaptive array that uses digital beamforming (combining signals in the digital domain) offers the most flexibility in terms of beamforming capability and the number of simultaneous receive beams that can be formed.

5G deployments at both sub-7 GHz and mm-Wave bands use adaptive arrays and are commonly called Advanced Antenna Systems or Active Antenna Systems. A notional 5G base station array is shown in Figure A-8 and has a total of 96 dual-polarized elements. The array's signal processing backend has the capability of implementing numerous MIMO beam sets from 2T2R (2 transmit beam and 2 receive beams) to 64T64R (64 transmit beams and 64 receive beams).

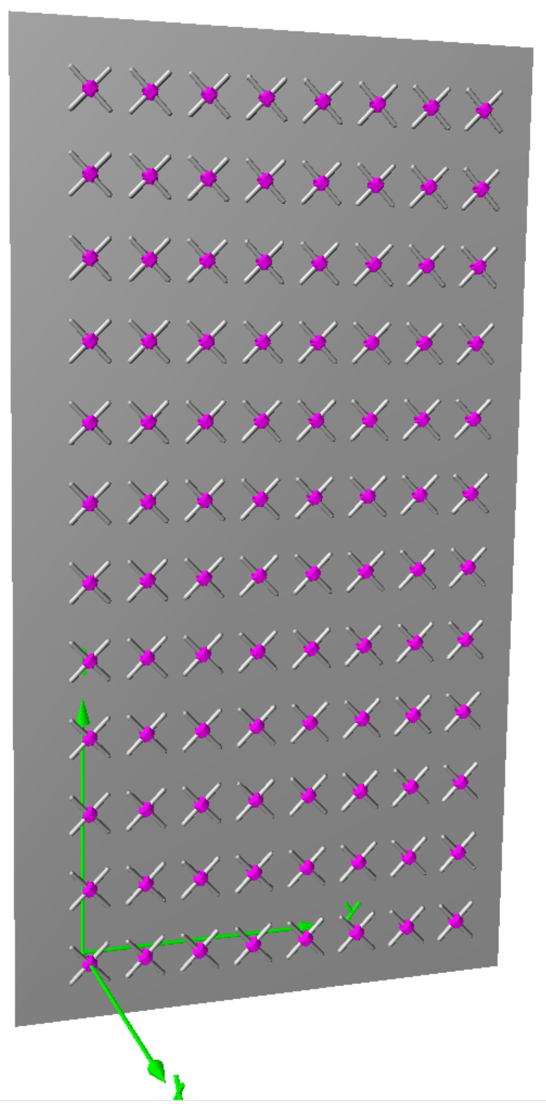

Figure A-8: Notional Depiction of a 5G Base Station Antenna System

The advantage of using adaptive or MIMO antenna systems in 5G and future communication systems is that it allows the system to be more resilient to in-band and OOB interference by adaptively optimizing beamforming for individual users or smaller coverage regions.

A.2.2 Filters

Receiver filtering protects the receiver from unwanted interference. In general, the first filter after the antenna will cover the band of operation of the receiver. For very wideband receivers, the band may be broken into sections through switch filter banks or through the use of multiplexers. In the heterodyne receiver front end, filtering that is placed after the antenna and prior to the first mixing stage must reject image frequencies. In a superheterodyne architecture, filtering after the mixer provides additional selectivity.

Common filter topologies include Butterworth, Chebyshev, Bessel, and Elliptic function filters. This is not an all-inclusive list; other topologies exist. Butterworth filters provide flat amplitude response, Bessel filters are employed for flat group delay[9] response, and Chebyshev filters tend to have steeper skirts in terms of selectivity; however, this comes with the trade-off of ripple in the amplitude passband. Elliptic filters have initial steep roll-off but they also have amplitude ripple in the stop-band. The terms Butterworth, Chebyshev, Bessel, and Elliptic describe primarily the mathematical analytic response of the filter designs. However, they do not describe the physical implementation of the design. The implementation will drive the cost, size, and weight [76].

Table A-1: Common Filter Topologies

Filter Response	Comments	Pros	Cons
Butterworth	Based on Butterworth Polynomial. Provides maximally flat amplitude response in the passband. "6n" dB/octave roll-off where "n" is the number of reactive elements.	Flat amplitude response.	Poor impulse response in the region near cutoff.
Chebyshev	Based on Chebyshev Polynomial. Selectivity/roll-off is a function of passband ripple and order of the filter.	Provides good out-of-band rejection. Can provide steep roll-off.	Pass-band amplitude ripple. Group Delay/Impulse response improves at the cost of reducing how fast the roll-off occurs.
Bessel	Gaussian type filter.	Produces maximally flat group delay. Best impulse response.	Poor selectivity and roll-off.
Elliptic		Fast roll-off.	Out-of-band amplitude fly-back.

Another consideration is the bandwidth of operation for the specific receiver. In general, sub-octave filters are desirable to reject transmit harmonics. In the case of extremely wideband

[9] *Group delay* is a measure of how the delay of a signal passing through a system or filter varies with frequency; a "flat" group delay indicates there is little to no spreading in frequency as the signal passes through the system (i.e., all frequencies in the signal are delayed by the same amount).

receivers that cover multiple octaves of bandwidth, designers should evaluate reasonable options that will meet the needs of the application. Examples include the use of switched filter banks for sub-octave filtering, the use of RF/microwave multiplexers for sub-octave filtering, and the use of tuned filters.

Of the filter topologies described, the Bessel filter typically has the slowest amplitude roll-off and generally poor selectivity in comparison with other topologies [76] [77]. However, specific receiver applications may require flat group delay. Flat group delay within the filter passband has traditionally implied or necessitated a slow amplitude roll-off in terms of selectivity. The traditional Bessel filter selectivity may leave the receiver vulnerable to interference. Today, however, with advances in electromagnetic (EM) and RF simulators, research has been ongoing to develop filters with flat in-band group delay and sharp out-of-band rejection. One such example is outlined in the following reference [78].

The topologies described above reflect design objectives for filters. Implementation requires selecting among numerous technologies that include:

- Dielectric resonators – Dielectric resonators are a very popular technology for RF and, occasionally, IF filters. These filters use small discs or cubes of low-loss high dielectric constant material as coupled microwave resonators to provide a low-cost, high-selectivity bandpass response [79]. They are also often referred to as ceramic filters, since ceramic is a common dielectric material used in their fabrication. Ceramic filters tend to have a very well-behaved frequency response (e.g., repeatable from unit to unit), have very good bandwidth and rejection performance, and are preferred for lower volume high-performance receivers.
- Surface acoustic wave (SAW) – SAW filters are available for both RF and IF frequencies of up to about 2.5 GHz. SAW RF filters use resonators that operate by converting the input electrical signal into acoustic waves, using printed coupled resonant transducers, that propagate along the surface of a piezoelectric substrate [80]. They are inexpensive and typically much smaller than dielectric resonators, which makes them an extremely popular choice for applications where size is of utmost importance, such as for receivers integrated into cellphones and other mobile devices.

  Unfortunately, there is little uniformity in the frequency response characteristics between different SAW filters, which makes generalizing their performance difficult. Older SAW filters exhibited great variation in center frequency with temperature, with a typical temperature coefficient of -30 ppm/ºC. So, for instance, over the temperature range of –30ºC to +85ºC, the center frequency of an older SAW filter operating in L-band (1000–2000 MHz) may vary by more than 5 MHz. Temperature-compensated SAW filters are now readily available with near-zero temperature coefficients but with slightly increased costs due to the complexity of their fabrication. At the lower IF frequencies, SAW filters use surface waves as time delay elements to achieve a finite element response (FIR) filter response similar to that resulting from digital filters. This is in contrast to implementing more traditional resonator style RF filters of higher frequency SAW devices.

  In FIR filters, amplitude and phase response are independent, which allows simultaneous near-brick-wall frequency response and relatively flat group delay characteristic. In addition to the obvious benefits of passing the signal with little amplitude and phase distortion, the sharp transition region between the pass and reject bands suppresses interference signals that can be very close to the signal, which pass through the less selective RF circuits. Unfortunately, however, implementing the surface acoustic time delays necessary inside the device results in a large insertion loss as shown in the receiver model, as well as large absolute time delays between the terminals of the actual physical device. Further, small but finite reflections within the device will cause a small amount of amplitude and phase ripple to be measured on the device response.

- Bulk acoustic wave (BAW) – BAW filters [81] operate in a similar fashion to SAW filters in that they both operate through the use of resonators in which electrical signals are converted to acoustic waves. The difference between BAW and SAW filters is that in BAW filters the acoustic waves propagate through the substrate rather than along the surface before they are converted back into electrical signals. BAW filters have surpassed SAW filters in mass-market RF applications because they can offer lower insertion losses and improved selectivity. BAW filters are readily available for frequencies up to about 6 GHz, and researchers have demonstrated operation of some BAW filters up to 24 GHz [82]. BAW filter technologies include free-standing bulk acoustic resonators and solidly mounted resonators. Older, uncompensated BAW filters tended to exhibit less sensitivity to temperature (by about two-fold) than uncompensated SAW filters, and as with SAW filters temperature-compensated products are readily available with near-zero temperature sensitivity. A principal BAW drawback with respect to SAW filters is that they are more difficult to manufacture and thus slightly more costly.
- Cavity filters – Cavity filters [79] offer low insertion loss and high out-of-band attenuation, with their main drawback being that they are extremely large and heavy. They operate using principles similar to those used by dielectric resonators, except that they utilize an air-filled cavity within a conductor rather than a dielectric block as the microwave resonator.
- Lumped Element Filters – Filters built using inductors, capacitors, and resistors are used at low-RF, IF, or baseband within many fielded receivers. Some lumped element filters that only utilize inductors and capacitors are referred to as LC filters, which follows from the common engineering symbols for inductance (L) and capacitance (C). Many receiver chipsets utilize external discrete inductors and capacitors as their only means for IF filtering. LC filtering suffers from filter response and group delay issues. It is difficult to obtain LC components with sufficient tolerance to ensure good response repeatability during manufacturing. They do have the advantage of better amplitude and phase ripple, and somewhat better insertion loss than SAW filters; however, they are not able to attenuate interference sources immediately adjacent to the passband as effectively as SAW IF filters. The amount of attenuation provided by such filtering depends on the design bandwidth of the LC filter and the order of the filter. Active resistor-capacitor filters are also quite common as are chipsets. These offer the benefit that they can be implemented internal to the chip; see, e.g., [83].

Although any of these technologies may be utilized in designs that employ the filter topologies described earlier, there are always imperfections such as parasitic resistances, inductances, and capacitances that vary with frequency and result in some undesired characteristics. As discussed in Section 2.2, technology selection for receivers involves trade-offs between performance (selectivity, insertion loss, differential group delay) and SWAP-C. As an example of these tradeoffs, Figure A-9 illustrates a size comparison of several RF bandpass filter options for a center frequency of 2 GHz and a 3-dB bandwidth of 60 MHz. The filter sizes and costs shown on the figure are representative of currently available, commercial products. Representative selectivity performance of these filter technologies is shown in Figure A-10. The cavity filter provides the best rejection of adjacent- and out-of-band interference, providing over 90 dB of attenuation at frequencies far from the center frequency, but it is significantly larger, heavier, and more costly than the alternatives. The SAW filter is the smallest and least expensive option, but provides the worst selectivity performance with less than 40 dB of attenuation at frequencies distant from the center frequency.

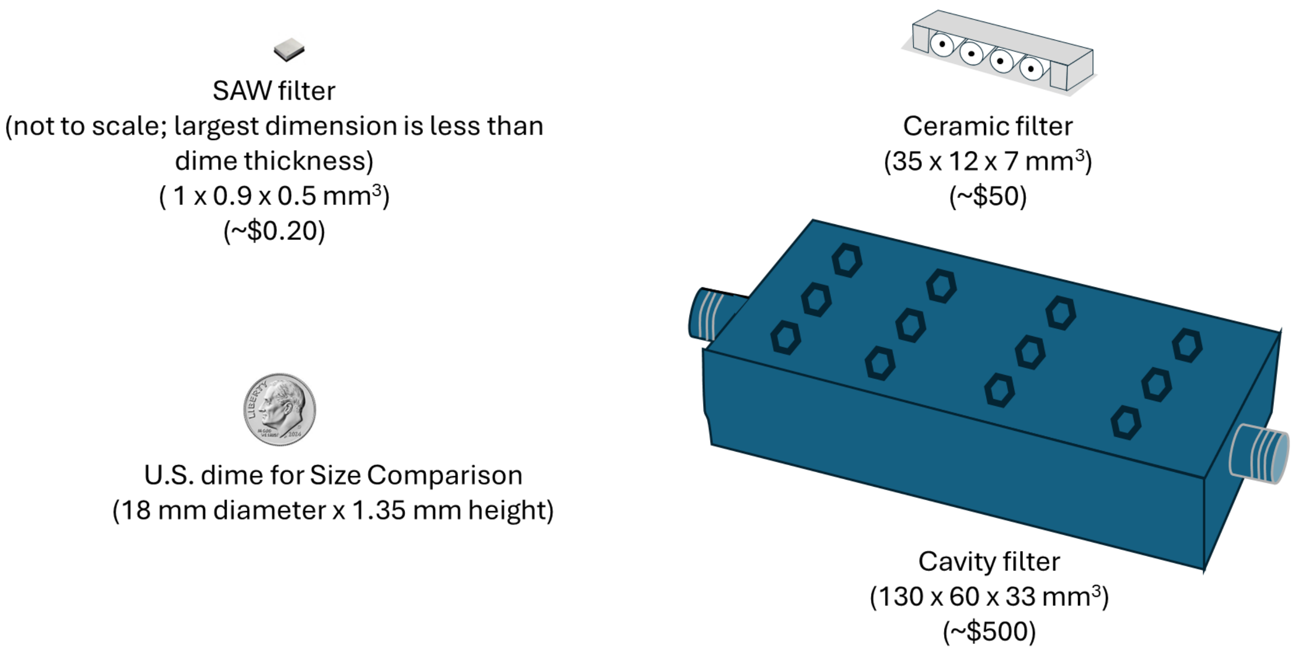

Figure A-9: Size Comparison of SAW, Ceramic, and Cavity Bandpass Filters with 2 GHz Center Frequency

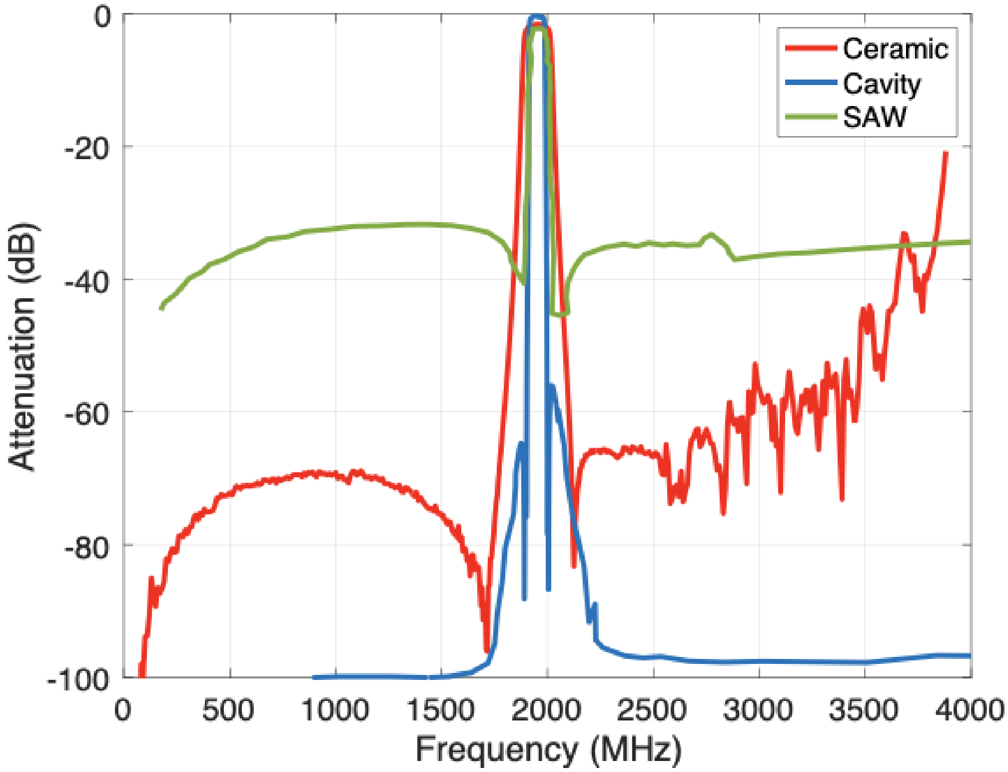

Figure A-10: Selectivity Performance Comparison of SAW, Ceramic, and Cavity Bandpass Filters with 2 GHz Center Frequency

An example of a sixth-order filter that achieves high selectivity and relatively flat group delay performance is discussed in the references. The design has relatively good out-of-band rejection. This particular filter exhibits higher passband insertion loss than what would typically be desired for a receiver front end [84].

Other examples of high-selectivity filters with flat group delay can be found in [85]. The particular filter operates in the 40 GHz region. High selectivity, flat group delay, and low insertion loss were noted.

Beyond the initial roll-off or selectivity of a bandpass filter, consideration also needs to be applied to the stopband or out-of-band rejection. Resonant structures based on quarter wavelength transmission lines, cavity filters, or acoustic wave filters can have spurious frequency responses providing poor out-of-band attenuation [86]. These regions typically occur at harmonics of the fundamental frequency, or in some cases due the physical nature of the filter the ultimate out-of-band rejection breaks down.

A conventional third-order microstrip hairpin filter is also discussed in the references. The S21 plot shows its attenuation in the vicinity of the second-harmonic spectral region is very poor [86].

However, methods to improve the second harmonic region were notes. The researchers noted the effects of the periodic rectangular grooves on layout which provided a vast improvement in the attenuation of the second harmonic region [86]. This further demonstrates how advances in modern EM simulators allow for the research and improvement of filter designs.

In summary, a review of recent technical literature demonstrates that microwave filter designs continue to progress and improve. Advances in EM simulators now allow for the research and development of filters that continue to evolve in performance.

A.2.3 Amplifiers

The first amplifier after the antenna is typically a low-noise amplifier that tends to set the overall noise figure and minimum sensitivity level of the receiver. Trade-offs in the receiver design need to balance the need for gain, noise figure, and linearity of the receiver. Generally high gain and low noise figure provide for a sensitive receiver; however, this comes with a trade-off in dynamic range and linearity as high-gain amplifiers typically have low power level input compression points. Amplifiers placed after the LNA, such as those in the IF section of a heterodyne receiver, play less of a role in setting noise figure and are generally chosen for high linearity attributes [72] [71].

A.2.4 Mixers

Mixers are typically active or passive in design. They are non-linear devices and mathematically behave as multipliers. The passive double balanced mixer can achieve high input compression points and good third-order intercept response. The linearity attributes of the double balanced mixer correlate with the local oscillator drive level. Consequently, a double balanced mixer with a +13 dBm LO drive level will outperform a similar mixer with a +7 dBm LO drive level in terms of third-order intercept performance. The active Gilbert cell mixer has the advantage that it can be placed in small monolithic microwave integrated circuit packages. However, it generally has diminished linearity with respect to the passive double balanced mixer designs [71] [72].

A.2.5 Frequency Synthesizers

In receiver architectures with mixers, such as the heterodyne approach, the synthesizer provides the tuning capability of the receiver. The synthesizer generates the local oscillator signal(s). The synthesizer is an intricate subcircuit and its operation is governed by control-loop theory. The frequency lock time, loop bandwidth, phase margin, and gain margin of the control loop within the synthesizer are critical parameters for design consideration. In general, the synthesizer operates from a very stable fixed frequency reference oscillator that is tolerant of the operating temperature for the receiver application. From this fixed frequency reference, the synthesizer will generate local oscillator signals that can be tuned to allow the receiver to operate over the frequency band of interest [72] [71].

A.2.6 Automatic Gain Control

Automatic Gain Control (AGC) is applied in a receiver to provide the same performance from the receiver while its input RF signal is varying over a range of levels. AGC is usually applied to the receiver's RF and IF stages and serves the purpose of maintaining the demodulator input at a near constant level. The AGC circuit forms a control loop and consequently is governed by control loop theory in terms of parameters such as feedback, response time, and stability. In the simplest case a detector is used to the sense the power level of the incoming RF/IF signal, the sensed level is translated to a corresponding control voltage, and the control voltage is applied to voltage controlled variable gain amplifiers or variable attenuators in order to provide the demodulator with a near constant IF signal level. In general, the control voltage has a linear correspondence to the sensed RF/IF signal power level. The design requirements for response time of the AGC loop is based, in part, upon the signal modulation. The response time is how fast the AGC reacts to changes in the incoming signal level. It is sometimes referred to as the attack time. The AGC does not react immediately to changes in signal level. It will hold for an averaging period and then move accordingly. The goal is to avoid triggering a change in AGC level due to any abrupt, instantaneous change in RF/IF signal level such as a brief transient signal fade [72].

AGC circuitry can significantly impact a receiver's immunity to interference. For instance, as noted in [87] a simple AGC approach is to apply the control voltage directly to the bias of a simple transistor amplifier. In this case, the VGA will have the undesired characteristic in that its compression level can lower significantly in some operational situations. More sophisticated circuitry included in some commercial RF integrated circuit (RFIC) devices strive to implement a far more ideal gain control curve than that of a simple transistor under bias gain control. However, depending on the particular implementation, they will also have other parameter variations as the gain control is varied. An idealized model of a VGA would contain a fixed amplifier plus variable attenuator. If the variable attenuator is in front of the amplifier, the VGA noise figure would be a function of the control voltage and the output compression point would remain constant. This is the preferred characteristic of an AGC that is more resistant to interference.

A.2.7 Baseband Processing

In modern receivers, baseband processing begins at the ADC. Here the analog IF signal or analog baseband signal is converted, through the action of the ADC, to digital data. At its most basic level the baseband processor will demodulate the incoming signal to useful data that is specific to the receiver's application. The baseband processing may be fairly simple or extremely complex and consist of devices such as custom programmed FPGAs (Field Programmable Gate Arrays), DSPs (Digital Signal Processors), and digital filters.

A.3 Interference Mechanisms

This section describes some common interference mechanisms to receivers.

A.3.1 Spurious Due to Image Frequency Blocker

The image frequency is separated from the desired frequency by a factor of two times the IF frequency in heterodyne receivers. The resulting spurious signal is converted by the receiver and falls on the same channel as the desired signal. The front-end pre-selector filter and the image reject filter typically protect the receiver from this type of spurious signal [71] [72].

A.3.2 ½ IF Spurious Due to Single Tone Blocker

The ½ IF spurious response can be generated by a single tone in-band or out-of-band blocker. The key parameter of importance is the second-order intercept point of the receiver. Within superheterodyne architectures this is typically governed by the mixer second-order performance.

The interference occurs when, internal to the receiver, the second harmonic of the blocking signal mixes with the second harmonic of the local oscillator. The spurious interference arises when a strong interference signal is present at ½ the IF frequency away from the desired signal [71] [72].

A.3.3 LNA Desensitization Due to Single Tone Blocker

The front-end LNA of the receiver typically sets the overall noise figure of the receiver and thereby the minimum sensitivity of the receiver. A strong single tone blocking signal that compresses the LNA will reduce the gain of the LNA and increase the noise floor on the output of the LNA [88].

A.3.4 Co-Channel Noise Due to Single Tone Blocker

An in-band single tone blocker that is in close frequency proximity to the desired signal will undergo reciprocal mixing in the receive channel. The blocker will mix with the phase noise of the local oscillator and this noise will be translated onto the desired IF channel and thereby act as co-channel interference. The blocking mechanism is due to the reciprocal mixing. More specifically it is not due to compression of the front-end LNA, the mixer, or other front-end components [89].

A.3.5 Co-Channel Noise Due to Out-of-Band Transmitter

Transmit signals can have significant out-of-band noise. Transmit noise falling within the receiver bandwidth can mask weak desired receive signals. In this case, filtering by the receiver will not be effective since the noise is within the receiver bandwidth.

A.3.6 Third-Order Intermodulation Spurious

Many "linear" elements within receivers actually have non-linear responses meaning their transfer functions comprise both the desired fundamental response and higher-order elements; the response of such "weakly non-linear" elements can be described by the power series expansion [90]. Such non-linear elements will create intermodulation products, known as intermodulation distortions, between disparate pure tones within a received signal. In the nominal, two-tone case, a received signal comprising pure tones f_1 and f_2 will pass through a non-linear element in a receiver, like an amplifier, adding frequency content to the signal at $mf_1 \pm nf_2$, where *m* and *n* are integers. The "order" of the distortion created by these products is given by the sum of *m* and *n*.

While many of these intermodulation products can be filtered out in post-processing, the third-order intermodulation distortion produced at $2f_1 – f_2$ and $2f_2 – f_1$ can prove particularly difficult to filter because it falls very close to the original tones, f_1 and f_2. Third-order intermodulation distortion also causes issues in communications systems where channels are close together or adjacent in frequency. An example of how third-order intermodulation distortion could affect such a system is shown in Figure A-11. Here, if Channels 3 and 5 are selected for use, third-order intermodulation distortion products will appear at 2*1.25 – 1.35 = 1.15 MHz and 2*1.35 – 1.25 = 1.45 MHz, meaning Channels 1 and 7 will not be suitable for use.

Channel	Center Frequency (MHz)	Status
1	1.15	Unavailable
2	1.2	Available
3	1.25	Selected
4	1.3	Available
5	1.35	Selected
6	1.4	Available
7	1.45	Unavailable

Figure A-11: Channel Planning in a System with Channels Spaced 50 kHz Apart. When Channels 3 and 5 are used, intermodulation distortions appear at Channels 1 and 7, making them unsuitable for use.

A useful parameter for understanding how resilient receivers are against third-order intermodulation distortion is Intermodulation Rejection (IMR). The equation used for calculating IMR is shown below:

$$IMR = \frac{1}{3}(2\,IP3 - 2S - CR)$$

Where:

IMR is the Intermodulation Rejection (dB)

IP3 is the input third-order intercept point (dBm)

S is the sensitivity of the receiver (dB)

CR is the co-channel rejection (dB)

In the above equation, the third-order intercept point represents the theoretical point where the third-order intermodulation distortion products are equal in amplitude to the desired signal's power. The IMR therefore is a calculation of the difference in sensitivity of the receiver and the input power level necessary to create interference.

A.3.7 Composite Triple Beat

The composite triple beat can develop in multi-carrier systems. Three or more interference tones create in-band on-channel interference. The interference forms through the combination of the multiple interference tones. [71].

The resulting composite triple beat tone is 6 dB higher than the third-order intermodulation discussed previously. If the interference tones and the desired channel are all equally spaced, then the resulting triple beat can fall directly on the desired channel [71] [91] [92].

A.3.8 Further Discussion on Common Receiver Interference Mechanisms

- *In-band interference* – In-band interference refers to either noise, spurious signals from external sources that fall within the receiver's band of operation, or signals from other services in the band that are sharing either legitimately or illegitimately. Wideband noise from nearby transmitters can fall within a receiver band and degrade receive sensitivity and in particular the reception of signals at or very close to the receiver minimum sensitivity level.

  Strong blocking signals that fall within the receiver band may be strong enough to compress the front-end low noise amplifier and consequently desensitize the receiver.

  Strong spurious signals that fall within the receiver band, even if not strong enough to compress the LNA, may still create reciprocal mixing products with the phase noise of the local oscillator and/or spurious signals on the local oscillator that fall within the IF bandwidth. This creates co-channel interference and degrades the sensitivity of the receiver.

  Strong spurious signals that fall within the band of receiver may also generate internal harmonics within the receive chain that mix with the fundamental or harmonics of the LO. The resulting spurious signals can fall within the IF bandwidth and create co-channel interference.

- *Reciprocal mixing* – The case where a strong spurious signal at the input to the receiver mixes with the noise sidebands of the local oscillator to produce co-channel interference at the intermediate frequency is the process of reciprocal mixing [93].

- *Image response* – The image-frequency spurious response is separated from the desired receiver frequency by a factor of two times the intermediate frequency in heterodyne receivers. The resulting spurious signal is converted by the receiver and falls on the same channel as the desired signal. The front-end pre-selector filter and the image-rejection filter typically protect the receiver from this type of spurious signal [71] [72].

- *Other spurious responses* – Other spurious responses can occur due to either receiver in-band interference or out-of-band interference. Strong signals located outside the receiver passband may interfere with receiver performance. This is typically due to poor filter selectivity in the front end of the receiver. The image response is an example of an out-of-band interference signal. The ½ IF response is also a particularly troublesome response. The ½ IF interference occurs when, inside the receiver, the second harmonic of the blocking signal mixes with the second harmonic of the local oscillator. The spurious interference arises when a strong interference signal is present at ½ the IF frequency away from the desired signal [71] [72].

  More generally, spurious responses due to the mixer within a heterodyne receiver can be described by the following expression:

  $$f_{IF} = |m \cdot f_{LO} \pm n \cdot f_s|$$

  where *m* and *n* are positive integers (including zero).

f_{LO} = local oscillator frequency
f_s = any frequency entering the receiver
f_{IF} = intermediate frequency which feeds to the baseband processor.

The equation allows for the calculation of spurious signals f_s entering into the IF region. Since f_s can be any signal, the equation also applies to the desired response [71] [72].

- *Aliasing* – Aliasing within a receiver is related to the sampling frequency of the analog-to-digital converter (ADC) and the incoming frequency. The Nyquist criterion states the sampling rate of the ADC must be at least twice the highest frequency in the signal to be sampled. If the incoming signal fails to meet the Nyquist criterion, then aliasing can occur. The system cannot sample the incoming signal fast enough. This incoming signal will be sampled and folded down into the frequency spectrum creating an alias signal. To prevent this, an anti-alias filter is employed. This filter significantly attenuates any signals entering the ADC that violate the Nyquist criterion. For example, if the ADC samples at 40 MHz, the anti-alias filter will significantly attenuate any signals at or above 20 MHz. Aliasing is a consideration in receiver design. In modern architectures the careful understanding, analysis, and use of different Nyquist zones allows for desired results with under-sampling ADCs [94].

  Figure A-12 illustrates the trends in ADC performance over the past several decades. Each point depicted in the figure represents the performance (sampling rate in megasamples/second and depth in bits) of a representative commercial ADC product with the year it was introduced noted in parentheses. Note that ADC performance with respect to both attributes (sampling rate and depth) has increased significantly over the years. Digital filtering is increasingly used within receivers to suppress adjacent-band interference as available ADC sampling rates and depths continue to grow. Importantly, the receiver's front end must remain linear (i.e., not saturate) for digital filtering to be an effective solution to mitigate interference effects.

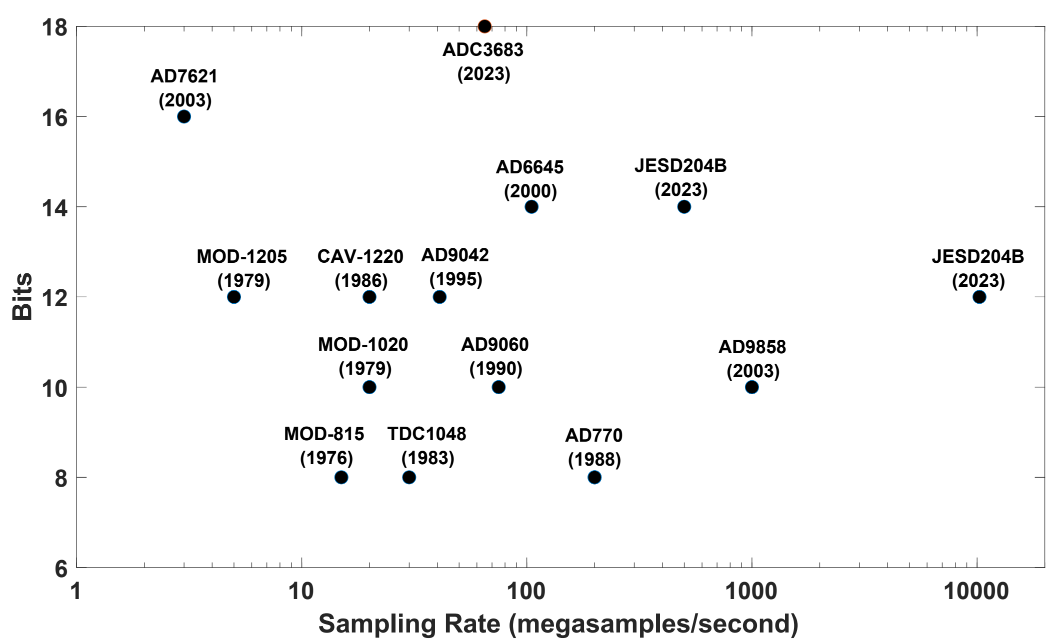

Figure A-12: Trends in Analog-to-Digital Converter Performance

- *Compression* – Compression of amplifiers occurs due to the physical limitations of the device. For small signals, the gain is relatively constant at a given frequency. As the signal input power increases, a point is reached where the gain begins to diminish. For RF amplifiers, the typical standard is to measure the 1-dB gain compression point, which is the power measured at the output of the amplifier when gain has diminished by 1 dB from the small-signal gain [71]. Figure 3-3 shows an example of gain compression.
- *Intermodulation* – Due to non-linear effects within the receiver, sum and difference frequency products form. The products of concern are those that fall within the receiver's band of operation. Third- and second-order products are of primary concern and are related to the receiver's third-order and second-order intercept points [72]. The third-order intercept point is discussed in A.3.6. The second-order intercept point is described in A.3.2.
- *EM coupling* – Isolation and grounding are critical to filter performance on printed circuit boards. Application notes from surface-mount filter manufacturers describe best practices for mounting RF filters on printed circuit boards (PCBs). Isolation of the input and output traces is critical at microwave frequencies. A filter that expects 50-dBc (decibels referred to the carrier) selectivity may only exhibit 30-dBc selectivity due to poor isolation of traces [95]. Likewise, poor grounding can reduce the filter's rejection by 20 dB. Pin-mounted filters should be avoided at microwave frequencies and it may be difficult to achieve 60 dBc rejection [95]. Consequently, off-the-shelf surface-mount filter performance should be verified on the actual PCB to ensure the filter is meeting the manufacturer's specified criteria. Poor PCB layout, grounding, and isolation may limit the filter's performance [95].

A.4 Mitigation of Interference: Key Concepts

- *Additional filtering* – For legacy systems or those already deployed in the field, it may be possible to place additional filtering on the front end of the system to improve overall selectivity. However, an analysis would be required to ensure the additional insertion loss of the new filter would not degrade the noise figure significantly and thereby degrade the system sensitivity. Another factor to consider is that receivers typically have a pre-selector filter directly at the front end where the antenna feeds to the receiver. Simply combining an external filter with the original front-end filter may not yield the desired results. Typically cascading two filters without some isolation between them can lead to poor selectivity in regions of the spectrum [71]. Consequently, analysis and testing would be required to ensure the desired selectivity performance is actually achieved.

  Beyond this, many fielded systems will be so integrated that the ability to place an external filter to block out-of-band spurious signals on the front end will not be feasible without a redesign of the system.

- *Linearity and dynamic range* – Improving the linearity of receiver designs will help with improving desensitization due to compression and generation of internal harmonics. However, increased linearity typically comes at the cost of additional current or voltage. For double-balanced mixers, improved IM performance requires higher LO oscillator drive levels. Increases in current-voltage characteristics or LO drive level implies an increase in power consumption, and for battery-operated devices the increase in linearity will impact battery life. Increased power consumption also has thermal implications as additional heat will need to be dissipated. Newer advances in gallium nitride (GaN) technology have led to the development of some high linearity low noise figure devices. For example, Qorvo has developed GaN amplifiers that include low-noise gain blocks such as the QPA9127 that operate into C-band with typical parameters of 1.4-dB noise figure, 20-dB gain, and 19.5-dBm output compression [96].

- *Other considerations* – Best practices in RF layout are required to ensure front-end RF filters are achieving the required rejection. For example, a stand-alone surface-mount filter may be measured on an evaluation board and exhibit exceptional selectivity and out-of-band rejection. However, when placed onto the actual PCB, poor layout, grounding, or isolation may degrade the actual performance of the filter. Additionally, impedance mismatch at a less-than-ideal connection may cause a portion of the signal to reflect back, a condition measured by the system's "return loss" in dB (note that lower values of return loss indicate more signal reflection, whereas an infinite return loss indicates the ideal case where no signal is reflected). Consequently, it is critical that during the design phase, verification is performed on the completed PCB or assembly to ensure the filter passband and selectivity characteristics are meeting requirements.
- *Applicability to fielded receivers* – As discussed in the previous paragraph, a case-by-case analysis would need to be performed to determine if providing an additional external filter is feasible without degrading other receiver performance parameters. Highly integrated receivers and handheld receivers may preclude the use of additional external filtering and require redesign.

A.5 Best Practices for Designing Interference-Resilient RF Receiving Systems

At the time of the writing of this report, MITRE is concurrently developing *Best Practices for Designing Interference-Resilient RF Receiving Systems*, to be released by NTIA in 2025. The purpose of this document is to include recommendations for:

- Selecting and implementing particular receiver components such as antennas, filters, and amplifiers in ways that will reduce the likelihood of out-of-band radio-frequency interference (RFI). When a recommendation would also help prevent in-band RFI, we note that fact as well.
- Avoiding receiver performance degradation that might result from inappropriate or excessive application of certain RFI-prevention techniques. The definition of "excessive" depends on the intended environment of the receiver.
- Ensuring that receivers intended for use by the U.S. Government will comply with all interference-prevention rules mandated in such cases.

We summarize the best practices detailed in this document below.

System-Level Considerations

Protect the system against adjacent-band RFI (present and future), as well as RFI that might originate within a transmitter of the same system to which the receiver belongs.

- Federal agencies procuring receiving systems should ensure that system specifications include requirements for continued operation in the presence of out-of-band interference that may be expected in spectrally proximate bands. Importantly, these requirements should not assume that the current use of adjacent spectrum will remain in place over the lifetime of the equipment. Many issues have resulted from such an assumption when the adjacent-band spectrum becomes repurposed.
- If the receiving system is part of a transceiver, care must be taken to prevent transmitter system noise from entering the passband of the receiver via shared components such as antennas.

Antennas

When designing or selecting an antenna for a receiving system, look for opportunities to suppress possible RFI by utilizing antenna directionality, adaptive beamforming and null-steering, and the inherent frequency selectivity of the antenna and its feed line.

- If the receiver location is fixed and the desired signal's direction of arrival (DOA) is predictable (e.g., in a radar or a point-to-point communications system), the receiving antenna should be directional. This protects not only against out-of-band but also in-band RFI.
- Shrouding a microwave dish receiving antenna can reduce undesired signals entering the receiver via the antenna's far sidelobes. This protects not only against out-of-band but also in-band RFI.
- If size, weight, and power, and cost (SWaP-C) permit, consider using a multiple-input, multiple-output (MIMO) receiving antenna with adaptive beamforming and null-steering. This protects not only against out-of-band but also in-band RFI.
- Within receiving systems that utilize waveguides, waveguide cutoff can effectively eliminate out-of-band interference at frequencies less than about 80% of the frequency at the lower end of the receiver's tuning range.
- Loose, cracked, or rusty bolts can be prolific radiators of harmonic or intermodulation interference and so should not be allowed to exist in an antenna, its feed line, or its rotary coupler (if any). This protects not only against out-of-band but also in-band RFI.

Filters

Employ filters as necessary to suppress unwanted signals and other undesired emissions, while avoiding unwanted side effects and remaining within tolerable SWAP-C limits.

- Receiving systems should include filters to suppress unwanted emissions at frequencies outside of the desired passband. Well-designed receiving systems often include multiple filters distributed throughout the equipment (e.g., within an active antenna, at the receiver RF input, and within various down-conversion stages). This protects not only against out-of-band but also in-band RFI, when IF filters are used.
- An "ideal" filter (unattainable in practice) would provide: high out-of-passband attenuation; little insertion loss, flat group delay, and ripple-free amplitude response within the passband; rapidly decaying impulse response; temperature stability; and low

SWaP-C. Choosing real-world filters involves numerous trade-offs amongst these parameters.

Amplifiers

When designing or selecting amplifiers, strike a balance between enhancing receiver sensitivity and avoiding desired-signal distortion.

- If maximum receiver sensitivity is desired, put a high-gain LNA in the receiver front end. Typically, a filter is placed between the antenna port and the LNA in order to attenuate incoming spurious signals.
- LNAs will distort input signals, including desired in-band signals and unwanted out-of-band signals, when their input power becomes too strong.
- Precede LNAs with filters to protect against strong out-of-band RFI.
- LNA gains should not be so high that they limit the dynamic range through restricting the upper bounds of incoming signals. The compression point of the LNA is the limiting factor on an LNA. Exceeding the compression points will result in signal distortion.
- Amplifiers placed after the LNA, such as those in the IF section of a superheterodyne receiver, should be chosen for high linearity attributes, to avoid signal distortion.
- Active antennas are used as part of some receiving systems, in which filters and LNAs are included within the antenna form factor.

Mixers

When designing or selecting mixers, try to achieve high input compression points without unduly diminishing linearity.

- Passive double-balanced mixers can achieve high input compression points and a good third-order intercept response.
- Active Gilbert cell mixers can be placed in small monolithic microwave integrated-circuit packages, but generally at the cost of diminished linearity in comparison with passive double-balanced mixer designs.

Automatic Gain Control (AGC)

Accomplish AGC in a manner that will not unduly lower the receiver’s compression level.

- A simple AGC design approach is to apply the control voltage directly to the bias of a simple transistor amplifier, but in some operational situations this may significantly lower the compression level.
- Placing a variable attenuator in front of a variable-gain amplifier (VGA) can help to stabilize the output compression point and thus help to protect the receiver against interference.

Analog-to-Digital Conversion (ADC)

Use ADCs in conjunction with filters so that signal components whose frequencies exceed half the sampling rate will be well attenuated.

- If incoming signals may sometimes contain frequency components exceeding half the sampling rate of the ADC, thus violating the Nyquist criterion, an anti-aliasing filter should be included to attenuate those components and minimize the resultant distortion.
- In modern architectures the careful understanding, analysis, and use of different Nyquist zones allows for desired results with under-sampling ADCs. With under-sampling, anti-alias filters are required. The anti-alias filter design specifications are dependent on the Nyquist zone.

Prevention of Non-Antenna-Coupled Interference

Prevent RFI from originating within the receiver or entering it along pathways that bypass the antenna.

- Signal traces on printed circuit boards (PCBs) should be isolated and grounded when RF filters are mounted on the boards, to prevent degradation of filter performance.
- Pin-mounting of filters should be avoided at microwave frequencies.
- Local-oscillator (LO) emissions should be shielded sufficiently to prevent them from interfering with other components of the receiver (or exceeding the receiver's tolerable spurious-emission limit).
- Filter performance should be verified on completed PCBs or assemblies to ensure that the device is meeting the specified passband and selectivity criteria.
- Shielded cavities should be analyzed during the design process with electromagnetic (EM) simulation tools to ensure oscillations will not occur at microwave frequencies. Subsequent testing of systems should be carried out to verify performance.
- PCB layout design rule checks should be utilized to verify there are no floating ground planes or unattached copper sections.
- Proper layout and grounding vias should be applied in accordance with component vendor datasheets to ensure performance.
- In U.S. military systems, the requirements of MIL-STD-461G RE102 (radiated electric-field emissions) and RS103 (radiated electric-field susceptibility) must be met.

Interference Mitigation

When retrofitting or redesigning a receiver to mitigate known cases of interference, ensure that the mitigation technique will not degrade the receiver's performance in other ways.

- When considering additional filtering to improve selectivity of preexisting receivers, take care to ensure (by analysis and testing) that the additional insertion loss would not significantly degrade the receiver's noise figure and sensitivity, and that the cascaded filters will be sufficiently isolated from each other to avoid interactions that would cause poor selectivity at some frequency offsets.
- Improving the linearity of receiver designs can help reduce desensitization that has been caused by compression and generation of internal harmonics. It also reduces amplifier distortion. This protects not only against out-of-band but also in-band RFI.

- When seeking to improve receiver linearity and dynamic range by increasing LO drive levels, keep in mind the resultant increase in power consumption with its possible adverse thermal effects and reduction of battery life.

Rules for Federal Receivers

When designing or specifying receivers for Federal agencies, comply with all applicable Government requirements unless previously waived, including:

- The receiver-related requirements embedded in Section 5 (Spectrum Standards) of the latest edition of the NTIA Manual *(Manual of Regulations and Procedures for Federal Radio Frequency Management),* issued by the National Telecommunications and Information Administration (NTIA).
- If the receiver is to be part of a radar, the requirements of Section 5.5 (Radar Spectrum Engineering Criteria (RSEC)) in the latest issue of the NTIA Manual.
- All parts of the Title 47 of the Code of Federal Regulations (47 CFR) identified in the NTIA Manual as requirements for the relevant class(es) of receiving systems.
- If the receiver is intended for U.S. military use, DoD MIL-STD-461G's requirements for control of conducted and radiated electromagnetic interference.

A.6 Emerging Technologies

Earlier subsections of this appendix have discussed some emerging technologies that can facilitate improved receiver interference immunity. These include:

- More capable adaptive array antennas.
- Continued progress toward the implementation and performance improvement of low SWAP-C filters at a wide range of frequencies. Research in this area is largely motivated by the growing number of bands utilized by 5G mobile devices. Some 5G mobile devices require over 100 bandpass filters. These are largely bulk acoustic wave (BAW) devices, but some additional technologies are used for the 5G higher frequency bands (e.g., the Frequency Range 2 [FR2] bands).
- Development of LNAs and mixers with improved linearity.
- Continued advancements in the sample rates and depth of ADCs, which allows increased dependence on digital filtering within receivers to suppress interference.

In interviews with receiver vendors some other emerging technologies that were mentioned include:

- Photonics receiver components.
- Electronically controllable bandpass filters with increased selectivity using advanced materials science development.
- Optimism that some quantum-based receiver components may be developed to the point of being useful for commercial or military products, e.g., Rydberg atom sensors.

A.7 Summary and Key Findings

In summary, the appendix provides an overview of common receiver architectures. It provides a description of receiver components and their function. The appendix also provides a discussion of common external interference mechanisms that degrade receiver performance. In general, the discussions are considered introductory, and the reader is encouraged to consult the references, textbooks, and technical literature for more in-depth information.

With regard to key findings, research of recent technical literature demonstrates that advances in filter technologies continue to evolve. Advances in electromagnetic (EM) simulation software now allow for the experimentation and design of unique microwave filter structures. These designs are generally planar structures realized in microstrip or strip-line. Research of these structures is also evolving with advanced or newly developed substrate materials. Prior to the EM simulation advances, flat group delay filters typically displayed poor amplitude selectivity such as those associated with the Bessel filter topology. However, as discussed in the appendix and references, advances in the EM simulation software have allowed for the experimentation and development of flat group delay filters with far improved selectivity. The references point out that the physically realized filter performance has good agreement with the EM simulated performance. It is anticipated that as EM simulation software continues to advance the development of unique, high performance, microwave structures will follow. The advances in the EM simulation capability are significant as they will allow designers and manufacturers to experiment and develop filter designs within the simulation environment with a high degree of confidence in the final realized physical hardware. In contrast, past methods involved a costly process of build, test, and iteration of filter designs to meet performance goals.

Appendix B Documented Electromagnetic Compatibility Requirements for RF Receivers

The URLs for the numbered references are in Table B-2. Frequency-stability and pulse-suppression requirements are not listed here.

Table B-1: Documented EMC Requirements by Publisher and Document

Ref.	Publi-sher	Document	Subject	Year	Specified or Measured Receiver EMC Characteristics							
					Sensi-tivity	CCPR	Selec-tivity	Block-ing	Over-load	Spur. Resp.	IM Rejec.	Spur. Emiss.
1	3GPP	TS 36.101	E-UTRA UE Radio Transmission and Reception	2024	•		•	•	•	•	•	•
2	3GPP	TS 36.102	E-UTRA UE Radio Transmission and Reception for Satellite Access	2024	•		•	•	•	•	•	•
3	3GPP	TS 36.104	E-UTRA BS Radio Transmission and Reception	2024	•		•	•	•		•	•
4	3GPP	TS 36.106	E-UTRA FDD Repeater Radio Transmission and Reception	2024			•				•	•
5	3GPP	TS 36.108	E-UTRA Satellite Access Node Radio Transmission and Reception	2024	•		•	•	•		•	•
6	3GPP	TS 38.101-1	Group RAN NR UE Radio Transmission and Reception, Standalone	2024	•		•	•	•	•	•	•
7	3GPP	TS 38.101-4	NR UE Transmission and Reception Performance	2024				•				•
8	3GPP	TS 38.104	Group RAN NR BS Radio Transmission and Reception	2024	•		•	•	•	•	•	•
9	3GPP	TS 38.106	Group RAN NR Repeater Radio Transmission and Reception	2024	•		•	•	•		•	•
10	3GPP	TS 38.141-2	NR BS Radiated Conformance Testing	2024	•		•	•	•		•	•
11	3GPP	TS 38.521-1	NR UE Conformance Specification for FR1	2024	•		•	•	•	•	•	•
12	3GPP	TS 38.521-2	NR UE Conformance Specification for FR2	2024	•		•	•	•			•
13	3GPP	TS 38.521-3	NR UE Conformance for FR1/FR2 Interworking	2024	•		•	•	•	•	•	•
14	AerCo	TOR-2013-00046	Adjacent-Band RFI to Consumer FM, TV, GPS	2013				•				
15	ATSC	A/74:2010	Digital TV Receiver Performance Guidelines	2010	•	•	•		•	•	•	
16	DoD	MIL-STD-188-141D	Performance Standards for MF/HF Systems	2017	•		•	•	•	•	•	
17	DoD	MIL-STD-188-164C	Interoperability of SHF SATCOM Terminals	2018						•	•	
18	DOT		GPS Adjacent Band Compatibility Assessment	2018			•					

19	ECC	Report 310	Evaluation of Receiver Parameters	2020	•	•	•	•	•	•	•	
20	ECC	Report 356	Receiver Resilience to Adjacent-Band Signals	2024	•		•	•				
21	ETSI	EG 203 336	Technical Parameters for Harmonized Standards	2020	•	•	•	•	•	•	•	•
22	ETSI	EN 300 176-1	Digital Cordless Radio Testing	2022	•			•			•	•
23	ETSI	EN 300 220-2	25-1000 MHz Short-Range Devices	2018	•			•				
24	ETSI	EN 300 328	2.4-GHz Wideband Data Links	2019				•				•
25	ETSI	EN 300 422-1	PMSE Wireless Microphones up to 3 GHz	2021	•		•	•				•
26	ETSI	EN 300 440	1-40 GHz Short-Range Equipment	2018			•	•				•
27	ETSI	EN 300 674-2-1	5795-5815 MHz DSRC Roadside Units	2022	•	•	•		•			•
28	ETSI	EN 300 674-2-2	5795-5815 MHz DSRC On-Board Units	2019	•		•					•
29	ETSI	EN 300 698	VHF Maritime Radiotelephones	2018	•	•	•	•		•	•	•
30	ETSI	EN 300 718-1	457-kHz Avalanche Beacons	2021	•			•				•
31	ETSI	EN 301 025	VHF DSC Radiotelephone Equipment	2021	•	•	•	•	•	•	•	•
32	ETSI	EN 301 390	Digital Fixed Radio Emissions and Immunity	2021								•
33	ETSI	EN 301 406-1	Digital Cordless Telecommunications Testing	2022	•			•			•	•
34	ETSI	EN 301 406-2	Digital Cordless Telecommunications	2023	•		•	•		•	•	•
35	ETSI	EN 301 444	1.5/1.6-GHz Satellite Earth Stations	2021			•	•				
36	ETSI	EN 301 598	470-694 MHz TV White Space Devices	2022	•		•	•				•
37	ETSI	EN 301 908-10	IMT-2000 3G Cellular Network BSs and UEs	2021	•			•			•	
38	ETSI	EN 301 908-13	IMT Cellular Network E-UTRA UEs	2022			•	•		•	•	•
39	ETSI	EN 301 908-14	IMT Cellular Network E-UTRA Base Stations	2021			•	•			•	•
40	ETSI	EN 301 908-15	IMT Cellular Network E-UTRA FDD Repeaters	2020			•					
41	ETSI	EN 301 908-18	E-UTRA/UTRA/GSM/ADGE MSR BSs	2021	•			•			•	•
42	ETSI	EN 301 908-2	IMT Cellular Network CDMA UTRA FDD UEs	2020	•		•	•		•	•	•
43	ETSI	EN 301 908-23	IMT Cellular Network BS Active Antennas	2023	•		•	•			•	•
44	ETSI	EN 301 908-24	IMT Cellular Network NR Base Stations	2023	•		•	•			•	•
45	ETSI	EN 301 908-3	CDMA DS (UTRA FDD) Base Stations	2019	•			•			•	•
46	ETSI	EN 301 908-5	IMT-2000, CDMA2000, and UMB Radios	2010			•	•			•	•
47	ETSI	EN 302 065-3-1	Short-Range UWB Devices for Vehicles	2021	•							•
48	ETSI	EN 302 065-4-1	Short-Range UWB Devices below 10.6 GHz	2021	•							
49	ETSI	EN 302 065-4-4	Short-Range Ultrawideband Devices	2022					•			
50	ETSI	EN 302 066	Short-Range Ground- & Wall-Probing Radars	2020	•			•				•

51	ETSI	EN 302 186	11/12/14-GHz Aircraft Earth Stations	2021			•	•		•		
52	ETSI	EN 302 208	RFID Equipment Between 865 and 921 MHz	2020	•		•	•		•	•	•
53	ETSI	EN 302 217-1	Fixed Point-to-Point Radio Systems	2021		•	•	•	•	•		•
54	ETSI	EN 302 217-2	Fixed Point-to-Point Radio Systems, 1-86 GHz	2021			•	•		•		•
55	ETSI	EN 302 264	77-81 GHz Short-Range Radars	2017		•		•				•
56	ETSI	EN 302 326-2	Multipoint Fixed Digital Radio Systems	2020		•	•	•	•	•	•	•
57	ETSI	EN 302 480	Mobile Comm. On Board Aircraft (MCOBA)	2021	•		•	•			•	•
58	ETSI	EN 302 502	5.8-GHz Broadband Wireless Access Systems	2017				•				•
59	ETSI	EN 302 567	60-GHz Multiple-Gbps Radio Equipment	2021	•		•					•
60	ETSI	EN 302 609	Euroloop Short-Range Comm System	2020	•	•		•	•		•	
61	ETSI	EN 302 617	UHF AM Aeronautical Mobile Ground Radios	2018	•		•	•	•	•	•	
62	ETSI	EN 303 132	VHF Maritime Survivor Locating Devices	2022	•	•	•	•	•	•	•	
63	ETSI	EN 303 135	8.5-10 GHz Coastal and Harbor Radars	2023			•	•	•			
64	ETSI	EN 303 213-5-1	1030/1090 MHz Surface MLAT Equipment	2023	•	•	•	•		•	•	•
65	ETSI	EN 303 213-6-1	9-9.2 and 9.3-9.5 GHz Airport Surface Radars	2019	•		•		•			
66	ETSI	EN 303 258	5725-5875 MHz Wireless Industrial Applics.	2020				•				•
67	ETSI	EN 303 276	5852-5900 Maritime Broadband Radio Links	2021	•	•	•	•	•	•	•	•
68	ETSI	EN 303 316	1.9-1.92 & 5855-5875 MHz Broadband DA2GC	2018	•		•	•				
69	ETSI	EN 303 340	Digital Terrestrial TV	2020	•		•	•	•			
70	ETSI	EN 303 345-2	AM Broadcast Sound Service	2021	•		•	•				•
71	ETSI	EN 303 345-3	FM Broadcast Sound Service	2021	•		•	•				•
72	ETSI	EN 303 345-4	Digital Audio Broadcast Sound Receivers	2021	•		•	•				•
73	ETSI	EN 303 345-5155	DRM Broadcast Sound Service	2021	•		•	•				•
74	ETSI	EN 303 347-1	2.7-2.9 GHz Meteorological Radars	2021			•	•	•			
75	ETSI	EN 303 347-2	5.25-5.85 GHz Meteorological Radars	2021			•	•	•			
76	ETSI	EN 303 347-3	9.3-9.5 GHz Meteorological Radars	2020			•	•	•			
77	ETSI	EN 303 363-1	1030/1090 MHz SSR Interrogators	2022	•	•	•	•	•		•	
78	ETSI	EN 303 363-2	1030/1090 MHz SSR Far Field Monitor	2023	•		•				•	
79	ETSI	EN 303 364-2	2.7-3.1 GHz Primary ATC Radar	2021	•		•		•			
80	ETSI	EN 303 364-3	8.5-10 GHz Primary ATC Radar	2019			•	•	•			
81	ETSI	EN 303 372-2	Satellite Broadcast Reception Indoor Unit	2021			•		•			
82	ETSI	EN 303 406	25-1000 MHz Social Alarms	2017			•	•			•	

83	ETSI	EN 303 413	GNSS User Equipment	2021				•				•
84	ETSI	EN 303 447	0.1-148.5 kHz Inductive Loops for Mowers	2022	•							•
85	ETSI	EN 303 520	430-440 MHz Wireless Endoscopy Devices	2019	•		•	•				•
86	ETSI	EN 303 661	MMW Ground-Based Synthetic Aperture Radars	2023	•							•
87	ETSI	EN 303 687	6-GHz WAS/RLAN	2023			•	•				
88	ETSI	EN 303 699	20- and 30-GHz Fixed Satellite Earth Stations	2021			•	•		•		
89	ETSI	EN 303 722	57-71 GHz Wideband Fixed Network Radios	2022	•			•				•
90	ETSI	EN 303 753	57-71 GHz Wideband Fixed & Mobile Radios	2023	•		•					
91	ETSI	EN 303 758	TETRA Radio Equipment	2021	•	•	•	•		•	•	•
92	ETSI	EN 303 980	11- and 14-GHz Band NGSO Satellite ESs	2022			•	•				
93	ETSI	EN 303 981	11/14-GHz NGSO Satellite Wideband ESs	2022			•	•				
94	ETSI	EN 304 220-1	25-1000 MHz Wideband Data Access Points	2022	•		•	•	•	•		•
95	ETSI	EN 304 220-2	25-1000 MHz Wideband Data Terminal Nodes	2022	•		•	•	•	•		•
96	FAA	Order 6050.32B	Spectrum Management Regs & Procedures	2019	•	•	•	•	•	•	•	
97	FAA		Compatibility of LightSquared with GPS	2012				•				
98	FCC	47 CFR 15.117	TV Broadcast Receivers	1989								
99	FCC	47 CFR 15.118	Cable Ready Consumer Electronics Equipment	1989								
100	FCC	47 CFR 22.970(b)	Unacceptable interference to part 90 non-cellular 800 MHz licensees from cellular radiotelephone or part 90-800 MHz cellular systems	1994	•						•	
101	FCC	47 CFR 27.1221(c)	Broadband Radio Service and Educational Broadband Service	2004		•						
102	FCC	47 CFR 27.1411-13	3700–3980 MHz Transition to 3.7 GHz Service	2023			•					
103	FCC	47 CFR 27.1510	Unacceptable interference to narrowband 900 MHz licensees from 900 MHz broadband licensees	2020	•						•	
104	FCC	47 CFR 80.121(b)(2)	Public coast stations using telegraphy	1986	•							
105	FCC	47 CFR 80.858(c)(1)	Technical Equipment Requirements for Cargo Vessels Not Subject to Subpart W: VHF Radiotelephone Receiver	1986								
106	FCC	47 CFR 80.874(b)	Technical Equipment Requirements for Cargo Vessels Not Subject to Subpart W: Radiotelephone Receiver	1998	•							

107	FCC	47 CFR 80.913(e)	Compulsory Radiotelephone Installations for Small Passenger Boats: Radiotelephone receivers	1986	•							
108	FCC	47 CFR 80.961(b)	Radiotelephone Installation Required for Vessels on the Great Lakes	2023	•							
109	FCC	47 CFR 87.151	Differential GPS Receivers	2023				•			•	
110	FCC	47 CFR 90.672(b)	Unacceptable interference to non-cellular 800 MHz licensees from 800 MHz cellular systems or part 22 Cellular Radiotelephone systems, and within the 900 MHz narrowband segments, and to narrowband 900 MHz licensees from 900 MHz broadband licensees.	1978	•						•	
111	FCC	47 CFR 96.17(a)(b)	Citizens Broadband Radio Service: Protection of existing fixed satellite service (FSS) earth stations in the 3600-3700 and 3700-4200 MHz Bands.	2015		•		•				
112	FCC	47 CFR 96.41(f)(d)	Citizens Broadband Radio Service: General radio requirements	2015								
113	ICAO	Annex 10	Aeronautical Telecommunications	2023	•	•	•	•	•		•	•
114	ITU-R	M.1460-2	2.9-3.1 GHz Radar Characteristics	2015	•		•					
115	ITU-R	M.1464-2	2.7-2.9 GHz Radar Characteristics	2015	•		•		•			
116	ITU-R	M.1465-3	3.1-3.7 GHz Radar Characteristics	2018	•		•					
117	ITU-R	M.1638-1	5.25-5.85 GHz Radar Characteristics	2015	•		•					
118	ITU-R	M.1849-2	Ground-Based Meteorological Radars	2019	•		•		•			
119	ITU-R	M.2013	Non-ICAO 1-GHz ARNS Systems	2012	•	•	•					
120	ITU-R	M.2059	4.2-4.4 GHz Radar Altimeters	2014	•		•	•	•			
121	ITU-R	M.2205	960-1164 and 5030-5091 MHz Band Studies	2010	•		•			•		
122	ITU-R	M.2235	960-1164 MHz AM(R)S Sharing Studies	2011	•	•	•					
123	ITU-R	SM.332-4	Selectivity of Receivers	1978		•	•	•		•	•	
124	NIST	Tech. Note 1952	LTE Impacts on GPS	2017			•	•				
125	NOAA		NEXRAD Technical Information	2022	•		•		•			
126	NPEF		Assessment of LightSquared Effects on GPS	2012				•				
127	NPEF		LightSquared Effects on GPS Receivers	2011			•	•				
128	NTIA	Manual, 3.9.10	162-174 MHz Radios Near Mexican Border	2023			•			•	•	
129	NTIA	Manual, 5.3.1.2	2-29.7 MHz Service	2023			•					
130	NTIA	Manual, 5.3.11	162-420 MHz Digital 6.25-kHz-Channel Radios	2023			•			•	•	

131	NTIA	Manual, 5.3.3.2	406.1-15350 MHz Fixed Service Radios	2023	•		•			•		
132	NTIA	Manual, 5.3.6.2	29.7-420 MHz Wideband Radios	2023			•			•	•	
133	NTIA	Manual, 5.3.7.3	138-420 MHz Narrowband Radios	2023			•			•	•	
134	NTIA	Manual, 5.5.7.1	Criteria A Radars	2023			•			•		
135	NTIA	Manual, 5.5.7.2	Criteria B Radars	2023			•			•		
136	NTIA	Manual, 5.5.7.3	Criteria C Radars	2023			•			•		
137	NTIA	Manual, 5.5.7.4	Criteria D Radars	2023			•			•		
138	NTIA	Manual, 5.5.7.5	449-MHz Wind Profiler Radars	2023			•			•		
139	NTIA	Report 13-490	RFI to 2.7-2.9 GHz Radars	2012			•		•			
140	NTIA	TR-06-444	RFI to Radar Receivers	2006		•						
141	NTIA		Cellular Device Test Report	2012				•				
142	RTCA	DO-160G	Environmental Testing for Airborne Equipment	2010	•	•						
143	RTCA	DO-181E	ATCRBS and Mode S	2011	•							
144	RTCA	DO-185B	Traffic Alert and Collision Avoidance System II	2008			•					
145	RTCA	DO-208	Airborne Supplemental Nav. GPS Equipment	1991	•	•	•					
146	RTCA	DO-229F	GPS/SBAS Airborne Equipment	2020			•					
147	RTCA	DO-253	GPS Local Area Augmentation System	2019		•	•					
148	RTCA	DO-262F	L-Band SATCOM Avionics	2021	•		•	•				
149	RTCA	DO-282C	Universal Access Transceiver for ADS-B	2022	•		•		•			
150	RTCA	DO-301	GNSS L1 Airborne Active Antenna	2006			•		•			
151	RTCA	DO-316	GPS/ABAS Airborne Equipment	2009			•					
152	RTCA	DO-362A	Unmanned-Aircraft Terrestrial C2 Links	2020	•		•			•	•	
153	RTCA	DO-373	GNSS L1/E1 & L5/E5a Airborne Active Ant.	2018			•		•			
154	RTCA	DO-401	Dual-Freq. SBAS Airborne Equipment	2023		•	•					
155	RTCA	Paper 274-20	C-Band 5G RFI Impact on Radar Altimeters	2020	•		•	•	•			
156	RTCM	11701.0	Installed Maritime VHF Radiotelephone Equipment Operating in High Level Electromagnetic Environments	2006								
157	RTCM	13500.1	Radio Layer for Real-Time DGNSS Applications	2023								
158	TIA	TIA-102.CAAB-E	Project 25 Land Mobile Radio Transceiver Performance Recommendations, Digital Radio Technology, C4FM/CQPSK Modulation	2022								
159	TIA	TIA-603-E	Land Mobile FM or pm Radio Standards	2016	•		•	•		•	•	•

Table B-2: Links to Referenced EMC Requirements Documents

Reference	URL
1	Specification # 36.101
2	Specification # 36.102
3	Specification # 36.104
4	Specification # 36.106
5	Specification # 36.108
6	Specification # 38.101-1
7	Specification # 38.101-4
8	Specification # 38.104
9	Specification # 38.106
10	Specification # 38.141-2
11	Specification # 38.521-1
12	Specification # 38.521-2
13	Specification # 38.521-3
14	powell.pdf (gps.gov)
15	A74-2010.book (atsc.org)
16	http://everyspec.com/MIL-STD/MIL-STD-0100-0299/MIL-STD-188-141D_55865/
17	http://everyspec.com/MIL-STD/MIL-STD-0100-0299/MIL-STD-188-164C_55855/
18	United States Department of Transportation Global Positioning System (GPS) Adjacent Band Compatibility Assessment (bts.gov)
19	ECO Documentation (cept.org)
20	ECO Documentation
21	EG 203 336 - V1.2.1 - Guide for the selection of technical parameters for the production of Harmonised Standards covering article 3.1(b) and article 3.2 of Directive 2014/53/EU (etsi.org)
22	EN 300 176-1 - V2.4.1 - Digital Enhanced Cordless Telecommunications (DECT); Test specification; Part 1: Radio (etsi.org)

23	EN 300 220-2 - V3.2.1 - Short Range Devices (SRD) operating in the frequency range 25 MHz to 1 000 MHz; Part 2: Harmonised Standard for access to radio spectrum for non specific radio equipment (etsi.org)
24	EN 300 328 - V2.2.2 - Wideband transmission systems; Data transmission equipment operating in the 2,4 GHz band; Harmonised Standard for access to radio spectrum (etsi.org)
25	EN 300 422-1 - V2.2.1 - Wireless Microphones; Audio PMSE up to 3 GHz; Part 1: Audio PMSE Equipment up to 3 GHz; Harmonised Standard for access to radio spectrum (etsi.org)
26	EN 300 440 - V2.2.1 - Short Range Devices (SRD); Radio equipment to be used in the 1 GHz to 40 GHz frequency range; Harmonised Standard for access to radio spectrum (etsi.org)
27	EN 300 674-2-1 - V3.1.1 - Transport and Traffic Telematics (TTT); Dedicated Short Range Communication (DSRC) transmission equipment (500 kbit/s / 250 kbit/s) operating in the 5 795 MHz to 5 815 MHz frequency band; Part 2: Harmonised Standard for access to radio spectrum; Sub-part 1: Road Side Units (RSU) (etsi.org)
28	EN 300 674-2-2 - V2.2.1 - Transport and Traffic Telematics (TTT); Dedicated Short Range Communication (DSRC) transmission equipment (500 kbit/s / 250 kbit/s) operating in the 5 795 MHz to 5 815 MHz frequency band; Part 2: Harmonised Standard for access to radio spectrum; Sub-part 2: On-Board Units (OBU) (etsi.org)
29	EN 300 698 - V2.3.1 - Radio telephone transmitters and receivers for the maritime mobile service operating in the VHF bands used on inland waterways; Harmonised Standard for access to radio spectrum and for features for emergency services (etsi.org)
30	EN 300 718-1 - V2.2.1 - Avalanche Beacons operating at 457 kHz; Transmitter-receiver systems; Part 1: Harmonised Standard for access to radio spectrum (etsi.org)
31	EN 301 025 - V2.3.1 - VHF radiotelephone equipment for general communications and associated equipment for Class "D" Digital Selective Calling (DSC); Harmonised Standard for access to radio spectrum and for features for emergency services (etsi.org)
32	EN 301 390 - V2.1.1 - Fixed Radio Systems; Point-to-point and Multipoint Systems; Unwanted emissions in the spurious domain and receiver immunity limits at equipment/antenna port of Digital Fixed Radio Systems (etsi.org)
33	EN 301 406-1 - V3.1.1 - Digital Enhanced Cordless Telecommunications (DECT); Harmonised Standard for access to radio spectrum; Part 1: DECT, DECT Evolution and DECT ULE (etsi.org)
34	EN 301 406-2 - V3.1.1 - Digital Enhanced Cordless Telecommunications (DECT); Harmonised Standard for access to radio spectrum; Part 2: DECT-2020 NR (etsi.org)
35	EN 301 444 - V2.2.1 - Satellite Earth Stations and Systems (SES); Land Mobile Earth Stations (LMES) and Maritime Mobile Earth Stations (MMES) providing voice and/or data communications, operating

	in the 1,5 GHz and 1,6 GHz frequency bands; Harmonised Standard for access to radio spectrum (etsi.org)
36	EN 301 598 - V2.2.1 - TV White Space Devices (TVWSD); Wireless Access Systems operating in the 470 MHz to 694 MHz TV broadcast band; Harmonised Standard for access to radio spectrum (etsi.org)
37	EN 301 908-10 - V4.3.1 - IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 10: Base Stations (BS), Repeaters and User Equipment (UE) for IMT-2000 Third-Generation cellular networks (etsi.org)
38	EN 301 908-13 - V13.2.1 - IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 13: Evolved Universal Terrestrial Radio Access (E-UTRA) User Equipment (UE) (etsi.org)
39	EN 301 908-14 - V15.1.1 - IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 14: Evolved Universal Terrestrial Radio Access (E-UTRA) Base Stations (BS) Release 15 (etsi.org)
40	EN 301 908-15 - V15.1.1 - IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 15: Evolved Universal Terrestrial Radio Access (E-UTRA FDD) Repeaters (etsi.org)
41	EN 301 908-18 - V15.1.1 - IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 18: E-UTRA, UTRA and GSM/EDGE Multi-Standard Radio (MSR) Base Station (BS) Release 15 (etsi.org)
42	EN 301 908-2 - V13.1.1 - IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 2: CDMA Direct Spread (UTRA FDD) User Equipment (UE) (etsi.org)
43	EN 301 908-23 - V15.1.1 - IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 23: Active Antenna System (AAS) Base Station (BS); Release 15 (etsi.org)
44	EN 301 908-24 - V15.1.1 - IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 24: New Radio (NR) Base Stations (BS) Release 15 (etsi.org)
45	EN 301 908-3 - V13.1.1 - IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 3: CDMA Direct Spread (UTRA FDD) Base Stations (BS) (etsi.org)
46	EN 301 908-5 - V4.2.1 - Electromagnetic compatibility and Radio spectrum Matters (ERM); Base Stations (BS), Repeaters and User Equipment (UE) for IMT-2000 Third-Generation cellular networks; Part 5: Harmonized EN for IMT-2000, CDMA Multi-Carrier (cdma2000) and Evolved CDMA Multi-Carrier Ultra Mobile Broadband (UMB) (BS) covering the essential requirements of article 3.2 of the R&TTE Directive (etsi.org)
47	EN 302 065-3-1 - V3.1.0 - Short Range Devices (SRD) using Ultra Wide Band technology (UWB); Harmonised standard for access to radio spectrum; Part 3: UWB devices installed in motor and railway vehicles Sub-part 1: Requirements for UWB devices for vehicular access systems (etsi.org)

48	EN 302 065-4-1 - V2.1.0 - Short Range Devices (SRD) using Ultra Wide Band technology (UWB); Harmonised Standard for access to radio spectrum; Part 4: Material Sensing devices; Sub-part 1: Building material analysis below 10,6 GHz (etsi.org)
49	EN 302 065-4-4 - V1.1.1 - Short Range Devices (SRD) using Ultra Wide Band technology (UWB); Harmonised Standard for access to radio spectrum; Part 4: Material Sensing devices; Sub-part 4: Exterior material sensing applications for ground based vehicles (etsi.org)
50	EN 302 066 - V2.2.1 - Short Range Devices (SRD); Ground- and Wall- Probing Radio determination (GPR/WPR) devices; Harmonised Standard for access to radio spectrum (etsi.org)
51	EN 302 186 - V2.2.1 - Satellite Earth Stations and Systems (SES); Satellite mobile Aircraft Earth Stations (AESs) operating in the 11/12/14 GHz frequency bands; Harmonised Standard for access to radio spectrum (etsi.org)
52	EN 302 208 - V3.3.1 - Radio Frequency Identification Equipment operating in the band 865 MHz to 868 MHz with power levels up to 2 W and in the band 915 MHz to 921 MHz with power levels up to 4 W; Harmonised Standard for access to radio spectrum (etsi.org)
53	EN 302 217-1 - V3.3.1 - Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas; Part 1: Overview, common characteristics and requirements not related to access to radio spectrum (etsi.org)
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Appendix C Abbreviations and Acronyms

Term	Definition
3GPP	Third-Generation Partnership Project
5G	Fifth Generation
5G NR	Fifth Generation New Radio
A/G	Air-Ground
ADC	Analog-to-Digital Converter
AGC	Automatic Gain Control
AMS	Aeronautical Mobile Service
AM(R)S	Aeronautical Mobile Route Service
ARNS	Aeronautical Radionavigation Services
AVSI	Aerospace Vehicle Systems Institute
BAW	Bulk Acoustic Wave
CCPR	Co-channel Protection Ratio
CEL	Cellular
CEPT	European Conference of Postal and Telecommunications Administrations
CFR	Code of Federal Regulations
CSMAC	Commerce Spectrum Management Advisory Committee
CTIA	Formerly the Cellular Telecommunications and Internet Association
DC	Direct Current
DD1494	Department of Defense Form 1494
DME	Distance Measuring Equipment
DoD	Department of Defense
EBT	Enhanced Bench Test
ECC	Electronic Communications Committee
EM	Electromagnetic
EMC	Electromagnetic Compatibility
ETSI	European Telecommunications Standards Institute
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FDR	Frequency Dependent Rejection
FIR	Finite Impulse Response

FM	Frequency Modulation
GaN	Gallium Nitride
GAV	General Aviation
GBAS	Ground-Based Augmentation System
GCF	Global Certification Forum
GDP	Gross Domestic Product
GLN	General Location/Navigation
GPS	Global Positioning System
HPR	High Precision
ICAO	International Civil Aviation Organization
ICAP	IEEE Conformity Assessment Program
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IIC	Incumbent Informing Capability
ILS	Instrument Landing System
IM	Intermodulation
IMR	Intermodulation Rejection
IRAC	Interdepartment Radio Advisory Committee
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
JF-12	Joint Frequency Allocation-to-Equipment
JI-FRAI	Joint Interagency-5G Radar Altimeter Interference
KCC	Korea Communications Commission
LNA	Low Noise Amplifier
LO	Local Oscillator
LTE	Long Term Evolution
MIMO	Multiple-Input Multiple-Output
NOAA	National Oceanic and Atmospheric Administration
NOI	Notice of Inquiry
NTIA	National Telecommunications and Information Administration
OMB	Office of Management and Budget
OOB	Out-of-Band
OSM	Office of Spectrum Management

ORAN	Open Radio Access Network
PCB	Printed Circuit Board
PTCRB	Formerly the PCS Type Certification Review Board
RED	Radio Equipment Directive
RF	Radio Frequency
RFI	Radio Frequency Interference
RNSS	Radionavigation Satellite Service
RSEC	Radar Spectrum Engineering Criteria
RTO	Recognized Test Organization
SAW	Surface Acoustic Wave
SHF	Superhigh Frequency
SNR	Signal-to-Noise Ratio
SPB	Spaceborne
SPS	Spectrum Planning Subcommittee
SRF	Spectrum Relocation Fund
SWAP-C	Size, Weight, Power, and Cost
TAC	Technical/Technological Advisory Committee
TEC	Telecom Engineering Centre
TIM	Timing
TSO	Technical Standard Order
TSOA	TSO Authorization
UHF	Ultrahigh Frequency
VHF	Very High Frequency
VOR	VHF Omnirange
VSWR	Voltage Standing Wave Ratio
WSMR	White Sands Missile Range