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Best Practices for Designing Interference-Resilient RF Receiving Systems

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Foreword

A radio-frequency (RF) receiving system consists of an RF receiver and the antenna through which signals enter the receiver from the outside world. Such systems often operate in a complex, multidimensional spectral environment comprising not only the desired signals they were designed to receive, but also a multitude of potentially interfering undesired signals that the systems must reject in order to fulfill their missions. Over the years, system designers have developed techniques to make their receivers as immune as possible to the harmful effects of RF interference (RFI), without degrading other measures of system performance. Best practices for applying those techniques have evolved as receiver technology has progressed.

This report begins with a summary of recommended best practices for designing interference-resilient receiving systems using current technology. The remainder of the report explains the background, rationale, and justification for the recommendations.

This document is intended for federal employees involved in the acquisition and procurement of RF receiving systems. This may include members of the defense acquisition workforce, Contracting Officers, Contracting Officer's Representatives (CORs), program managers, acquisition planners, technical experts or systems engineers. The intent is to educate and provide awareness of best practices associated with the development of receiving systems with a specific focus on the mitigation of out-of-band radio frequency interference.

In this context, the terminology "radio frequency interference" is limited to human-manufactured radio transmission sources that unintentionally interfere with and degrade the operational performance of a federal radio receiver system. Intentional and/or adversarial interferers are not considered here. The frequency domain which describes the operational or tuning range of a radio receiver system is termed as "in-band" operation. Consequently, all frequencies not encompassed by the "in-band" operational range are termed as "out-of-band". Having established that the radio receiver system operates over a specific frequency band, this document addresses best practices in radio receiver system development for the mitigation of out-of-band interference signals. In many cases, however, practices that will mitigate out-of-band interference will also help to mitigate in-band interference.

This document was developed, in part, to increase awareness that the radio frequency spectrum is becoming increasingly congested. As technology evolves, the frequency spectrum continues to be auctioned and reallocated. Design methods should be employed to help protect federal receiving systems from out-of-band RFI in the evolving spectral environment. This concept is the primary emphasis of the report.

It is important to be aware of radio sources operating in frequency bands surrounding the desired receiving systems operational band. Even if today the surrounding frequency bands have no concerning signals, it is necessary to take precautions in the design or procurement of radio receiver systems to guard against interfering signals. In the future, the surrounding frequency bands may be auctioned, allocated and populated with transmission sources which could then corrupt the receiving system's operational band.

This document provides general concepts and terminology of receiving systems, their associated components, and suggests best practices for mitigation of radio interference in the context described previously (i.e. out-of-band interference). It should enable federal employees to engage with industry partners in discussions early in the design process on the concerns of the evolving spectral environment and the need for improved receiver system immunity to interference signals – whether those signals exist in the present spectral environment or not. For a procurement requirement to purchase commercial-off-the-shelf (COTS) systems, early in the acquisition planning phase it should enable the market research team to have an awareness of technical parameters as may be needed for an analysis of alternatives. For example, if several COTS receiver systems are being examined, then an awareness of each receiving system's immunity to interference signals will formulate another key performance parameter for consideration.

Finally, this report is not intended to be a receiving system design guide. The design of receiving systems requires detailed analysis and numerous trade-offs which are highly dependent on the end application as well as size, weight, cost, power consumption, operational environment, life expectancy, reliability, maintainability, availability, and many other parameters.

Though this guide provides a brief overview of receiver concepts, it is assumed those involved in the purchase of receiving systems have an awareness of their system requirements and their operational environment. Further it is assumed that each federal agency will have subject matter experts and technical expertise which can be relied upon for guidance during the procurement process. The subject of radio frequency engineering is extensive. References such as technical texts and published research papers are provided within this report for further research on topics.

Summary of Best Practices

The practices that we describe below 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.

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 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. (See Section 3.1.)
- 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. (See Section 3.1.)
- 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. (See Section 3.3.)
- 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. (See Section 3.4.)

- 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. (See Section 3.4.)

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. Section 4 of this report provides an overview of common filter technologies and the trade-offs among these constraints and 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, low-noise amplifier (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 [1]. Section 5.1 details some of the trade-offs and considerations regarding the LNA.
- 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 (See Section 5.1.)
- Amplifiers placed after the LNA, such as those in the intermediate-frequency (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. (See Section 5.2.)
- 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. (See Section 5.4.)
- 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. (See Section 5.4.)

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. (See section 5.5.)
- 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 [2] [3] [4].

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.
- For further discussion of these issues, see Section 6.

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.
- For further discussion of these issues, see Section 7.

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.

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1 Introduction

1.1 Background

Radio-frequency (RF) interference (RFI) is a key limiting factor on the performance of RF receiving systems. As technology has evolved over the years, many new techniques have been developed to protect or "immunize" receivers against RFI, but the growing complexity of the equipment has created many new ways in which interference problems can arise. Often the RFI results from transmitter imperfections, the changing spectral environment, or mistakes in equipment deployments, but in many cases the root cause of the RFI is within the receiver. This document identifies many of the ways in which interference can disrupt the operation of RF receivers and recommends design practices that can greatly reduce the likelihood of such problems occurring.

An RF receiving system consists of an RF receiver and the antenna through which signals enter the receiver from the outside world. Such systems often operate in a complex, multidimensional, and continually changing spectral environment comprised of not only the desired signals they were designed to receive, but also a multitude of potentially interfering undesired signals that the systems must reject in order to fulfill their missions. Figure 1-1 illustrates the situation.

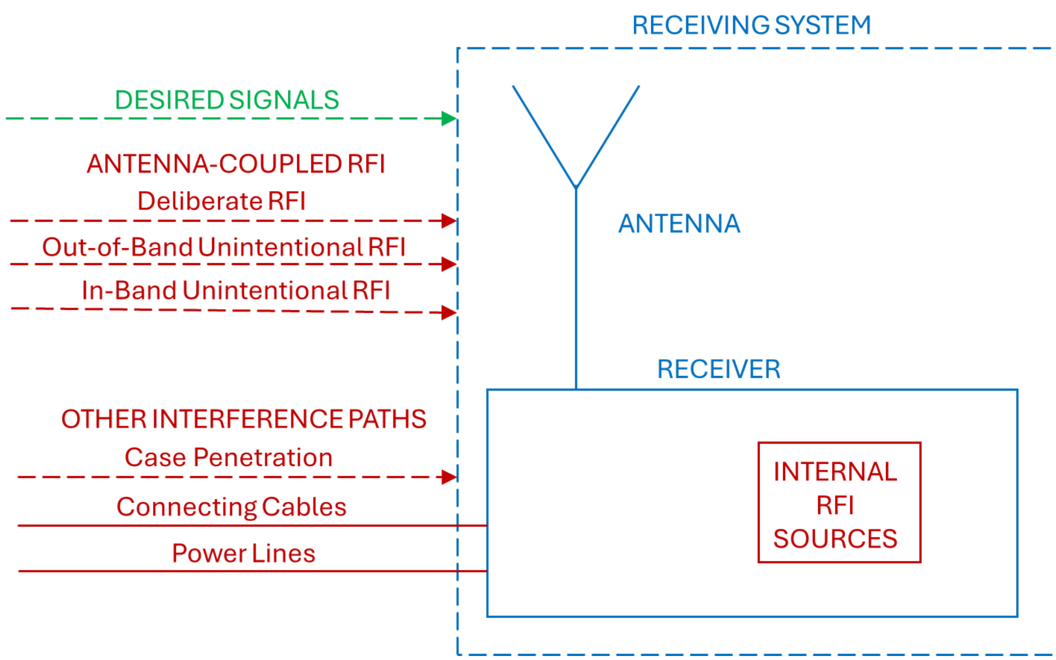

Figure 1-1. An RF Receiving System and Its Electromagnetic Environment

Interference can enter the receiver from its antenna, by direct case penetration, via cables and power lines, or from sources within the receiver itself. The impacts of the interference depend on the purpose of the overall system (communications, navigation, or surveillance), the receiver's inherent resilience to interference, and the type of interference (deliberate or unintentional). In a communications receiver, either type of RFI may degrade signal quality or, if strong enough, cause complete denial of service. In a navigation system such as GPS, either type of RFI can cause inaccurate positional estimates or denial of service, while deliberate spoofing can completely mislead the overall system into following a course chosen by the malefactor rather than the one intended by the user of the system. In surveillance systems such as radars, interference can manifest itself as missed targets, false targets, or false detection of rain cells. The effects of unintentional interference can be prevented or minimized through proper receiver-design practices, and operational means such as adequate frequency-reuse distances. This report focuses on design practices that will make receiving systems as resilient as possible to external and internal sources of unintentional RFI.

Techniques available for preventing unintentional RFI in a receiving system include:

- Spatial mitigation methods such as antenna directionality, null-steering, and minimum frequency-reuse distances between RF systems
- Spectral isolation techniques such as band allocations, channel assignments, and filtering
- Temporal techniques such as pulsed-waveform discrimination and time-division duplexing
- Prevention of signal distortion that would generate unwanted frequency components
- Employing grounding, bounding, shielding, and proper printed-circuit-board layout to suppress non-antenna-coupled RFI

1.2 Purpose

This document is intended for federal employees with roles in the acquisition and procurement of RF receiving systems, including members of the defense acquisition workforce, Contracting Officers, Contracting Officer's Representatives (CORs), program managers, acquisition planners, technical experts, and system engineers. It may also potentially be useful for equipment designers. The intent is to educate and provide awareness of best practices associated with the development of receiving systems with a specific focus on the mitigation of out-of-band radio frequency interference.[1]

Incorporating RF receiver design decisions into the acquisition lifecycle will help ensure that the RF receivers meet performance, cost, and schedule requirements. This is particularly relevant to new acquisitions. In particular, it should not be presumed that the spectrum environment will remain static. The spectral environment continues to change at an increasing rate, meaning spectrum allocations and assignments in the band and in adjacent or nearby bands could change over time particularly as next-generation technologies are deployed. Acquisition and procurement decisions should consider SWaP-C trade-offs as well as performance and expected operational lifespan of the system.

The purpose of this document is to assist federal employees involved in acquisition and procurement as they:

1. Determine if an acquisition or procurement utilizes RF receiving systems.
    a. Engage with stakeholders early to identify potential acquisition or procurements that utilize RF receiving systems.

[1] This document assumes those involved in the purchase of receiving systems have an awareness of their system requirements and operational environment. Further it assumes that each federal agency will have subject matter experts and technical expertise which can be relied upon for guidance during the procurement process. For a more intensive treatment of the technical topics raised in this document, see the resources compiled in Section 10.

2. If so, identify requirements for RF receiving systems.

3. Develop a Request for Information to conduct Market Research:
   a. To identify potential suppliers
   b. To understand the current state of technology and pricing
   c. To schedule one-on-one industry discussions with private industry
   d. To develop a draft RFP for early release to private industry with guidance requesting comments and recommendations

4. Identify risks to mission impact and recommend risk mitigation strategies[2].

5. Develop acquisition and procurement guidance, including:
   a. Requirements that include detailed specifications that outline the technical requirements for the RF receiver
   b. Analysis of alternatives that assesses the feasibility of various options and examines trade-offs, such as performance, cost, schedule, and risk, of RF receiving system options
   c. Integration of the RF receiver with the other system components
   d. Testing to verify performance against specifications; consider third-party verification of test results to ensure objectivity and compliance
   e. Contracting documents should include a clear definition of the RF receiver design requirements, performance metrics, and acceptance criteria. They should specify any relevant standards and certifications that the RF receiver must comply with.
   f. Evaluation criteria should include technical capability and compliance with RF design requirements so that contractors are assessed based on their ability to meet the specified requirements.

By embedding these elements into federal contracts, agencies can ensure that RF receiver design requirements are clearly communicated, evaluated, and enforced throughout the acquisition process, leading to successful project outcomes.

1.3 Scope

As described in Background (1.1), this document focuses on best practices for mitigating radio frequency interference in federal radio receiver systems. The document is generally limited in scope to unintentional interference from human-manufactured radio transmission sources, and thus excludes treatment of intentional or adversarial sources. The document further distinguishes between "in-band" and "out-of-band" operations, where "in-band" refers to the frequency range within which the radio receiver operates, and "out-of-band" encompasses all other frequencies. While the primary emphasis of this guide is on mitigating out-of-band interference, the practices discussed herein may also be applicable to reducing in-band interference.

[2] See Section 8, which identifies design considerations for meeting mission requirements.

1.4 Organization of Report

- Section 2 of this report briefly describes the most widely used architectures used in RF receivers and lists components and functions that most of them have in common.
- Section 3 describes best practices for specifying characteristics of receiving antennas.
- Section 4 addresses issues that arise in designing filters for RF receivers, and identifies best practices for resolving them.
- Section 5 describes component attributes as well as issues and recommends best practices for implementing amplifiers, mixers, frequency synthesizers, AGC, and baseband processing.
- Section 6 recommends best practices for preventing non-antenna-coupled interference.
- Section 7 recommends practices for mitigating RFI in preexisting receivers.
- Section 8 describes best practices and considerations for specifying a receiver that meets its mission requirements.
- Section 9 identifies regulations that should be followed when designing receivers for U.S. Government use.
- Section 10 includes a list of additional sources for the various topics introduced throughout this document.

2 Receiver Architectures

Three basic architectures are commonly used at present in RF receivers:

- Superheterodyne
- Homodyne
- Direct RF Sampling

The following section contains background information to provide a general context on these receiver architectures. The choice of a particular architecture is driven by design requirements. As a general comment, it is likely more important for federal agencies procuring receivers to develop system specifications for receivers without prescribing an architecture to the vendor; although this section details some trade-offs between typical architectures, federal agencies will get best value if they allow the vendor experts to use their judgement on design to include new emerging technologies.

As this section is tutorial in nature, it does not provide best practices or specific recommendations.

2.1 Superheterodyne Receiver

The superheterodyne architecture involves at least one mixing stage, and in some cases two or three mixing stages, to translate the incoming RF signal down to an intermediate frequency (IF), on which it is passed to the baseband processor. These architectures require significant frequency planning to ensure spurious signals will not mix into the desired passband. The frequency plan analysis takes into consideration the front end RF frequencies, RF bandwidth, the LO frequencies, the IF frequencies and the IF bandwidth(s). The goal is to plan the frequencies so as to avoid incoming external spurious responses and to the extent possible avoid mixing products [5] [6] from entering the IF channel and corrupting the desired signal.

Superheterodyne architectures are generally complicated, but they are able 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.

The image frequency is typically an out-of-band interference signal to which the superheterodyne architecture is susceptible. Filtering within the receiver front end prior to the first mixer is required to ensure the image frequency is rejected sufficiently.

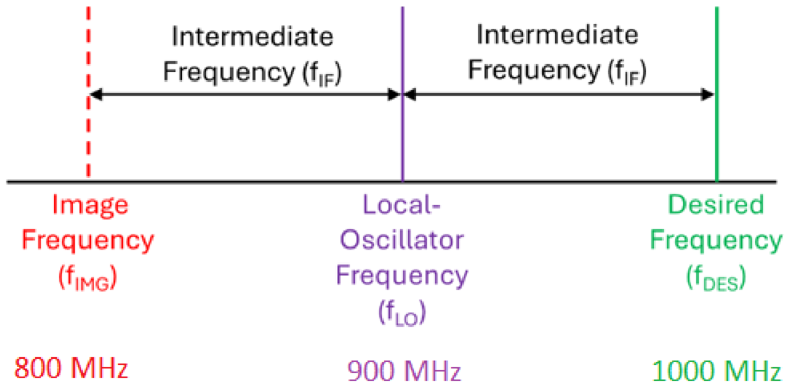

Figure 2-1. Example of Desired, Local-Oscillator, Intermediate, and Image Frequencies

As an example, consider the scenario shown in Figure 2-1. A desired RF signal at 1000 MHz mixes with the LO output at 900 MHz to yield a desired 100-MHz intermediate-frequency (IF) signal that the receiver subsequently detects or demodulates.

In the same example, the image frequency is at 800 MHz. If an undesired signal is present at 800 MHz, it will also mix with the 900-MHz LO output to yield, at the same 100-MHz IF, an undesired mixer output posing a risk of cochannel interference. (The mathematics of this phenomenon is described in more detail in Section 5.2.)

To prevent interference on the image frequency, a front end image filter is required prior to the receiver's first mixing stage. The image filter must reject the image frequency while passing the desired signal. The image filter should also significantly reject the LO frequency to aid in preventing LO leakage at the antenna port. The amount of image rejection necessary requires technical analysis and must be based on the receiver performance requirements.

This example has discussed the effects of the image frequency being down-converted to the desired IF. Section 5.2 will also discuss other frequency products that can form during the mixing process. References [1], [7], [8] discuss more on the image frequency.

2.1.1 Single Conversion

A block diagram of the single-conversion superheterodyne receiver is shown in Figure 2-2. The concept is to down-convert the incoming RF signal to a common IF frequency by mixing it with the output of an LO. 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. Surface acoustic wave (SAW) filters are often employed in the IF sections [1].

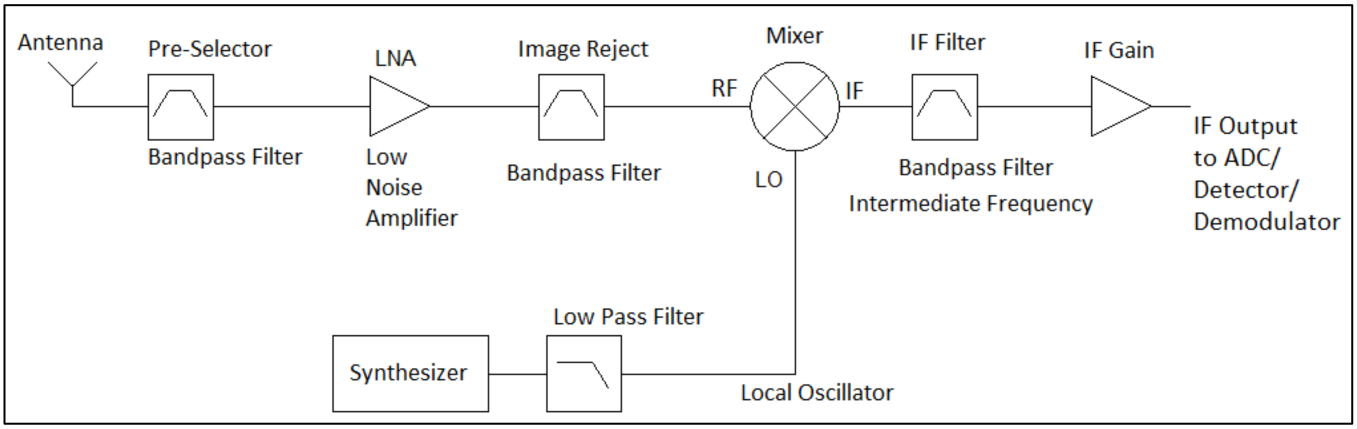

Figure 2-2. Single-Conversion Superheterodyne Block Diagram

2.1.2 Dual and Triple Conversion

A dual-conversion superheterodyne architecture is shown in Figure 2-3. 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. As shown in the previous discussion the image frequency is located two times the IF away from the desired frequency. However, suppose the receiver needs to translate the incoming RF signal down to a very low IF frequency. In this case the image frequency may be in such close proximity to the incoming desired RF signal that adequate selectivity within the image filter is difficult to achieve. To solve this issue dual conversion is often used by first up-converting to a high IF frequency. This up-conversion translation results in pushing the image frequency further away from the desired signal. The desired RF signal can then be translated/mixed down a second time to the final IF frequency.

The drawback with dual or triple conversion is the increase in cost and the number of components required. For dual conversion, at a minimum, a second LO is required as well as an additional mixer and filters. All of this will increase the SWaP-C and overall design complexity of the receiving system. Along with the SWaP-C increase, additional costs may be incurred during development testing and production testing to verify operation.

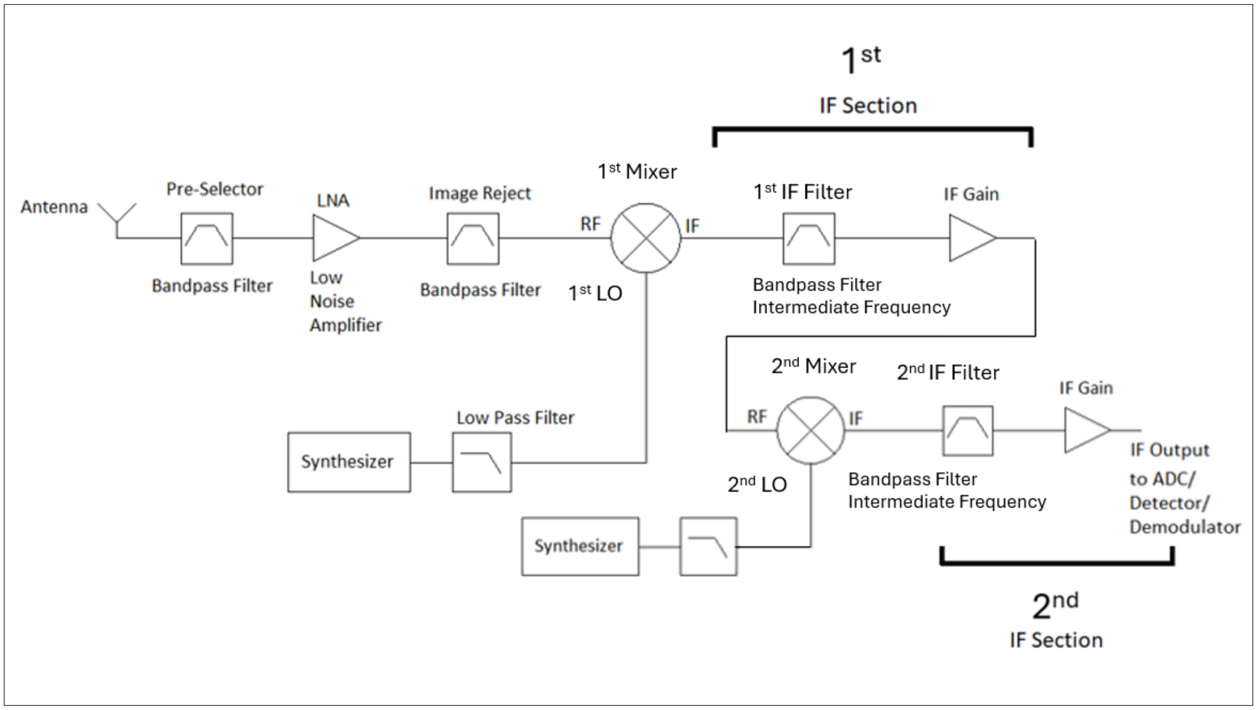

Figure 2-3. Dual-Conversion Superheterodyne Block Diagram

2.2 Homodyne Receiver

A homodyne (a.k.a. direct-conversion, zero-IF, or direct-IF) receiver directly converts the incoming RF signal to baseband. In general, it has a simpler and lower-cost design than heterodyne receivers. Depending on the bandwidth of the captured signal, the overall sampling speed of its analog-to-digital conversion (ADC) is less demanding. The homodyne receiver does not require image-rejection filters [9] [5].

A homodyne receiver block diagram is shown in Figure 2-4. The incoming RF signal is split into two paths. Each RF path's waveform is then mixed with the in-phase (I) or quadrature (Q) output of the LO, whose frequency is set to match that of the incoming desired RF frequency. The outputs of the I and Q paths, which contain the baseband signal of interest [10], are then low-pass filtered [9] [5] .

LO leakage is one concern for the homodyne/direct-conversion receiver. The LO-RF isolation of the mixer and the reverse isolation of the LNA help reduce the LO leakage. If sufficient LO signal makes its way to the receive antenna port it can radiate and act as an interference signal to other nearby receivers [9] [11].

Furthermore, LO leakage power can be reflected back into the receiver from the receiver antenna port and then amplified by the LNA. This spurious signal will then be mixed down to direct current (dc) and appear as a dc-offset at the baseband [9] [11].

The second-order intercept point is also a concern for the direct-conversion receiver. Any spurious signal that enters the direct conversion receiver passband will mix down to form a dc component regardless of the frequency of the spurious signal. This can be shown mathematically with a Taylor series expansion. The dc component acts as dc offset [12]. The amount of dc offset is dependent on the spurious signal strength. Consequently, careful design consideration is usually given to ensure adequate second order intercept point (IP2) system level performance.

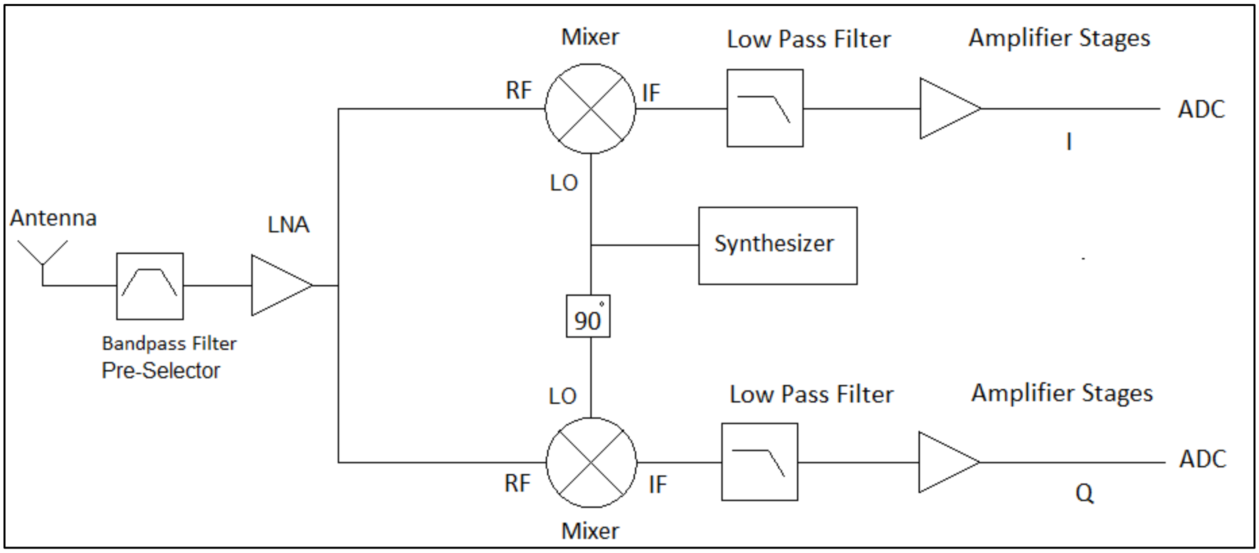

Figure 2-4. Homodyne Receiver Block Diagram

2.3 Direct RF Sampling Receiver

Advances in ADC technology have enabled the development of direct RF sampling receivers, in which no mixing is required. The receiver, depicted in Figure 2-5, typically employs bandpass filtering and an LNA. The incoming RF signal is then sampled at a high data rate. Direct sampling of L-band (1–2 GHz) and S-band (2–4 GHz) signals is currently achievable [13].

The direct RF sampling receiver removes the need for mixers, LOs, and the intermediate frequency back-end found in the heterodyne architectures. Likewise, it removes the need for mixing down to the I/Q signals of the direct conversion approach. Removing these components reduces the complexity of the RF front end. The reduced component count of the RF front end consequently saves on SWaP-C of the analog front end.

RF filtering and an LNA are still required in the front end of the direct RF sampling receiver. As with the other receiver architectures it is important to guard against strong out-of-band interference signals that may overwhelm the ADC.

Some form of gain control may be necessary in the RF front end depending on the dynamic range requirements of the receiver. The gain control may be implemented through AGC, variable gain amplifiers, or variable attenuators. In some cases, filtering may be as simple as shown in the diagram or the use of tuned filters or switched filter banks may be required depending upon the application.

The technology for direct RF sampling receivers is rapidly evolving and the cost of the integrated high speed ADC/field-programmable gate array (FPGA)/digital signal processor (DSP) is currently elevated.

The high speed ADCs, FPGA, and DSP, though packaged in relatively small form factor, still have considerable power consumption requirements. High power consumption requires thermal management.

The ADCs are capable of functioning at extremely high speeds (64 giga-samples per second). As a result, the ADCs require highly precise clock timing devices with low jitter.

The high-speed ADCs also have the potential to act as electromagnetic interference/RFI sources to nearby circuits. Consequently, additional shielding or isolation may be necessary.

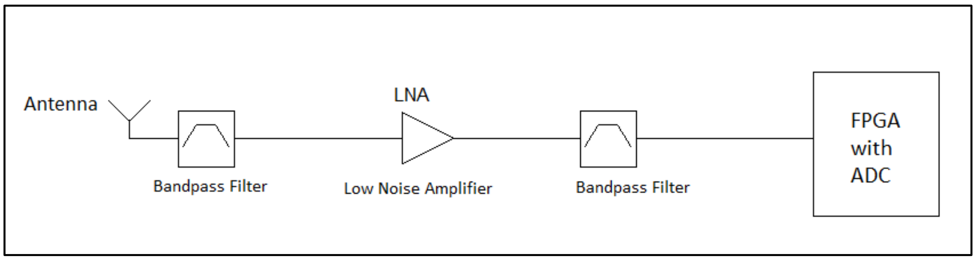

Figure 2-5. Direct RF Sampling Receiver Block Diagram

2.4 Receiver Architecture Comparison

The choice of receiver architecture depends on several factors including the specific application, performance requirements, cost, size, weight, and power consumption. A comparison of the trade-offs for each architecture is shown in the following table.

Table 2-1. Comparison of Receiver Architectures

Receiver Architecture	Pros	Cons	Use Case
Superheterodyne Single Conversion	Typically provides high selectivity	Moderate complexity Moderate cost Tuning speed of LOs can limit the ability to sweep quickly across the spectrum of interest May require custom SAW for BAW filters for IF filtering Image frequency is a concern	The IF selectivity provides the ability, if desired, to focus on narrowband signals of interest
Superheterodyne Dual or Triple Conversion	As with single conversion, it provides high selectivity. Can provide narrowband, high selectivity analog IF filtering.	Compared to single conversion -- Very complex design Increases SWAP Several more components increase cost May require IF SAW or BAW filters Tuning speed of LOs can limit the ability to sweep quickly across the spectrum of interest Image frequency is a concern	As with single conversion, the IF selectivity provides the ability, if desired, to focus on narrowband signals of interest The choice of dual or triple conversion is driven by design requirements. Primarily to achieve either more IF selectivity or to avoid specific spurious responses within the frequency plan. Since the cost, size, and power consumption, all increase with dual or triple conversion , these architectures are only used if necessary to meet specific design requirements.
Direct Conversion / Homodyne	The image frequency is not an issue for Direct	Possible LO leakage to the antenna port	May provide capability to scan large portions of the spectrum very quickly as might be used, for

	Conversion/ homodyne architectures. [9] [11] [14] No need for IF SAW or BAW filter. With the direct conversion receiver, the incoming desired frequency is down-converted to zero-IF. Less expensive low pass filters and gain stages can be employed. [9] [11] Generally lower cost, fewer components, and lower complexity then superheterodyne architectures Very popular architecture in modern receiver designs due to lower cost and lower complexity	More susceptible to 2nd order intermodulation effects than a superheterodyne architecture [12] LO leakage creating DC offsets [9] [11]	example, in Intelligence, Surveillance, and Reconnaissance (ISR) systems Many software defined radios implement this architecture
Direct RF	May have wide bandwidth when used with high speed ADCs. Highly adaptable for various use cases. Smaller physical size. Utilizes high speed ADC. Most of the filtering and performance occurs within the FPGA or RF-ASIC. The FPGA can be reprogrammed for different use cases without the need for new hardware.	Cost is currently very high for state-of-the-art FPGA/RF-ASIC and ADC Power consumption may still be significant	Likely the future of RF receivers as the technology matures and costs come down

2.5 Receiver Components and Functions

Most RF receivers have most or all of the following components that affect their resilience to RFI:

- Antennas
- Filters
- Amplifiers
- Mixers
- Frequency synthesizers

Most receivers perform some or all of the following functions that protect against RFI or are affected by it:

- Automatic gain control (AGC)
- Baseband processing
- Pulsed-waveform discrimination (in many radars)

Subsequent sections of this report describe best practices for designing and implementing those components and functions in a manner that will make the receiver as interference-resistant as possible without unduly degrading the other performance metrics of the receiver.

3 Best Practices for 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 passively transduces the incident electromagnetic (EM) field into an output RF voltage, current, and power. Its major characteristics include:

- Directionality
- Polarization
- Adaptivity
- Adjacent-band rejection

In general, we can distinguish between two types of antennas: passive and active. Passive antennas rely solely on their physical structure to receive (and transmit) signals. In contrast, active antennas incorporate additional electronic components, such as LNAs, to enhance signal reception by amplifying weak signals directly at the antenna. Active antennas additionally often include internal filters to protect the LNA from strong signals that might cause interference or damage to the system.

3.1 Directionality

To mitigate interference, the antenna can be designed to exhibit a directional radiation pattern. Antennas and their associated radiation patterns are generally classified as omnidirectional and directional. An omnidirectional radiation pattern is typical of dipole or monopole antennas and exhibits constant gain in one plane, typically the horizontal (phi) plane as shown in Figure 3-1.

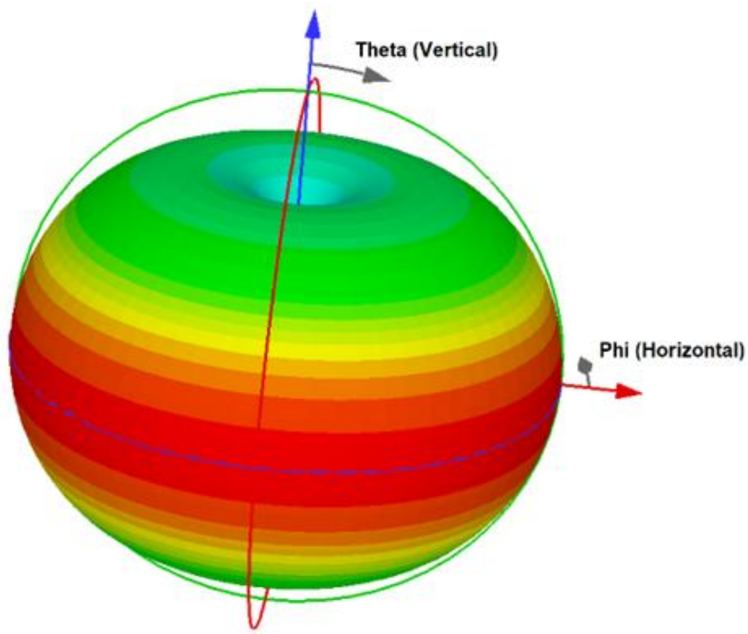

Figure 3-1. Example Omnidirectional Radiation Pattern

The directional antenna's radiation pattern is more focused and generally has a significant increase in gain in one direction. An example directional antenna radiation pattern is presented in Figure 3-2. 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.

An increase of X decibels (dB) in an antenna's gain in a certain direction will increase the power received by receivers in that direction by X dB. The direction of maximum gain is generally called the antenna's (main) beam. In all directional antenna patterns, some of the radiated power is wasted in unwanted lesser beams called sidelobes, as shown in Figure 3-2.

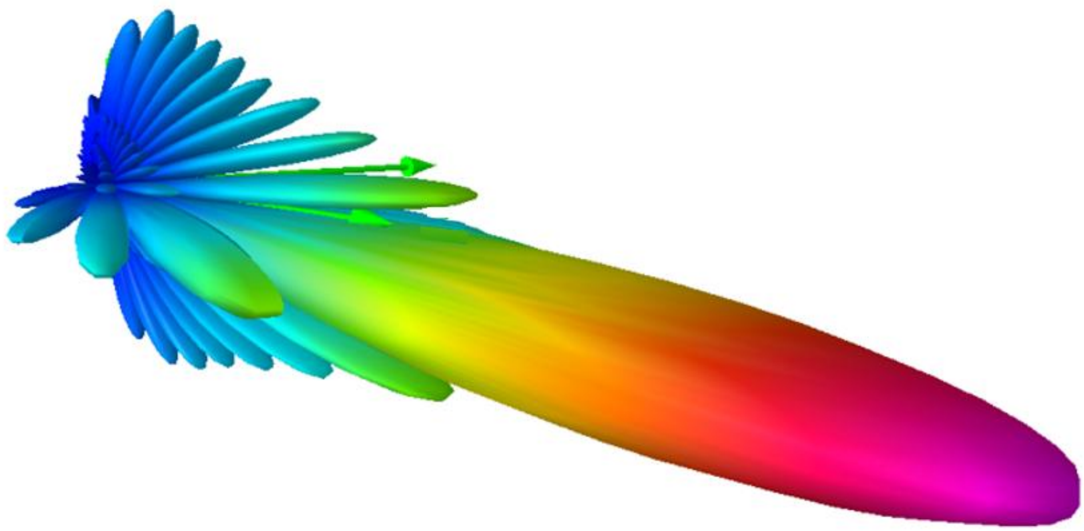

Figure 3-2. A Directional Radiation Pattern

A cylindrical metallic "shroud" wrapped around the edge of a microwave dish receiving antenna can block undesired signals from entering the receiver via the antenna's far sidelobes.

3.2 Polarization

Every antenna has horizontal or vertical polarization, or some combination of the two such as slant or circular polarization. Ideally, two RF systems whose antennas use orthogonal polarizations (e.g., horizontal and vertical, or right- and left-hand circular) could completely reject each other's potentially interfering signals. Real-world imperfections, motions of platforms, variable antenna orientations, and polarization variations within sidelobes generally preclude attainment of that ideal. However, when all the antennas are fixed, such as those of parallel two-way point-to-point microwave links, cross-polarization losses as high as 30 dB can be utilized to protect the two systems against mutual RFI.

3.3 Adaptive Arrays

Adaptive antenna arrays are a special class of antennas that can adapt their radiation or beam patterns so as to:

- Form a directional beam pattern that can point to any direction within a defined angular range;
- Form multiple, simultaneous directional beams pointing in different directions;
- Form multiple, simultaneous nulls that can point in different directions to mitigate noise, multipath, and interference;

- Implement real-time tracking of radar targets or multiple users in a communication system; and/or
- 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 (“elements”) whose received signals are combined in either the analog or the digital domain 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 in sub-7-GHz and millimeter-wave bands use adaptive arrays and are commonly called advanced antenna systems or active antenna systems. A key advantage of using adaptive or MIMO antenna systems in 5G and future communication systems is that they allow the system to be more resilient to interference by adaptively optimizing beamforming for individual users or smaller coverage regions. A notional 5G base station array with a total of 96 dual-polarized elements is depicted in Figure 3-3. The array’s signal processing back end has the capability of implementing numerous MIMO beam sets from 2T2R (2 transmit beams and 2 receive beams) to 64T64R (64 transmit beams and 64 receive beams).

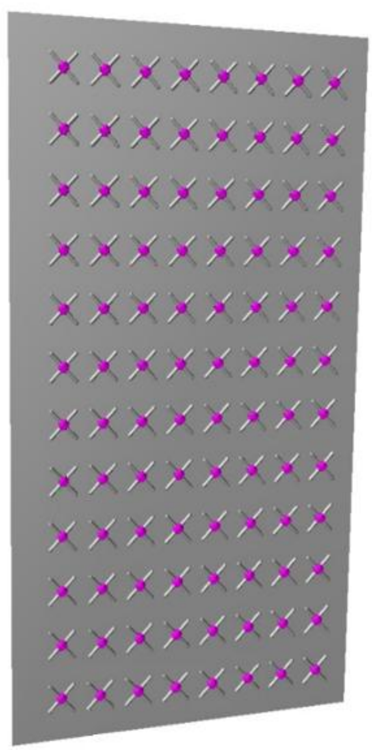

Figure 3-3. Notional 5G Base Station Antenna

3.4 Adjacent-Band Rejection

Antennas and their feed lines can play a modest role in rejecting interference from adjacent frequency bands. From the receiving system's perspective, the antenna is the first bandpass filter in the system. The antenna is impedance-matched to the receiving system within a specified voltage standing-wave ratio (VSWR), which varies with frequency and results in a frequency-dependent mismatch loss that determines how much power is delivered to the receiving system. However, to provide even 20 dB of adjacent-band interference rejection, the out-of-band antenna VSWR would have to be 400:1, which is atypical of most antennas in frequency ranges within reasonable proximity of the receiving system's operating band. Because of the high values of VSWR necessary to provide 10 to 20 dB of rejection, the antenna is not usually considered a sufficient bandpass filter, and other mechanisms of frequency dependent rejection are implemented within the receiving system.

If the antenna is connected to the receiver by a hollow metallic waveguide, as is common in microwave radars, the phenomenon of waveguide cutoff could be used to provide nearly absolute protection against relatively low-frequency adjacent-band interference. Standard rectangular waveguides are sized so that their cutoff frequencies are about 80% of the lower limits of the normal operating ranges of the systems they serve. 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. But at such large frequency offsets, it is usually relatively easy to achieve adequate adjacent-band rejection by other means, i.e., filters, without relying on waveguide cutoff.

Loose, cracked, or rusty bolts can be prolific radiators of out-of-band harmonic and/or intermodulation interference and so should not be allowed to exist in an antenna, its feed line, or its rotary coupler (if it has one).

4 Best Practices for Filters

Filtering protects the receiver against interference by selectively attenuating undesired incoming signals whose frequencies differ from those of the desired signal. In general, the first filter after the antenna is an RF filter covering the tuning range of the receiver. Figure 4-1 depicts an idealized representation of a bandpass filter, with a flat response in the passband, sloping symmetrical skirts, and a level response floor.

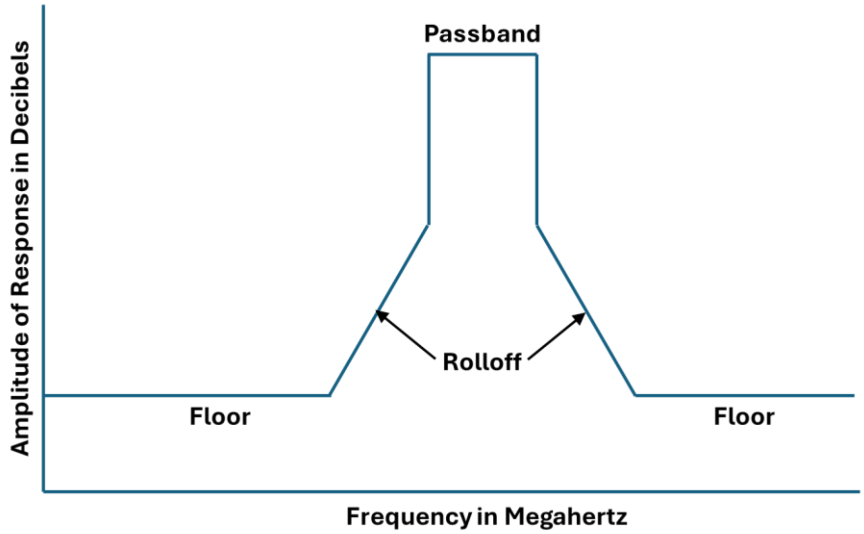

Figure 4-1. Amplitude Response of an Ideal Filter

Desirable characteristics of ideal filters in most applications include those listed below. (In real life, some but definitely not all of these characteristics can be achieved or at least approximated in a single filter.)

- Flat (i.e., frequency-independent), ripple-free amplitude response within the passband
- Little if any insertion loss (of the desired signal) within the passband
- Low return loss resulting from reflections caused by impedance mismatch
- Steep roll-off of amplitude response outside the passband
- High attenuation (low amplitude response) beyond the roll-off region
- Flat group delay of signal’s sinusoidal components within the passband
- Rapidly decaying impulse response
- Stability of the above metrics over a wide range of temperatures
- Low SWaP-C

Figure 4-2 shows an example of the measured selectivity of an actual radar RF filter.

Some receivers may use switched filter banks or multiplexers to break the front end preselector filtering into sections. 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 around the IF frequency. In other cases, “notch” filters are used to attenuate specific frequencies where spurious responses would otherwise occur.

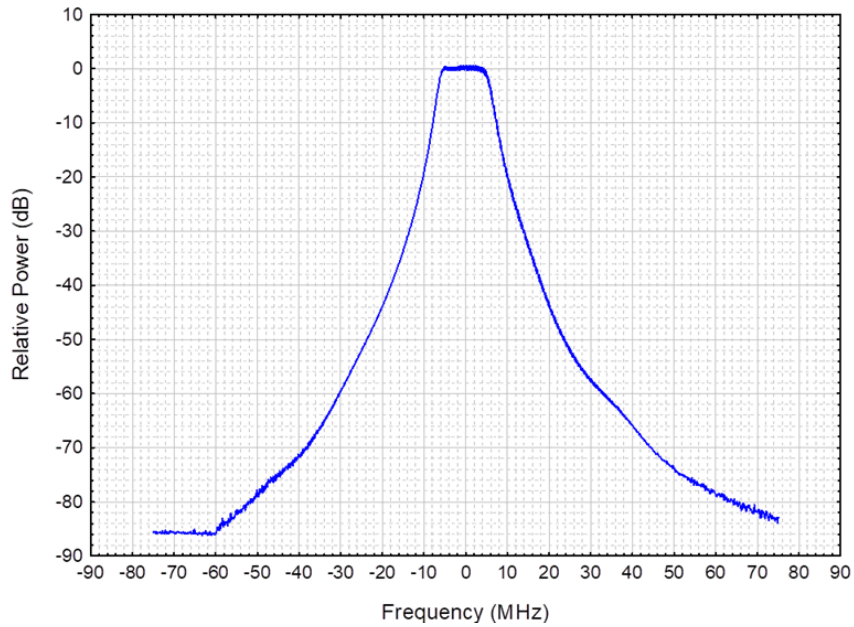

Figure 4-2. Example of a Measured Radar RF Filter Response

4.1 Filter Topologies

Common filter topologies include Butterworth, Chebyshev, Bessel, and Elliptic function filters. (This is not an all-inclusive list; other topologies exist.) Table 4-1 compares their major characteristics. Butterworth filters provide flat amplitude response. Bessel filters are employed for flat group delay response, in which the delay of a signal passing through the filter is constant with respect to frequency. Chebyshev filters tend to have steeper skirts in terms of selectivity, although this comes with the trade-off of ripple in the amplitude passband. Elliptic filters have initial steep roll-off, at the cost of amplitude ripple in the passband and stopband.

Table 4-1. 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.	Passband 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

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 [15].

Another consideration is the bandwidth of operation for the specific receiver. In general, sub-octave filters are desirable to reject harmonics. In the case of 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 [15]. 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 EM and RF simulators, research has been ongoing to develop filters with flat in-band group delay and sharp out-of-band rejection [16]. One such example is outlined in [17].

4.2 Filter Implementation Technologies

The topologies described above reflect design objectives for filters. Implementation requires selecting among numerous technologies that include (but are not limited to):

- Dielectric resonators
- SAW filters
- BAW filters
- Cavity filters

- Lumped-element filters

4.2.1 Dielectric Resonators

Dielectric resonators are very popular for use in 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 [18]. They are also often called 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.

4.2.2 Surface Acoustic Wave Filters

SAW filters are available for both RF and IF frequencies up to about 2.5 GHz. SAW RF filters use resonators that convert the input electrical signal into acoustic waves, using printed coupled resonant transducers, that propagate along the surface of a piezoelectric substrate [19]. 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 now are 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 impulse 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.

4.2.3 Bulk Acoustic Wave Filters

BAW filters [20] operate similarly 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 [21]. BAW filter technologies include free-standing bulk acoustic resonators and solidly mounted resonators. Older, uncompensated BAW filters tended to exhibit roughly 50% less sensitivity to temperature 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.

4.2.4 Cavity Filters

Cavity filters [18] 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.

3D printing technology is now helping to advance the study of microwave cavity filters. The 3D printing allows for rapid prototyping of low cost, light weight custom microwave filters. One recent study demonstrated an improvement in the thermal expansion characteristics of filters developed with stereolithography resins [22].

Other research continues on non-resonant mode microwave filters that for certain applications may provide size reduction and performance improvements [23].

4.2.5 Lumped-Element Filters

Lumped-element filters, which are built using inductors, capacitors, and resistors, are used at low RF, IF, or baseband within many fielded receivers. Some lumped-element filters that utilize only inductors and capacitors are referred to as LC filters. 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, but 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. Judicious use of poles and zeros in filter design can be employed to increase attenuation in one frequency sub-band while reducing or eliminating it in another sub-band. Active resistor-capacitor filters are also quite common, as are chipsets. These offer the benefit that they can be implemented internally to the chip; see, e.g., [24].

4.2.6 Comparison of Filter Technologies

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 earlier, technology selection for receivers involves trade-offs among performance (selectivity, insertion loss, differential group delay) and SWaP-C. As an example of these trade-offs, Figure 4-3 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 in the figure are representative of currently available commercial products.

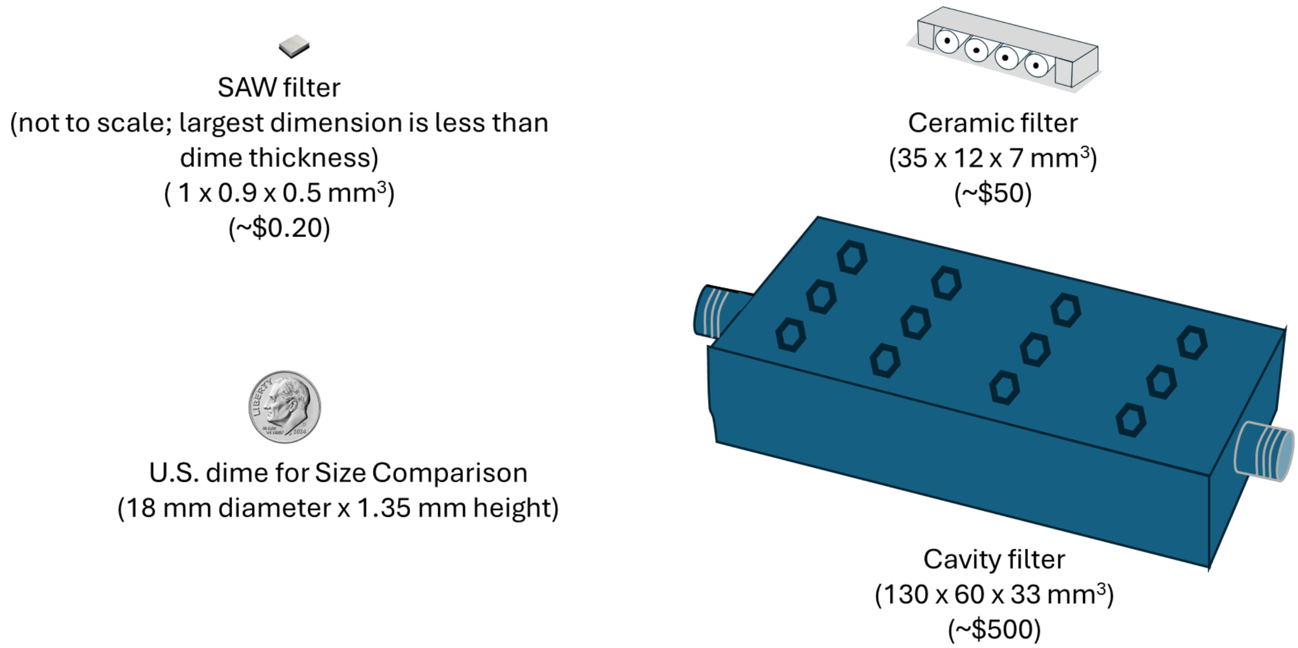

Figure 4-3. Sizes of SAW, Ceramic, and Cavity Bandpass Filters (2-GHz Center Frequency)

Representative selectivity performance of these filter technologies is shown in Figure 4-4. The cavity filter provides the best rejection of adjacent- and out-of-band interference, potentially 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.

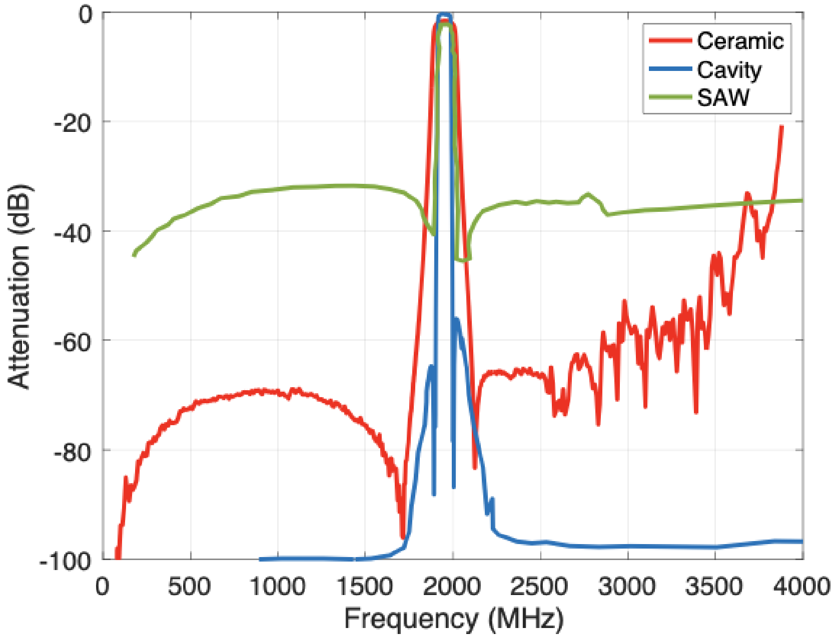

Figure 4-4. Selectivity of SAW, Ceramic, and Cavity Bandpass Filters (2-GHz Center Frequency)

An example of a sixth-order filter that achieves high selectivity and relatively flat group delay performance is discussed in [17]. The design has relatively good out-of-band rejection and higher passband insertion loss than would typically be required for a receiver front end. Examples of high-selectivity filters with flat group delay and low insertion loss in the 40-GHz region can be found in [25].

Beyond the initial roll-off or selectivity of a bandpass filter, the stopband (out-of-band) rejection also needs to be considered. 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 [26]. These regions typically occur at harmonics of the fundamental frequency. In some cases, because of the physical nature of the filter, the ultimate out-of-band rejection breaks down.

A conventional third-order microstrip hairpin filter is discussed in [26]. Its attenuation in the vicinity of the second-harmonic spectral region was originally very poor, but the researchers noted the effects of the periodic rectangular grooves on layout that provided a vast improvement in second-harmonic attenuation. This further demonstrates how advances in modern EM simulators allow for the research and improvement of filter designs.

The foregoing comparison of filter technologies is a general one. Designs and manufacturing capabilities are constantly evolving, allowing each technology to improve on any shortcomings. Recent technical literature indicates that microwave filter designs continue to progress and improve. Advances in EM simulation software now allow experimental design of unique microwave filter structures, in both planar structures realized in microstrip or stripline and more volumetric structures realized through a variety of architectures. Often these structures use advanced or newly developed dielectric materials, allowing development of filters with far improved selectivity and SWaP characteristics. The ongoing advances in EM simulation capabilities also allow designers and manufacturers to experiment and develop filter designs within the simulation environment with a high degree of confidence in the performance of the realized physical hardware, contrasting with past methods that required a costly build/test/iterate process to meet performance goals.

5 Best Practices for Other Receiver Components and Functions

Most RF receivers also comprise other components such as amplifiers, mixers, and/or frequency synthesizers, and perform functions such as AGC, baseband processing, and/or pulsed-waveform discrimination. All of these components and functions have an impact on receiver resilience to interference.

5.1 Amplifiers

In terms of overall receiver system analysis there are various methods of describing linearity, primarily in the form of the 1 dB compression point, second-order intercept point, and third-order intercept point. The 1 dB compression point and third-order intercept point are described in the context of amplifiers in the following paragraphs. However, these same concepts apply to other components within the receiver as well. The governing equations and their use are expanded upon in the reference texts [1] [5].

The first amplifier after the antenna is typically an LNA 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 superheterodyne receiver, play less of a role in setting noise figure and are generally chosen for high-linearity attributes [1].

5.1.1 Gain Compression

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 $20 \log_{10} K$ dB. The straight line in Figure 5-1 shows the input-output voltage characteristic for an ideal constant-gain LNA. But, as also illustrated in the figure, 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. Amplifier saturation distorts the desired signal and performance suffers.

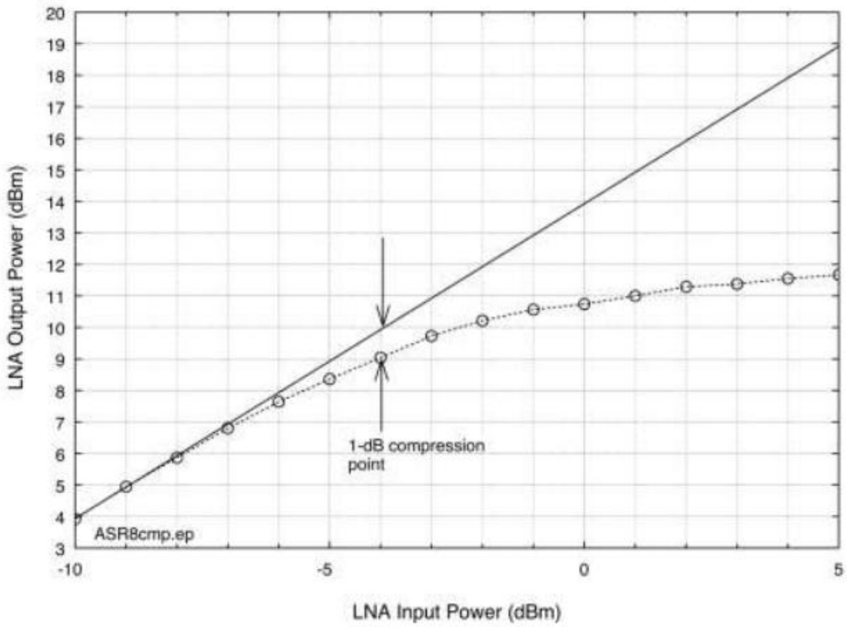

Figure 5-1. Example of an Amplifier Gain-Compression Curve

Amplifier saturation can also enable the generation of intermodulation (IM) products (IMPs), another type of interference. 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 create at the LNA output two third-order IMPs (at $2f_1 - f_2$ and $2f_2 - f_1$), which may fall within the receiver passband and degrade receiver performance. Figure 5-2 shows an example of third-order IMPs created by two intermodulating input signals. This can be measured at the LNA output.

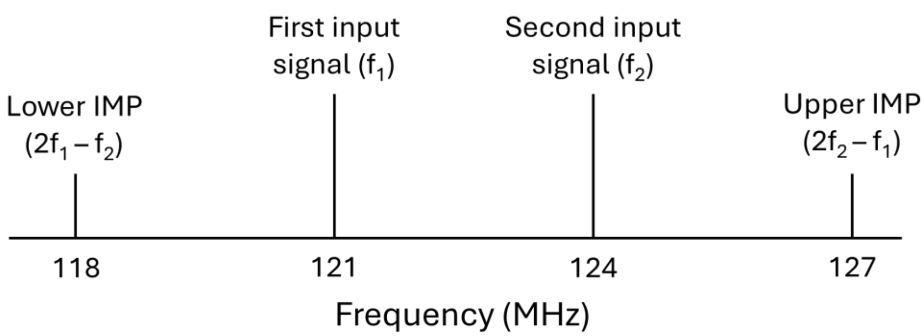

Figure 5-2. Example of Two-Signal, Third-Order Intermodulation Products

To understand the trade-offs in gain, noise figure, and linearity, the designer will develop a cascade analysis of the receiver to evaluate the interactions of parameters. The example below (Figure 5-3) shows a simple cascade for a single conversion superheterodyne receiver similar to the block diagram shown in Figure 2-2. This example examines cascaded gain, noise figure and third order input intercept point. The cascades usually contain much more detail. The cascaded calculations may be expressed in different formats and receiver designers often have their own criteria for the how the data and calculations are presented. The simple analysis depicted may be done as a first order approximation. However, detailed receiver cascade analysis is usually done in professional RF software development tools. More on cascade analysis is described in reference [5]. The governing equations are in references [1] [5].

The table shows in-band loss for the filters and the in-band gain of the amplifiers, associated noise figures, and third order input intercept point. Gains and losses are expressed in dB.

Example	Calculated							
Receiver	Cumulative		In-Band Loss		In-Band Loss		In-Band Loss	
	Values	Device	Preselector		Image			
Cascaded		Parameters	Filter	LNA	Filter	Mixer	IF Filter	IF Amplifier
Gain (dB)	24.0	Device Gain (dB)	-1	20	-2	-7	-2	16
Noise Figure (dB)	3.8	Device Noise Figure (dB)	1	2	2	7	2	4
Input IP3 (dBm)	-0.2	Device Input IP3 (dBm)	∞	5	∞	21	∞	12

Figure 5-3. Example of Cascade Analysis for Single Conversion Superheterodyne Receiver

5.1.2 Desensitization

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 are called *desensitization*. Wideband noise from nearby transmitters can fall within a receiver band and also degrade receive sensitivity, inhibiting 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 undesired signals that fall within the receiver band, even if not strong enough to compress the LNA, may still create reciprocal mixing products [6] with the phase noise of the LO and/or spurious signals on the LO that fall within the IF bandwidth. This creates interference and degrades the sensitivity of the receiver.

5.2 Mixers

A mixer enables the translation of an 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. Mixing the RF signal with LO output at frequency f_{LO} generates a large number of second-, third-, and higher-order IMPs of the form

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

where m and n are nonnegative integers. 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. One of those products is the intermediate frequency f_{IF} to which an incoming signal at the frequency f_{DES} 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 5-4). Designers of superheterodyne receivers must ensure that for every possible value of the desired frequency, the corresponding image-frequency response will be well attenuated by an image-rejection filter.

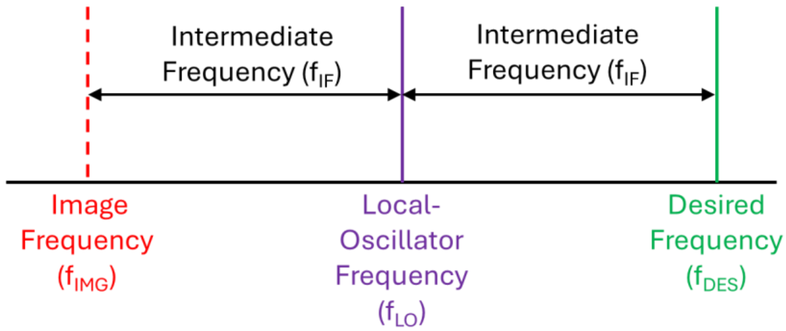

Figure 5-4. Relationships of Desired, Local-Oscillator, Intermediate, and Image Frequencies

Other spurious responses can occur because of strong undesired signals outside the receiver passband. Such responses are typically due to poor filter selectivity in the front end of the receiver. One troublesome example is the half-IF response that occurs when the undesired signal's second harmonic mixes with the LO's second harmonic, causing RFI when a strong undesired signal is present at half the IF frequency away from the desired signal [1].

A passive double-balanced mixer can achieve a high input compression point and a good third-order intercept response, which reduce receiver susceptibility to spurious responses. The linearity attributes of the double-balanced mixer correlate with the LO 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. Alternatively, the active Gilbert cell mixer has the advantage that it can be placed in small monolithic microwave integrated circuit packages, but at the cost of diminished linearity [1].

5.3 Frequency Synthesizers

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 the worst-case Doppler shift between the two radios. In receiver architectures with mixers, such as the superheterodyne approach, the synthesizer provides the tuning capability of the receiver by generating the LO signal(s). The synthesizer is an intricate subcircuit whose 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 design parameters. 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 LO signals that can be tuned to allow the receiver to operate over the frequency band of interest [1].

5.4 Automatic Gain Control

AGC is applied in a receiver to provide constant performance while the input RF signal varies 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 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 (VGAs) or variable attenuators in order to provide the demodulator with a nearly 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 are based, in part, upon the signal modulation. The response time (sometimes called the attack time) is how fast the AGC reacts to changes in the incoming signal level. 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 [5].

AGC circuitry can significantly impact a receiver's immunity to interference. For instance, as noted in [27], 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 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 more nearly 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 parametric variations as the gain control is varied. An idealized model of a VGA would contain a fixed amplifier plus a 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.

5.5 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, DSPs, and digital filters.

Aliasing within a receiver is related to the sampling frequency of the ADC and the incoming frequency. The Nyquist criterion states that 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 because 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-aliasing 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-aliasing filter will attenuate any signals at or above 20 MHz. In modern architectures the careful understanding, analysis, and use of different Nyquist zones allows for desired results with under-sampling ADCs [28].

Figure 5-5 illustrates trends in ADC performance over the past several decades. Each point depicted in the figure represents the performance (sampling rate in mega-samples per second and depth in bits) of a representative commercial ADC product, with the year it was introduced noted in parentheses. (The JESD204B appears twice in the figure, to show its sampling rate for each of two different depth values.) 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. Other DSP interference mitigation techniques include adaptive noise and interference cancellation techniques wherein noise or interference signals are estimated using advanced signal processing algorithms and then "subtracted" from the received signal.

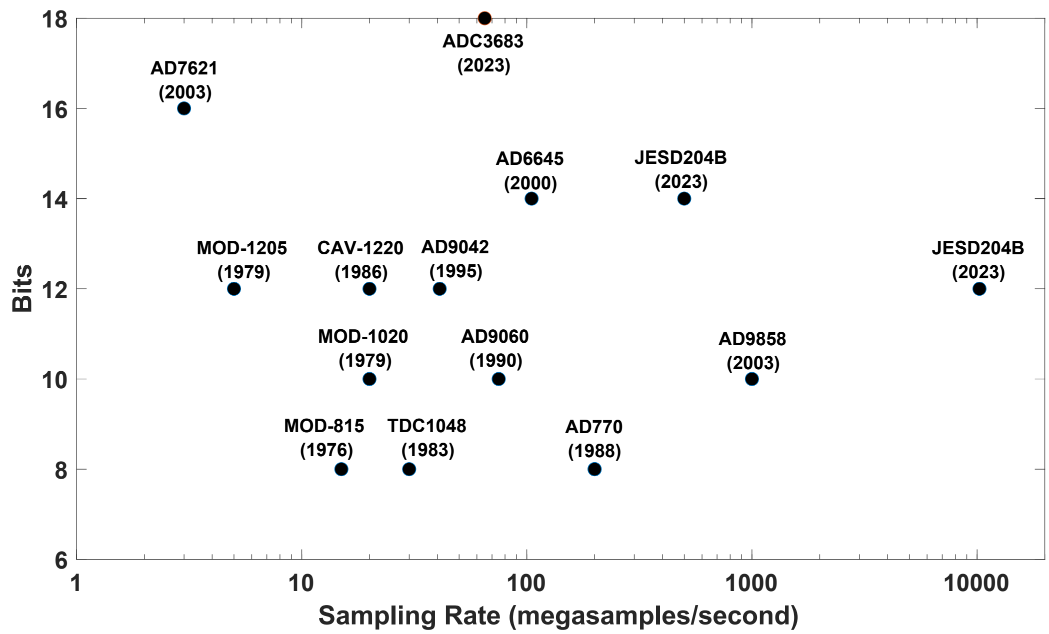

Figure 5-5. Trends in Analog-to-Digital Converter Performance

6 Prevention of Non-Antenna-Coupled Interference

Application notes [29] from surface-mount filter manufacturers describe best practices for mounting RF filters on PCBs to provide adequate isolation and grounding. Poor PCB layout, grounding, and/or isolation may limit the filter's performance. Isolation of the input and output traces is critical at microwave frequencies. A filter designed for a selectivity of 50 dBc (decibels referred to the carrier) might actually exhibit only 30 dBc of selectivity because of poor isolation of traces. 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 [29]. 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. PCB layout design rule checks should be utilized to verify 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.

Best practices in RF layout are required to ensure that 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 quantified 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 should be performed on the completed PCB or assembly to ensure that the filter's passband and selectivity characteristics are meeting requirements.

PCB layouts should also use design rule checks to verify that no floating ground planes or unattached copper sections exist. Shielded cavities should be analyzed during the design process with EM simulation tools to ensure that oscillations and resonances will not occur at microwave frequencies. Subsequent testing of systems should be carried out to verify that no oscillations occur within shielded cavities, in particular, those with amplifier sections. Proper layout and grounding vias should be applied in accordance with component vendor datasheets to ensure performance.

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).

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.

7 Best Practices for Mitigating RFI in Existing Receivers

Opportunities may sometimes arise to improve the interference immunity of preexisting receivers by retrofitting or upgrading them to improve their selectivity and/or linearity. However, any such improvements should be implemented with care to avoid unintended consequences that could result in overall reductions in receiver performance.

7.1 Improving Selectivity

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 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. Consequently, analysis and testing would be required to ensure the desired selectivity performance is actually achieved. Beyond this, many fielded systems, especially handheld devices, 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.

7.2 Improving Linearity

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. 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 and/or LO drive level imply 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, since 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 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 [30].

8 Best Practices for Satisfying Mission Requirements

Throughout this document, we have enumerated best practices and considerations for designing receivers resilient to interference. However, evaluation of whether a given receiver is "good enough" ultimately relies on its ability to perform its intended mission. Moreover, if careful consideration is not given to a receiver's intended mission, design considerations that could pose a risk to its mission may be overlooked. In this section, we provide a top-down analysis of the design considerations relevant to a given mission requirement. The list of mission requirements included here is non-exhaustive, but instead intended to be representative of the major mission elements for contemporary receiving systems.

8.1 Spectral Environment Requirements

The spectral environment refers to the emission characteristics in the range of radio frequencies over which the receiver operates, as well as the frequencies in bands adjacent to the receiver's operating range. Missions may require that receivers perform in spectral environments that are dynamic and/or congested, and receive signals of various bandwidths and signal strengths from transmitters that are mobile, fixed, or transmitting from unknown locations. In the following subsections, we enumerate the design considerations inherent to each of these requirements.

8.1.1 Operating in a Dynamic Spectral Environment

In a dynamic spectral environment, the emission characteristics and frequency range over which a receiver operates may be highly variable. This dynamism may also apply to emissions in adjacent bands. To satisfy their mission, receivers intended to operate in such environments should be designed to account for the spectral variability they will encounter. Considerations toward this end are listed below.

Architecture Considerations:

- Superheterodyne architectures require extensive frequency planning, which may preclude them from operations that require dynamic frequency allotments. (2.1)
- Direct RF architectures have FPGAs that can be reprogrammed for different use cases without the need for new hardware; this may make them a suitable choice for operating in dynamic environments. (2.3)

Antenna Considerations:

- Adaptive arrays can dynamically adjust their beam patterns to optimize reception and mitigate interference, which can support operations in changing spectral environments. (3.3)
- Directional antennas may limit the ability of a receiver to adapt to a dynamic spectral environment. (3.1)

Other Component Considerations

- Frequency synthesizers provide tuning capabilities to handle frequency shifts in dynamic environments. (5.3)

- AGC can support the ability of a receiver to maintain consistent performance despite varying received signal levels. (5.4)

8.1.2 Operating in a Congested Spectral Environment

Missions may require that a receiver operate in a shared frequency band, or with services operating in nearby adjacent bands. General design practices for this requirement include choosing components that enable high selectivity of desired signals and maximal rejection of potential interferers. Specific design considerations are itemized below.

Architecture Considerations:

- Architectures that offer the highest selectivity, such as superheterodyne, will be the most suitable for congested environments. (2.1)

Antenna Considerations:

- Directional antennas and adaptive arrays with beamforming capabilities can mitigate interference by focusing on specific directions and nulling out others. (3.1, 3.3)
- If the antenna is connected to the receiver by a hollow metallic waveguide, as is common in microwave radars, the phenomenon of waveguide cutoff could be used to provide nearly absolute protection against relatively low-frequency adjacent-band interference. (3.4)

Filter Considerations:

- Filter topologies that offer high selectivity and a steep roll off, such as Chebyshev, enable the highest protection to adjacent band interferers. (4.1)
- Filter topologies that have poor selectivity, such as Bessel, are likely not suitable for usage in spectrally congested environments. (4.1)
- Filter implementations that offer the highest selectivity (e.g., cavity filters) are similarly critical for rejecting adjacent-band interference. (4.2)

8.1.3 Received Signal Strength

Certain missions may require that receivers are able to capture signals that are very weak or, alternatively, very strong. We list several considerations for either of these extremes here.

Filter Considerations:

- For weak received signals, filters with low insertion loss help preserve signal strength and improve the noise figure of the receiver. (4.2)

Other Components:

- For weak received signals, LNAs with high gain are essential for improving sensitivity and receiving the signal. (5.1)
- For strong received signals:

    - High-linearity amplifiers and mixers are necessary to handle strong signals without distortion or compression. (5.1, 5.2)
    - Proper AGC design helps maintain performance by adjusting gain to prevent saturation from strong signals. (5.4)

8.1.4 Received Signal Bandwidth

Missions may require that the bandwidth of the received signals of interest are anywhere from wideband to narrowband. The design considerations for meeting constraints at the extremes are listed below.

Architecture Considerations:

- Superheterodyne receivers can be designed with multiple IF stages to handle both wideband and narrowband signals effectively. (2.1)

Filter Considerations:

- Use of filters with appropriate bandwidths is a critical design consideration.
    - Sub-octave filters or switchable filter banks can be used for wideband signals. (4.1)
    - Narrowband bandpass filters can provide selectivity for narrowband signals. (4.1, 4.2)

8.1.5 Transmitter Location

Missions may require that a receiver capture signals from transmitters at fixed, mobile, and/or unknown locations. The selection of antenna may be especially important for this requirement.

Antenna Considerations:

- Adaptive arrays and/or MIMO systems with beamforming capabilities are effective for tracking and receiving signals from changing or unknown locations. (3.3)
- Directional antennas with fixed beam patterns are suitable for receiving signals from known, fixed locations. (3.1)
- In fixed antenna systems, such as those of parallel two-way point-to-point microwave links, cross-polarization losses as high as 30 dB can be utilized to protect the two systems against mutual RFI. (3.4)

8.2 System Requirements

System-level requirements include constraints on the SWaP-C of the receiving system, the minimum data rates and maximum latency that the system must enable, and the physical environment in which the system must operate. Considerations for meeting each of these requirements are listed in the following subsections.

8.2.1 SWaP-C Requirements

Missions may place constraints on the permissible SWaP-C of a receiver. In general, as the performance and robustness of the receiver improves, its SWaP-C increases. Specific design considerations for meeting SWaP-C constraints are summarized below.

Architectures:

- Superheterodyne with Dual or Triple Conversion tends to have the highest SWaP-C. (2.1)
- Direct RF architectures are low in size and weight, but high in cost and power consumption. (2.3)
- Homodyne receivers offer simpler designs with the lowest SWaP-C of receiver architectures. (2.2)

Filters:

- SAW filters are compact and tend to be low SWaP-C. (4.2.2)
- Cavity filters, while offering excellent performance, tend to be large and costly. (4.2.4)

Other Components:

- Efficient LNAs can help meet low power constraints. (5.1)

8.2.2 Data Rates and Latency

A receiving system may be required to maintain a minimal data rate or constrain a maximal latency.

Architecture Considerations:

- Direct RF sampling receivers can reduce latency by minimizing the number of processing stages. (2.3)

Other Component Considerations:

- High sampling rate ADCs are necessary to handle high data rate signals without aliasing, while advanced DSP capabilities enable high data rates to be handled efficiently. (5.5)
- Efficient processing algorithms and fast ADCs also contribute to low-latency. (5.5)

8.2.3 Operating in an Environment with Extreme Weather and/or Variable Temperatures

Missions may require that a receiver maintain stable performance while operating in conditions with extreme or highly variable weather and temperature conditions. Considerations for meeting this requirement are included below.

Antenna Considerations:

- Robust antenna designs, potentially with protective shrouds or coatings, can help maintain performance in adverse weather. (3.1)

Filter Considerations:

- Temperature-stable filters, such as temperature-compensated SAW or BAW filters, are essential to maintain performance across temperature variations. (4.2.2, 4.2.3)

Other Components:

- Frequency synthesizers must be selected so that their fixed-frequency reference oscillator is stable for the range of expected operating temperatures. (5.3)

9 Compliance with Federal Rules and Regulations

Designers of receivers that will or may be procured by Federal agencies should follow the relevant rules and regulations that the U.S. Government has mandated for the design of RF devices, including receivers. In particular, designers of such receivers should:

- Comply, to the extent not waived by the Government, with 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) [31].
- For any receiver that is part of a radar system, comply, to the extent not waived by the Government, with the requirements of Section 5.5 (Radar Spectrum Engineering Criteria (RSEC)) in the latest edition of the NTIA Manual.
- Comply, to the extent not waived by the Government, with all parts of 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.
- For receivers intended for U.S. military use, comply with DoD MIL-STD-461G's requirements for control of conducted and radiated electromagnetic interference [32].

10 Additional Sources

The material in this document has touched on a number of different topics relevant to the design and implementation of interference-resilient receivers. To constrain the scope of this guide, we have largely refrained from delving into the technical details that a full treatment of each topic would merit. However, many excellent resources exist for each of the topics covered in this guide. We have included a list of many such resources, categorized by topic, in the following table.

Table 10-1. Technical References by Topic

Topics	Recommended Publications
Filter Design	A. Zerev, "Handbook of Filter Synthesis", John Wiley and Sons, 1967 F. Taylor and A. Williams, "Electronic Filter Design Handbook", 4th edition, McGraw-Hill, 2006 G. Matthaei; L. Young; E.M.T. Jones, "Microwave Filters, Impedance-Matching Networks, and Coupling Structures", McGraw-Hill, 1964 C. Bowick, "RF Circuit Design", 2nd edition, Newnes, 2007 D. M. Pozar, "Microwave Engineering", 4th Edition, John Wiley & Sons, 2012
RF Receiver Design – includes Superheterodyne Receivers	U. L. Rohde and T. T. N. Bucher, "Communication Receivers: Principles and Design", McGraw-Hill, 1988 U.L. Rohde; J.C. Whitaker; H. Zahnd, "Communication Receivers: Principles and Design", 4th edition, McGraw-Hill, 2017 P. Vizmuller, "RF Design Guide – Systems, Circuits, and Equations", Artech House, 1995
Antennas	C.A. Balanis, "Antenna Theory", 4th edition, John Wiley & Sons, Inc., New York, 2016 J. Kraus, "Antennas", 2nd edition, McGraw-Hill, 1988
Papers on Direct Conversion Receivers	B. Razavi, "Design Considerations for Direct-Conversion Receivers", IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing ,Volume: 44, Issue: 6, June 1997 A.A. Abidi, "Direct-conversion radio transceivers for digital communications", IEEE Journal of Solid-State Circuits, Volume: 30, Issue: 12, December 1995 D. Stuetzle, "Understanding IP2 and IP3 Issues in Direct Conversion Receivers for WCDMA Wide Area Basestations" Linear Technology Magazine, June 2008 C.D. Hull, R.R. Chu, J. Leong Tham, "A Direct-Conversion Receiver for 900 MHz (ISM Band) Spread-Spectrum Digital

	Cordless Telephone”, IEEE Journal of Solid-State Circuits, Volume 31, No. 12, December 1996
Papers/ Discussions / Video on Direct Sampling RF Receivers	R. Hosking, Mercury Systems, May 2023: https://militaryembedded.com/radar-ew/rf-and-microwave/exploiting-direct-rf-fpgas-for-electronic-warfare R. Hosking, Mercury Systems, October 2023: https://militaryembedded.com/radar-ew/rf-and-microwave/direct-rf-the-transformation-of-critical-defense-systems Ian Dunn “Conquer the Challenges Facing Next-Gen Front Ends” , Microwaves & RF, Sept. 9, 2024 Mercury Systems: “Direct RF technology transforms EW and radar defense systems” “https://www.youtube.com/watch?v=CKzl45ytCNY R. Uppal, IDST, September 2024: https://idstch.com/technology/electronics/unlocking-the-potential-of-direct-rf-fpgas-a-game-changer-in-wireless-communication/
Texts and Papers discussing IP2, IP3, and/or Noise Figure	P. Vizmuller, “RF Design Guide – Systems, Circuits, and Equations”, Artech House, 1995 U. L. Rohde and T. T. N. Bucher, “Communication Receivers: Principles and Design”, McGraw-Hill, 1988 R. Sagers, “Intercept Point and Undesired Responses”, IEEE Transactions on Vehicular Technology, Volume: VT-32, No. 1, February 1983 R. A. Witte, “Spectrum and Network Measurements”, Prentice Hall, 1991 H. T. Friis, “Noise Figures of Radio Receivers”, in Proceedings of the IRE, vol. 32, no. 7, pp. 419-422, July 1944 C. Bowick, “RF Circuit Design”, 2nd edition, Newnes, 2007

11 References

[1] P. Vizmuller, RF Design Guide – Systems, Circuits, and Equations, Norwood, MA: Artech House, 1995.

[2] Analog Devices, Linear Circuit Design Handbook, Newnes/Elsevier, 2008.

[3] D. Buchanan, Performance of an IF sampling ADC in Receiver Applications, Analog Devices, Inc., 2002.

[4] C. E. Shannon, "Communication in the Presence of Noise," *Proceedings of the IRE,* vol. 37, no. 1, pp. 10-21, 1949.

[5] U. L. Rohde and T. T. N. Bucher, Communication Receivers: Principles and Design, McGraw-Hill, 1988.

[6] G. Earl, "Consideration of Reciprocal Mixing in HF OTH Radar Design," in *IET, Seventh International Conference on HF Radio Systems and Techniques*, 1997.

[7] National Instruments, "Super-Heterodyne Signal Analyzers Description and Applications," [Online]. Available: https://download.ni.com/evaluation/rf/Super_Heterodyne_Signal_Analyzers.pdf.

[8] L. W. Couch, Digital and Analog Communication Systems, Second Edition, Macmillan Publishing, 1987.

[9] B. Razavi, "Design Considerations for Direct-Conversion Receivers," *IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing,* vol. 44, no. 6, 1997.

[10] N. S. A. Arshad, S. Z. Ibrahim and M. S. Razalli, "Six-Port Demodulator in Homodyne Direct Conversion Receiver," in *2014 2nd International Conference on Electronic Design(ICED)*, Penang, Malaysia, August 2014.

[11] A. Abidi, "Direct-conversion Radio Transceivers for Digital Communications," *IEEE Journal of Solid-State Circuits,,* vol. 30, no. 12, 1995.

[12] D. Stuetzle, "Understanding IP2 and IP3 Issues in Direct Conversion Receivers for WCDMA Wide Area Basestations," *Linear Technology Magazine,* June 2008.

[13] J. Felix, "Altera-Analog-Enabled Direct-RF Device Portfolio," Product Marketing Intel Corporation, 2019.

[14] R. C. J. L. T. C.D. Hull, "A Direct-Conversion Receiver for 900 MHz (ISM Band) Spread-Spectrum Digital Cordless Telephone," *IEEE Journal of Solid-State Circuits,* vol. 31, no. 12, 1996.

[15] A. Zerev, Handbook of Filter Synthesis, John Wiley and Sons, 1967.

[16] R. Gómez-García, L. Yang, M. Malki and J. M. Muñoz-Ferreras, "Flat-Group-Delay RF Planar Filters With Transmission Zeros Using Transversal Circuits," *IEEE Transactions on Circuits and Systems,* October 2023.

[17] Y. W. Lin, J. C. Lu, C. Y. Chang and C. K. Liao, "High Selectivity and Flat Group Delay Parallel-Coupled Microstrip Bandpass Filter with Lumped-Element K-Inverters," in *The 40th European Microwave Conference*, 2010.

[18] D. M. Pozar, Microwave Engineering, 3rd Edition, Hoboken, New Jersey: John Wiley & Sons, 2005.

[19] A. Coon, "Saw Filters and Competitive Technologies - A Comparative View," in *IEEE Ultrasonics Symposium*, 1991.

[20] F. Z. Bi and B. P. Barber, "Bulk Acoustic Wave RF Technology," *IEEE Microwave Magazine,* 2008.

[21] Yang, He, Fang, et al., "Advanced RF filters for wireless communications," *Chip,* vol. 2, no. 4, 2023.

[22] G. P. L. S. a. R. Stringfellow, "3D Printed, Self-Temperature Compensated Microwave Cavity Notch Filters," *IEEE Access,* vol. 9, 2021.

[23] S. B. a. R. V. Snyder, "Nonresonating Modes Do It Better!: Exploiting Additional Modes in Conjunction With Operating Modes to Design Better Quality Filters," *IEEE Microwave Magazine,* vol. 22, no. 1, pp. 20-45, 2021.

[24] Gramegna, G., et al., "A 56-mW 23-mm2 Single-Chip 180-nm CMOS GPS Receiver With 27.2-mW 4.1-mm2 Radio," *IEEE Journal of Solid-State Circuits,,* vol. 41, no. 3, 2006.

[25] N. Aslani-Amoli, F. Liu, M. Swaminathan, C. G. Zhuang, N. Z. Zhelev, S. H. Seok and C. Kim, "Ultra-Miniaturized, High-Performance Filters on Alumina Ribbon Ceramic Substrates for 5G Small-Cell Applications," in *IEEE Transactions on Components, Packaging and Manufacturing Technology*, 2024.

[26] S. Chatterjee and T. K. Das, "Compact Hairpin-Line Bandpass Filter with Harmonic Suppression by Periodic Grooves," in *IEEE 19th Mediterranean Microwave Symposium*, 2019.

[27] D. B. J. G. A. V. D. Christopher J. Hegarty, "An overview of the effects of out-of-band interference on GNSS receivers," *NAVIGATION: Journal of the Institute of Navigation,* vol. 67, no. https://navi.ion.org/content/67/1/143, pp. 143-161, 2020.

[28] Texas Instruments, *Why Oversample When Undersampling Can Do The Job? Texas Instruments Application Report SLAA594A,* July 2013.

[29] Lark Engineering, "The Better the Ground, the Better the Performance: Application Note WD00111-0915," Lark Engineering.

[30] Qorvo, *Datasheet QPA9127 and QPQ4900.*

[31] NTIA, "Manual of Regulations for Federal Radiofrequency Spectrum Management," [Online]. Available: https://www.ntia.gov/publications/redbook-manual.

[32] Department of Defense, *Interface Standard: Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, MIL-STD-461G,* 2015.

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Appendix A Abbreviations and Acronyms

Term	Definition
5G	Fifth Generation
ADC	Analog-to-Digital Conversion (or Converter)
AGC	Automatic Gain Control
BAW	Bulk Acoustic Wave
CFR	Code of Federal Regulations
DSP	Digital Signal Processor
FIR	Finite Impulse Response
FPGA	Field-Programmable Gate Array
GaN	Gallium Nitride
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IM	Intermodulation
IMP	IM Product
LNA	Low Noise Amplifier
LO	Local Oscillator
MIMO	Multiple-Input, Multiple-Output
NTIA	National Telecommunications and Information Administration
PCB	Printed Circuit Board
RF	Radio Frequency
RFI	Radio Frequency Interference
SAW	Surface Acoustic Wave
SNR	Signal-to-Noise Ratio
SWaP-C	Size, Weight, Power, and Cost
VGA	Variable-Gain Amplifier
VSWR	Voltage Standing Wave Ratio