Co-location Deployment Considerations for Direct RF Sampling Transceivers

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Abstract

The first wave of 5GNR network deployment is expected to coexist and co-locate with existing networks for faster and more economical rollouts. In light of the rapid adoption of highly integrated merchant silicon solutions for the radio unit (RU), such as the Zynq® UltraScale+™ RFSoC DFE, and the use of direct radio frequency (RF) sampling technology, this white paper examines the implications and considerations of co-locating a 5GNR radio with other high-power radios in proximity on design and architectural choices. It provides an in-depth analysis for an example receiver design with RF sampling data converters to illustrate how it can best handle the co-location requirements over traditional zero intermediate frequency (ZIF) receivers. Furthermore, it examines the general challenges faced by ZIF architecture for wideband 5G radio design that is solved by RF sampling data converters.

Introduction

The 5G new radio (NR) network is designed with the expectation that it will coexist with legacy networks for many years. Operators around the world have spent billions building out the 2G/3G/4G network on radio equipment and site acquisition. As such, there is substantial interest in leveraging and repurposing the existing infrastructure for the 5G network rollout to speed up its deployment and reduce costs. This includes sharing the existing 4G core networks, adding capacity to the backhaul, and adding on to the existing radio towers. The co-location deployment scenario of multiple radios next to each other means that the new 5G radio must be able to operate in compliance in the presence of high-power interference from the exiting radios and at the same time not interfere itself.

The 5G new radio could be co-locating with many different types of legacy radios that include permutations of the following radio access technologies (RATs).

- 5GNR time division duplexing (TDD), 5G frequency division duplexing (FDD).
- 4G long-term evolution (LTE) TDD, 4G LTE FDD.
- 3G, 2G RATs such as GSM, UMTS, CDMA, etc.

For example, a 5GNR TDD base station transceiver (BTS) could be co-located with another 5GNR FDD BTS, or a 5GNR TDD BTS could be co-located with a 4G TDD. The co-located radios might or might not be synchronous in transmit and receiver time frames.

When located in close proximity to an existing radio, the 5G radio must be designed such that it does not transmit excessive power in the neighboring radio's receive band (UL). Furthermore, its own receiver must have the ability to handle very high input power from the neighboring radio while at the same time maintain the ability to receive very low power signals from user equipment (UE).

3GPP Requirements for Co-location

To make co-location deployment feasible, the 3GPP TSG RAN4 group has published additional requirements in the BTS radio specification [REF 1] for co-locating 5G radios. On the transmit direction, it specifies the maximum output power limit at each of the co-locating BTS bands in Table 6.6.5.2.4-1 for type 1-C and type 1-H 5G NR BTS. The following table is from [REF 1].

Note: Type 1-C is an NR base station operating at FR1 with a requirement set consisting only of conducted requirements defined at individual antenna connectors [REF 1]. Type 1-H is an NR base station operating at FR1 with a requirement set consisting of conducted requirements defined at individual transceiver arrary boundary (TAB) connectors and OTA requirements defined at RIB [REF 1].

The first ten wireless bands for co-location are listed in the table.

Table 1: **TX Out-of-Band Power Limit for Co-location**

Type of Co-located BS	Freq. Range for Co-location Requirement	Basic Limits			Measurement Bandwidth
		WA BS	MR BS	LA BS	
GSM900	876-915 MHz	−98 dBm	−91 dBm	−70 dBm	100 kHz

Table 1: **TX Out-of-Band Power Limit for Co-location** *(cont'd)*

Type of Co-located BS	Freq. Range for Co-location Requirement	Basic Limits			Measurement Bandwidth
		WA BS	MR BS	LA BS	
DCS1800	1710-1785 MHz	–98 dBm	–91 dBm	–80 dBm	100 kHz
PCS1900	1850-1910 MHz	–98 dBm	–91 dBm	–80 dBm	100 kHz
GSM850 or CDMA850	824-849 MHz	–98 dBm	–91 dBm	–70 dBm	100 kHz
UTRA FDD band I or E-UTRA band 1 or NR band n1	1920-1980 MHz	–96 dBm	–91 dBm	–88 dBm	100 kHz
UTRA FDD band II or E-UTRA band 2 or NR band n2	1850-1910 MHz	–96 dBm	–91 dBm	–88 dBm	100 kHz
UTRA FDD band III or E-UTRA band 3 or NR band n3	1710-1785 MHz	–96 dBm	–91 dBm	–88 dBm	100 kHz
UTRA FDD band IV or E-UTRA band 4 or NR band n4	1710-1755 MHz	–96 dBm	–91 dBm	–88 dBm	100 kHz
UTRA FDD band V or E-UTRA band 5 or NR band n5	824-849 MHz	–96 dBm	–91 dBm	–88 dBm	100 kHz
UTRA FDD band VI, XIX, or E-UTRA band 6, 19	830-845 MHz	–96 dBm	–91 dBm	–88 dBm	100 kHz

For instance, if the 5GNR BTS is co-located with a wide-area base station operating in the PCS1900 band, then its transmitter output power must not exceed –98 dBm/100 kHz in the 1850 MHz to 1910 MHz frequency range at any time. This is the *basic limit* as indicated in the previous table. There are sub-clauses for mMIMO systems that have many antenna ports. On the receive direction, the 5G receiver must have the dynamic range specified in the following table [REF 1 Table 7.5.3-1]. Specifically, for a wide-area base station, it must be able to tolerate an out-of-band continuous wave (CW) signal at +16 dBm at the receiver connector without degrading its receiving sensitivity by more than 6 dB.

***Note*:** The following table is taken directly from [REF 1] specification to illustrate the requirements.

Table 2: **RX Out-of-Band Blocking for Co-location**

Freq. Range of Interfering Signal	Wanted Signal Mean Power (dBm)	Interfering Signal Mean Power for WA BS (dBm)	Interfering Signal Mean Power for MR BS (dBm)	Interfering Signal Mean Power for LA BS (dBm)	Type of Interfering Signal
Frequency range of co-located downlink operating band	$P_{REFSENS}$ +6 dB [1]	+16	+8	X [2]	CW carrier

Notes:

1. $P_{REFSENS}$ depends on the BS channel bandwidth as specified in Table 7.2.2-1, 7.2.2-2, and 7.2.2-3 [REF 1].
2. x = –7 dBm for NR BS co-located with Pico GSM850 or Pico CDMA850.
   x = –4 dBm for NR BS co-located with Pico DCS1800 or Pico PCS1900.
   x = –6 dBm for NR BS co-located with UTRA bands, E-UTRA bands, or NR bands.
3. The requirement does not apply when the interfering signal falls within any of the supported uplink operating bands or in Δf_{OOB} immediately outside any of the supported uplink operating bands.
4. For unsynchronized base stations (except in band n46 and n96), special co-location requirements might apply that are not covered by the 3GPP specifications.

While this is the 3GPP compliance specification, most network operators prefer that the 5G receiver sensitivity level does not get degraded at all. Along with the transmit direction, these specifications are much more stringent than without co-location.

In subsequent sections, the meaning of these co-location requirements are examined in terms of filtering needs and the implications on receiver architecture design to handle such high dynamic range. Specifically, a working example of the recently auctioned C band in the U.S. is analyzed, with a frequency range from 3700 MHz to 3980 MHz. It will be shown that these co-location requirements do not impose any significant additional filtering requirements when using direct RF sampling versus direct conversion transceivers (RFICs).

C-band Example Design Requirements

The 5G network and the mid-band spectrum (CBRS and C band in the United States) has created tremendous interest in new RU form factors. In particular, mMIMO systems with up to 32 to 64 antennas promise to greatly enhance the BTS capacity and coverage in the mid bands. The deployment of these mMIMO panels in the United States will likely be co-located on the same radio towers with existing PCS band or 4G/5G n2 band radios, both at downlink (DL) frequencies from 1930 MHz to 1990 MHz and uplink (UL) frequencies from 1850 MHz to 1910 MHz. The PCS/n2 band is of interest in this example case study because the second order harmonic distortion (HD2) and second order intermodulation (IMD2) products created by signals in this band fall directly onto the new C-band (3700 MHz – 3980 MHz). Other co-locating bands such as UMTS/n1 (2100 MHz) and 700M/800M are easier to design for in general and the analysis method would be the same.

The following table summarizes the high-level design requirements for the C-band system.

Note: The receiver noise figure is a few dBs better than the equivalent reference sensitivity requirement from the 3GPP specification [REF 1, section 7.2].

Table 3: **C-Band High-level Design Requirements**

Parameter	Value
5G BTS band	C-band, 3700 MHz to 3980 MHz
Occupied bandwidth/instantaneous BW	200 MHz/280 MHz
Duplex mode	TDD
Antenna configuration	32 TX/32 RX
5G BTS type	Type 1-H, wide area
TX power per antenna connector (TAB)	10W (40 dBm)
Total system TX power	320W (55 dBm)
RX noise figure (NF) per antenna receiver	≤ 2.5 dB
Co-location band	PCS/n2, UL: 1850 MHz – 1910 MHz, DL: 1930 MHz – 1990 MHz, FDD duplex

The analysis in this white paper mainly focuses on the co-location requirements mentioned in the previous section. Other 3GPP BTS requirements, such as TX SEM, RX narrow-band blocking, etc., are not directly included in this discussion as there are no specific co-location considerations for these requirements.

Transmitter Implications

The following two figures illustrate the typical RF signal lineup for transceivers with direct RF conversion and ZIF conversion architectures, respectively. The RF components for both architectures are very similar, with overall transceiver performance largely determined by the dynamic range and impairments of the data converters. Besides the usual non-linear harmonic distortions of the data converters, the impairments might include converter alias products, DC offsets, and images created from IQ imbalance, where applicable.

Figure 1: **Typical Transceiver RF Lineup with RF Sampling Data Converters**

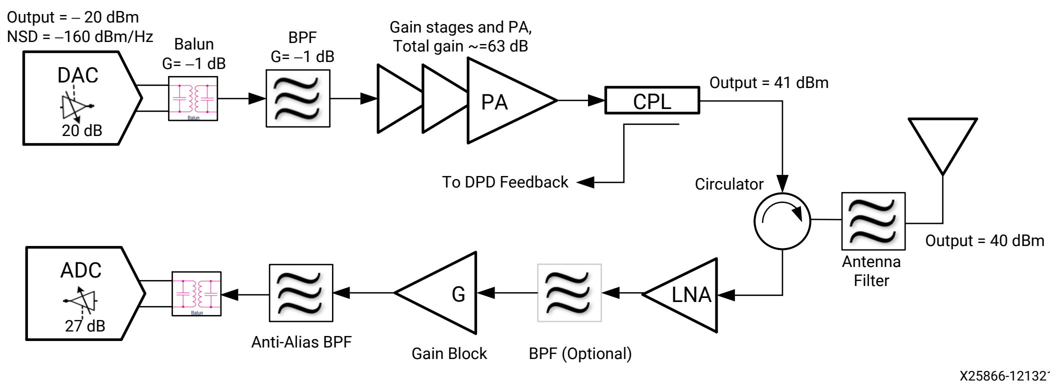
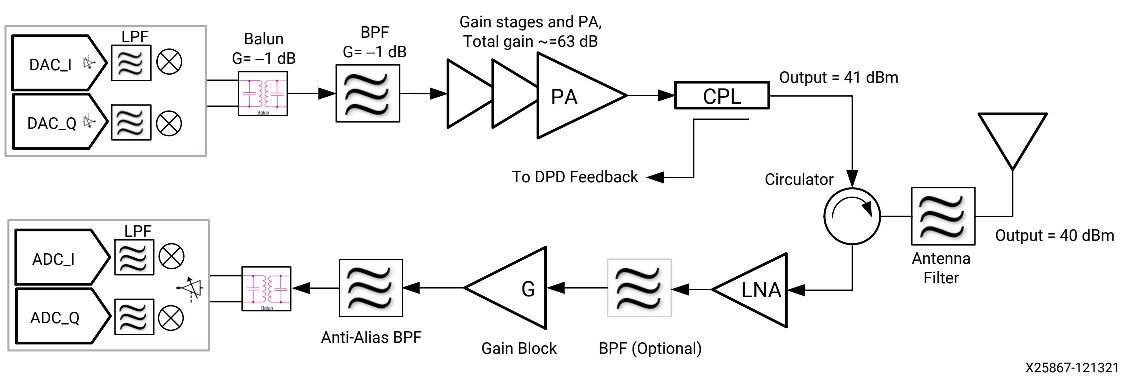


Figure 2: **Typical Transceiver RF Lineup with Zero IF Architecture**



The co-location requirement for the transmitter is straightforward. On the transmit direction, the design must ensure the output power density in the band from 1850 MHz to 1910 MHz be less than –98 dBm/100 kHz according to Table 1. Because this is a wide area type 1-H BTS with 32 possible active transmitters, it must also conform to the sub-clause for BTS type 1-H in 6.6.5.4 in [REF 1]. Specifically, it must account for emissions from more than one transmitting antenna. Using the second criteria in the conformance requirement, the emission limit becomes:

–98 dBm/100 kHz – 10log10(8) = –107 dBm/100 kHz

The value 8 in the logarithm term represents the number of counted transceiver array boundary (TAB) connectors in the TAB connector TX minimum cell group [REF 1].

This out-of-band emission requirement is largely the responsibility of the antenna filter in the radio architectures shown in the previous figures. The bandpass filter (BPF) following the DAC and balun output helps, but only to the degree that it filters the PCS band noise down to below the thermal noise level of –174 dBm/Hz. Because the noise spectral density (NSD) at the output of the DAC is roughly –160 dBm/Hz, any BPF with a reasonable rejection performance works. Inexpensive filters such as the Johanson 3750BP14D0900 [REF 2] in a 0603 footprint or similar are good candidates. This particular filter provides more than 50 dB of rejection in the PCS band.

Typical values for the TX cascade gain stages that are commercially available are shown in the following table.

Table 4: **Typical Cascade Gain Stage Parameters**

Gain	Value
Total gain at 3.8 GHz	63 dB
Total gain at 1.9 GHz	63 dB
RMS output power	41 dBm
# of gain stages	Three or four stages
Wide-band cascade noise figure	6 dB

Without loss of generality, the total gain of the amplifier stages is assumed to be the same at both 1.9 GHz and 3.8 GHz because most low-power gain blocks have higher gain at 1.9 GHz than 3.8 GHz, while it is the opposite for the final power amplifier. The output noise level at 1.9 GHz after the circulator (with IL = –0.3 dB) is:

–174 dBm/Hz + 6 dB NF + 62.7 dB Gain = –105.3 dBm/Hz or –55.3 dBm/100 kHz

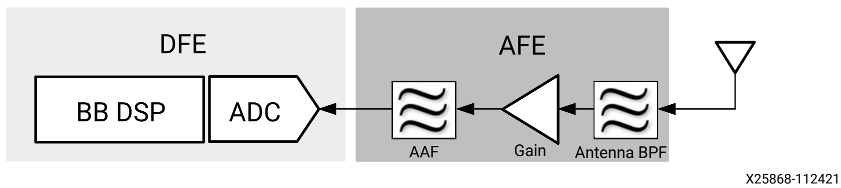
To meet the –107 dBm/100 kHz requirement with, for example, 10 dB of design margin, the antenna filter needs to provide 62 dB (–55.3 – (–107) + 10) of rejection in the PCS band. This level of rejection is not very difficult to achieve given the PCS band is 1.8 GHz away from the lower edge of the C-band. The typical rejection value for commercially available antenna filters is in the 75 dB range. The cost and complexity of the antenna filter is often constrained by the close-in operating band unwanted emissions (OBUE) rather than the co-location requirement.

Receiver Implications

The co-location requirements have more impact on the uplink receiver design because it needs to handle a much larger input signal dynamic range. The signal level can be as low as the RX reference sensitivity level specified in 3GPP [REF 1, Section 7.2] and as high as the 16 dBm CW from the co-locating PCS BTS. The 3GPP specification allows a 6 dB desensitization of the receiver under this deployment scenario. However, in practice, the desensitization could be avoided with proper design choices. Furthermore, the 3GPP specification uses a CW for the blocker, but in a real deployment, the blocker comes in the form of wireless carriers such as GSM, WCDMA, LTE, or NR carriers with similar RMS power, and with multiple transmitting carriers.

The high-level block diagram for either RF sampling or ZIF architecture receiver is summarized in the following figure. The analog front end (AFE) is composed of the RF lineup while the DFE includes the analog-to-digital converter (ADC) and the base-band DSP processing blocks. The AFE is mainly composed of filters and amplifiers. The total gain typically ranges from 25 to 40 dB with some adjustability to achieve the desired 2.5 dB system noise figure and be able to handle the 3GPP in-band blocking requirements [REF 1]. Two amplifier stages are generally needed to provide such large gain. These stages come either in two separate devices or in a single device package such as the F0473B from Renasas or the QPB9348 from Qorvo.

Figure 3: **High-level Receiver Block Diagram**



A design goal of the receiver in co-location deployment is to filter the 16 dBm interferer and any nonlinear products it generates from the active components in the AFE to a level well below the minimum wanted signal prior to the OFDM symbol demodulation. The minimum wanted signal power in this case is the targeted reference sensitivity level for the system. The filtering is provided by a combination of the various filters in the receiver chain that include the antenna BPF, optional BPF (shown in Figure 1 and Figure 2), anti-alias filter, ADC band selection digital down-converter (DDC), and the carrier selection DDC in the DFE baseband DSP. Each of the filter stages serves a slightly different purpose and the rejection needs are dependent on the component selection and the architecture of the receiver.

Design Approach

A general design approach for handling the 16 dBm blocker is outlined in this section.

1. The antenna BPF must filter the blocker to a level such that:
   a. It does not saturate/overdrive the first gain stage (LNA) of the AFE.
   b. The HD2 and IMD2 products generated by the gain stages from the blocker are well below the power of the wanted signal so that the 3GPP required 95% throughput is met. As illustrated in Figure 4 and Figure 5, the HD2 and IMD2 products from signals in the PCS band fall directly on the C-band. Although the specification only uses CW for the blocker, the multi-carrier scenario should also be considered in the analysis as the IMD2 generated is typically 6 dB higher than the HD2 product. This can be seen from a measurement of an LNA performance in Figure 6.

Figure 4: **HD2 and HD3 Products of a Continuous Wave in the PCS Band**

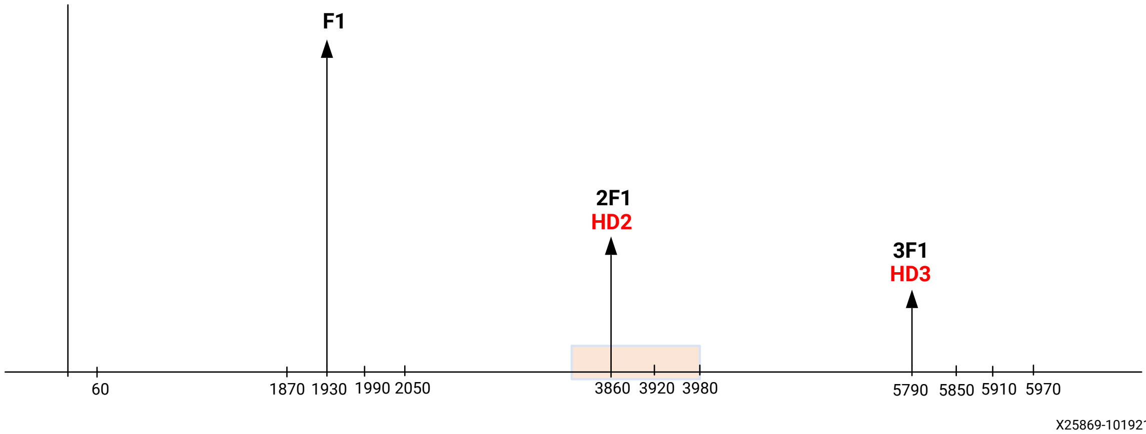


Figure 5: **Harmonic Products of Two Wireless Carriers in the PCS Band**

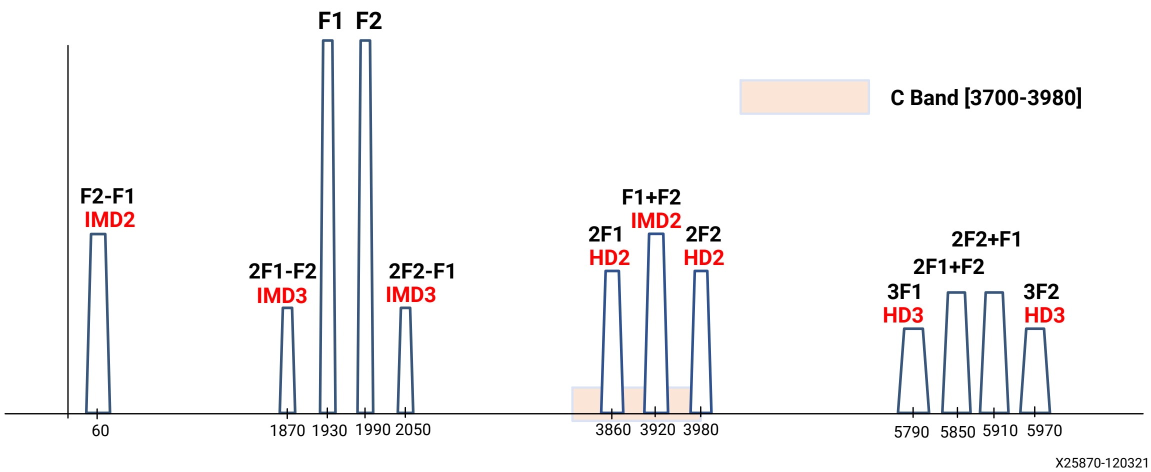
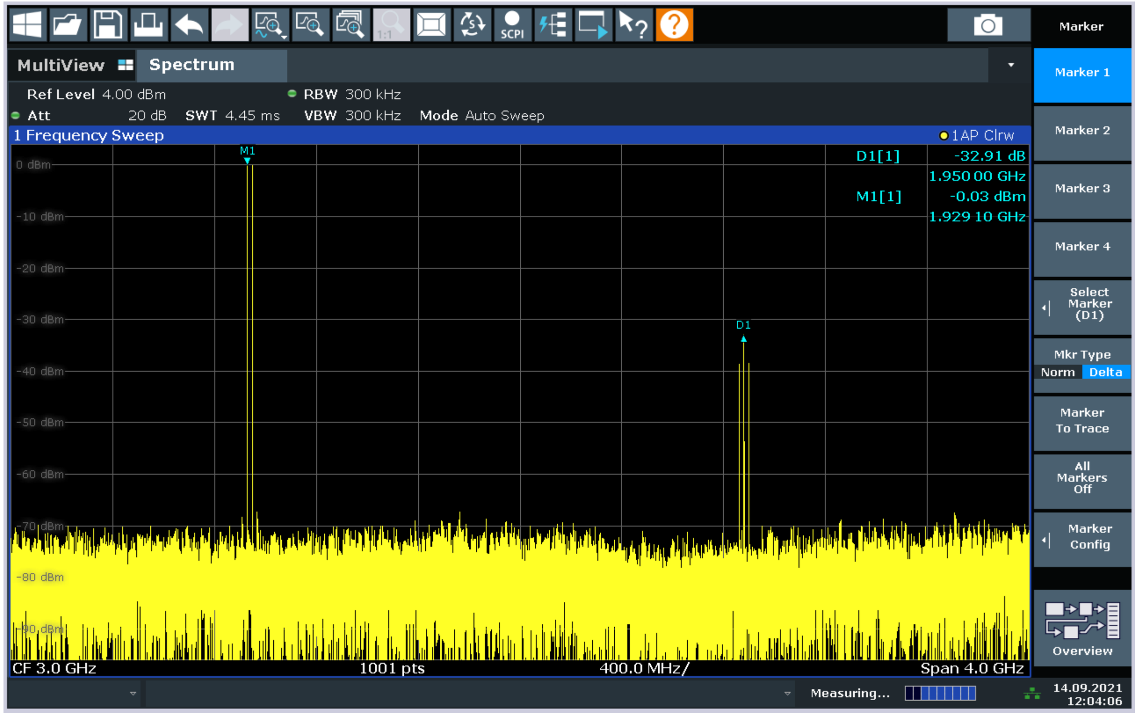


Figure 6: **Actual IMD2/HD2 Measurement on Qorvo QPL9058 (V_{DD}=5.0V) LNA at 0 dBm output. OIP2 = 33 dBm at $5V_{DD}$; OIP2 = 29 dBm at $3.3V_{DD}$.**



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2. The features of the optional BPF between gain stages are as follows:
    a. The purpose of the optional BPF shown in Figure 1 and Figure 2 is to provide additional filtering of the blocker in case the antenna filter does not have enough rejection to prevent the second amplifier from generating IMD2/HD2 products that can desensitize the receiver.
    b. The cost and footprint of this BPF is rather negligible and can be leveraged to relax the antenna filter requirement, and in turn to lower the cost and weight of the system. As in the TX lineup, the Johanson 3750BP14D0900 [REF 2] is a very good candidate with a 0603 size footprint.
3. An anti-alias BPF is needed for both RF sampling and ZIF receivers to get the best system NF, and it serves the following purposes:
    a. Provides additional filtering of the blocker so that it does not saturate/overdrive the ADC input.
    b. Provides last stage filtering of the blocker so that if the ADC alias of the blocker falls on the wanted C-band, it will be lower than the wanted signal to avoid desensitization. The filter rejection amount needed for this purpose is typically high. This scenario is common for a convenient RF-ADC sampling rate of 2949.12 MSPS. However, more 5G optimal devices, such as the Zynq UltraScale+ RFSoC DFE, provide additional options for the designer to frequency plan such an adverse scenario, and, consequently, remove the need for high-rejection filtering.
    c. Provides filtering for out-of-band noise and spurs that would otherwise alias/fold onto the first Nyquist zone at the ADC output.

   d. For a ZIF receiver, this anti-alias BPF also serves as a cleanup filter prior to the complex mixer in the demodulator. The current state of ZIF RFICs typically has active mixer and gain stages that feed the ADC input. M x N products of significant level from the mixer can be detrimental to the receiver sensitivity.

4. The digital filters are used as follows:

   a. Advanced devices, such as the RFSoC DFE, have hardened, low-power digital filters throughout the datapath to further remove remnants of the interferer. With GHz's of Nyquist bandwidth and flexible frequency planning, the designer can place the blocker alias outside of the C-band. In this case, the digital filter is used to remove the blocker prior to the symbol demodulator, which eases the analog filtering.

Example Receiver Design with Zynq UltraScale+ RFSoC DFE

In this receiver design example, standard catalog components are used with the Zynq UltraScale+ RFSoC DFE to achieve the design targets outlined in the following table for the C-band co-location deployment. A detailed analysis for each filter is provided in this section. Co-location deployments with other bands can be similarly analyzed.

Table 5: **C-Band Receiver Design Target Specification**

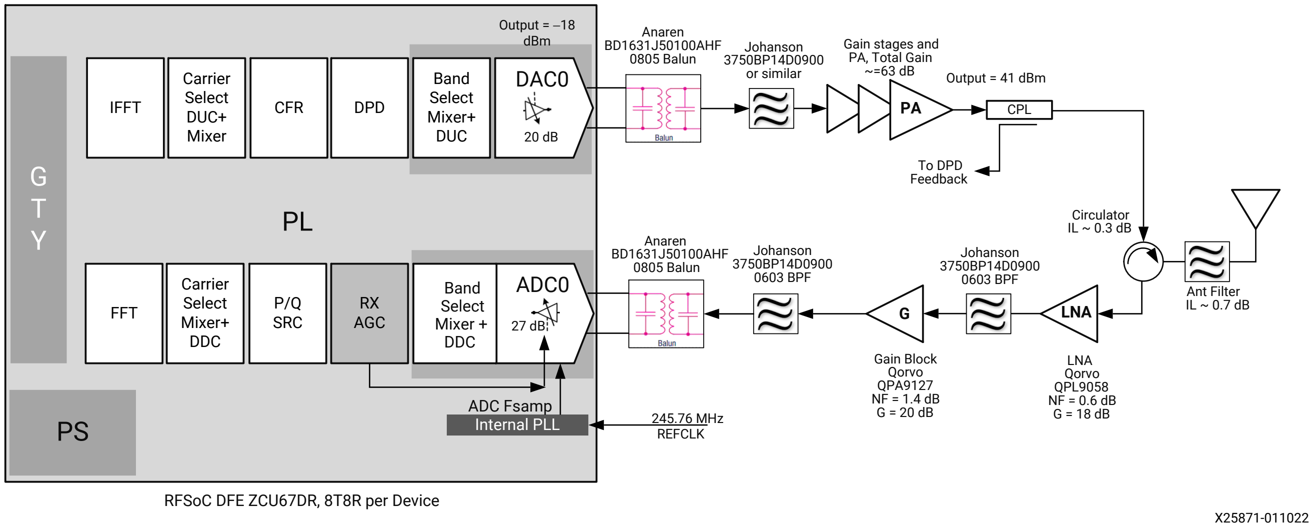
Design Parameter	Specification	Notes
Operating band	C-band	
Co-locating band	1900M PCS / n2 band	
Receiver NF	≤ 2.5 dB	~ 3.4 dB better than 3GPP reference sensitivity specification.
Equivalent reference sensitivity for 100 MHz NR carrier, i.e., minimum wanted signal	–99 dBm	[REF 1] 3GPP reference sensitivity specification is –95.6 dBm for 100 MHz carrier, which is equivalent to a 5.9 dB NF receiver. 95% throughput is equivalent to –1 dB SNR. A 2.5 dB NF receiver is 3.4 dB better than the 3GPP specification.
PCS band blocker signal level	16 dBm	CW
RX NF desensitization due to blocker	~ 0.1 dB	3GPP specification allows 6 dB of desensitization. However, in practice, no desensitization is desirable. Consequently, the design target is to reduce any in-band interference due to the blocker to 10 dB below the wanted signal level.
Final in-band signal to interference ratio (SIR) due to blocker	10 dB	
Maximum allowed interference from blocker that fall in-band, *referenced to antenna input*	–109 dBm	

In summary, the receiver must be able to receive a –99 dBm NR100 MHz signal in the presence of a 16 dBm CW blocker in the PCS band. As such, any in-band interference created by the blocker must be at –109 dBm or less for a SIR of 10 dB or better.

***Note*:** This target of –99 dBm for the wanted signal is 9.4 dB (6 dB for desensitization allowance, 3.4 dB for better ref sensitivity) better than the 3GPP specification.

If the blocker aliases directly onto the wanted C-band, then the total analog filtering rejection needed at 1900 MHz is 16 – (–109) = 125 dB. If the blocker does not alias directly onto the C-band, less rejection is required. In the following example design, both scenarios are examined and the best way to distribute the filtering along the RF lineup is assessed.

Figure 7: **Receiver Lineup Design Example**



The receiver lineup in this figure shows an example design using standard catalog components that can be used to meet the target requirements listed in the table above. The antenna filter is typically a custom part for mMIMO systems as the size and mechanical fitting is very specific to the design, and, as such, no specific part is indicated.

Antenna Filter

The antenna filter must filter the 16 dBm blocker to a level such that:

- It does not overdrive the LNA.
- The HD2 and IM2 generated by the LNA is lower than –109 dBm, referenced to the antenna input.

The LNA and gain blocks tuned for the C-band are generally optimized at 3800 MHz and have reduced dynamic range performance at 1900 MHz in the form of P1dB, IP2, and IP3. The Qorvo QPL9058 (operating with 3.3 V_{DD}) and QPA9127 specifications are summarized in the following table. The IP2 specification for the devices is not published in the datasheets. The values used are from actual measurement using the respective evaluation kit.

***Note*:** At 1900 MHz, the gain is usually about the same as at 3800 MHz while the IP2/IP3 are significantly worse.

The QPL9058 LNA can be operated at two supply voltages, 5.0V and 3.3V. 3.3V V_{DD} is used here for lower power at the expense of linearity. The data in the following table is quoted for 3.3 V_{DD} unless otherwise noted.

Table 6: **Specifications for RX Amplifiers at 1900 MHz and at 3800 MHz**

	QPL9058 (3.3 V_{DD})		**QPA9127 (5 V_{DD})**	
Parameter	At 3800 MHz	At 1900 MHz	At 3800 MHz	At 1900 MHz
Gain	17.4 dB	18 dB	21 dB	20 dB
Output P1dB	17.6 dBm	15 dBm	19.5 dBm	19.5 dBm

Table 6: **Specifications for RX Amplifiers at 1900 MHz and at 3800 MHz** *(cont'd)*

	QPL9058 (3.3 V_{DD})		QPA9127 (5 V_{DD})	
Output IP3	33 dBm	26 dBm	35 dBm	33 dBm
Output IP2 (2 tones)	40 dBm (3.3 V_{DD}) 46 dBm(5 V_{DD})	29 dBm (3.3 V_{DD}) 33.5 dBm (5 V_{DD})		32.5 dBm
Input IP2 (referenced to antenna input)	22.6 dBm (3.3 V_{DD}) 28 dBm (5 V_{DD})	11 dBm (3.3 V_{DD}) 16 dBm (5 V_{DD})		12.5 dBm
Noise figure	0.6 dB	0.4 dB	1.4 dB	1.2 dB

- To meet goal #1 with 10 dB of margin, the antenna filter rejection at 1900 MHz needs to exceed 29 dB.

  16 dBm + 18 dB gain – filter rejection(dBm) ≤ 15 dBm – 10 dB margin

- To meet goal #2 using the IP2 formula IMD2 = 2*Power_in – IIP2

  2*Power_in – 11 dBm ≤ –109 dBm → Power_in ≤ –49 dBm

Which means the antenna filter rejection at 1900 MHz needs to be at least 16 dBm – (–49 dBm) = 65 dB.

This is more stringent than goal #1 and similar to that of the TX emission filter requirement of 62 dB. This requirement is independent of the type of ADC architectures used and, as previously noted, filters with 75 dB of rejection are commonly available. Without loss of generality, an antenna filter rejection of 70 dB at 1900 MHz is assumed for the subsequent analysis.

Optional Bandpass Filter

The BPF between the two gain stages in this design is the Johanson 3750BP14D0900 [REF 2]. It comes in a 0603-package size and at a minimal cost while providing more than 50 dB of rejection at 1990 MHz. It is a very effective way to provide additional filtering of the blocker to reduce the IMD2/HD2 generated by the second stage amplifier. Again, referencing all calculations to the antenna input, the IMD2/HD2 product after the second stage amplifier is as follows (with two filters).

Blocker power (reference to antenna input) = 16 dBm – 70 dB – 50 dB = –104 dBm

IMD2 due to QPA9127 Amp = 2*Pwr_in –IIP2 = 2*(–104) – (12.5 dBm) = –220.5 dBm

The HD2 is typically 6 dB lower than the IMD2, and both are significantly below the target interference power level of –109 dBm. Without this BPF, the HD2/IMD2 is at ~–120.5 dBm using the above formula, which is also below the target level of –109 dBm, making this filter optional in this example RF lineup. It is useful for cases where a different second stage gain amplifier is chosen that has worse second order products, or if the designer wants to provide additional margin for component performance variation.

Anti-alias Filter

The AAF used here is the same filter as the optional bandpass filter for its high performance, small footprint, and low cost. This filter is critical in filtering out-of-band noise that would otherwise alias back into the first Nyquist zone at the ADC output. An advantage of the RF sampling ADC is the very wide Nyquist bandwidth it can provide, typically greater than 1 GHz. This gives more relaxed requirements for the anti-alias filtering. In practice, the AAF passband can be as large as the ADC Nyquist bandwidth and as small as the desired band as long as the aliased noise does not fold on top of the wanted band. Additional band specific selection and anti-alias filtering is then carried out by the built-in DDC in the ADC.

The other function of the AAF in a co-location deployment is to provide further filtering of the blocker to prevent desensitization of the receiver. The amount of filtering depends on the ADC alias location of the blocker with the chosen ADC sampling rate. There are two scenarios:

- Scenario A: The blocker alias falls directly onto the wanted C-band, implying the blocker must be ≤ –109 dBm at the input of the ADC (referenced to the antenna input).
- Scenario B: The blocker alias falls outside the wanted C-band, and no filtering of the blocker is needed if it does not saturate the ADC input. This scenario is where direct RF sampling offers more flexibility through appropriate frequency planning.

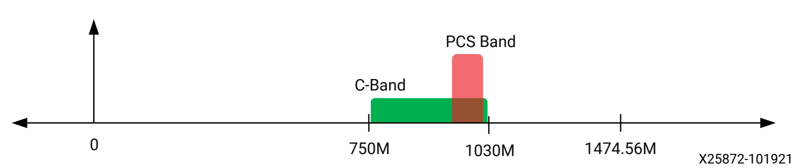
Scenario A

In scenario A, the design sets the ADC sampling rate to 2949.12 MSPS. According to the sampling theorem, all frequency content greater than the Nyquist frequency is aliased back to Nyquist zone 1, and as a result:

- The C-band baseband frequency at the ADC output lands at 750.88M – 1030.88 MHz.
- The PCS band baseband frequency at the ADC output lands at 959.12M – 1019.12 MHz.

The PCS band falls on top of the wanted C-band as illustrated in the following figure.

Figure 8: **Baseband Frequency Location at ADC Output with Fs = 2949.12 MSPS**



With the high performance of the AAF, the 16 dBm blocker at the ADC input is reduced to (again, referenced to the antenna input, and for ease of computation, assuming the total gain of the other components is the same at 1900M and 3800M):

16 dBm – 70 dB – 50 dB – 50 dB = –154 dBm

This is much lower than the target of –109 dBm. As the analysis shows, it is rather easy to handle the co-location blocker in the worst design scenario due to the availability of low-cost high-performance ceramic chip filters. It is not necessary to over design the cost sensitive antenna filter because it is far more efficient to filter the blocker in later stages of the RX chain. Without the optional BPF, the blocker aliased power would be –104 dBm. While this is sufficient to meet the 3GPP specification, it does not provide the desired margin. The optional BPF in this case provides ample design margin for minimal added cost.

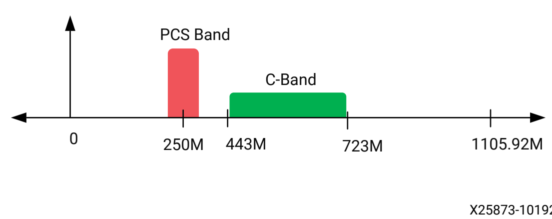
Scenario B

Unlike receivers based on the ZIF architecture, the RF sampling converter provides a very wide Nyquist bandwidth that allows the designer to frequency plan the blocker alias to fall outside of the wanted band. Typically, only a few ADC sampling rates are feasible with the RF sampling ADC due to the need for the ADC sample rate to be integer multiples of the 5G radio baseband rates like 30.72 MSPS. To ease this constraint, devices like the RFSoC DFE have built-in high performance, low-power fractional re-samplers to give the designer more options in frequency planning. The available conversion rates include $^{2}/_{3}$, $^{3}/_{4}$, $^{4}/_{5}$, and $^{5}/_{6}$ with more than 85 dB of anti-alias filtering performance.

Instead of setting the ADC sample rate to 2949.12 MSPS (96 x 30.72M) as in the previous scenario, a sample rate of 2211.84 MSPS can be used for the ADC to move the aliased PCS band completely outside the C-band as illustrated in the following figure.

- The C band aliases to 443.68M – 723.68 MHz.
- The PCS band aliases to 221.84M – 281.64 MHz.

Figure 9: **Baseband Frequency Location at the ADC Output with Fs = 2211.84 MSPS**



The following two figures illustrate the use of the built-in 2/3 PQ re-sampler to convert the data rate back to integer multiples of the 5G baseband rate. With this frequency plan, the blocker power can be large at the ADC input as long as it does not saturate the ADC front end. It is then removed by the highly selective digital filters in the band select DDC in the ADC core, the P/Q re-sampler, and the DFE carrier select DDC. In this design, the ADC's full-scale input power is approximately 1 dBm, which equates to –32.4 dBm referenced at the antenna input with the AFE gain being 33.4 dB. For reference, the first 70 dB of filtering from the antenna filter is already enough for this purpose. As such, there is no consideration required for the blocker alias issue at the ADC when choosing the filter lineup. An antenna filter with 70 dB of rejection with just the AAF would be more than enough in this case. The optional BPF can be eliminated without any penalty.

Figure 10: **DFE Sampling Rates at Each Stage**

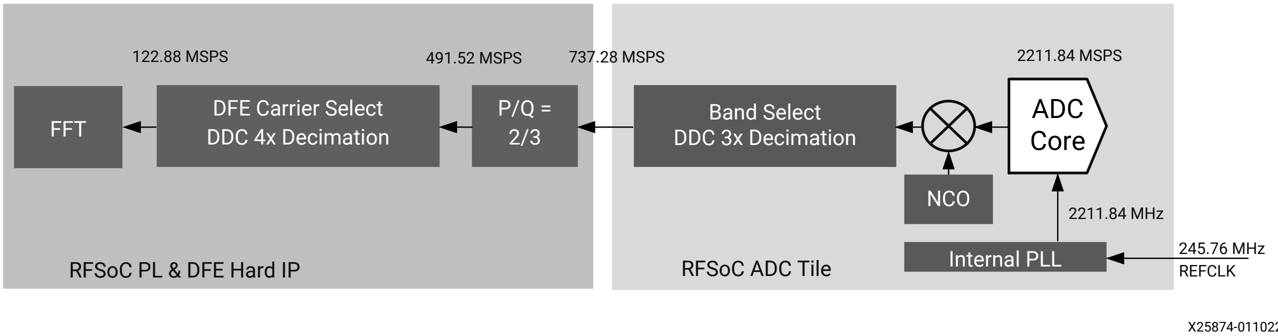
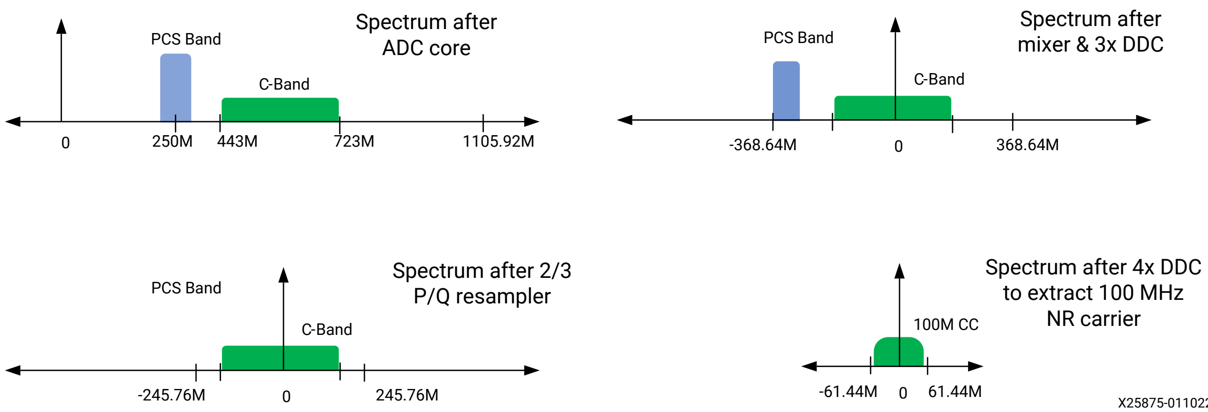


Figure 11: **Baseband Spectrum at Each Stage of the DFE**



The rich feature set of the Zynq UltraScale+ RFSoC DFE along with the fast ADC sampling speed give the radio architect many choices for handling even more complex co-location deployments. One of which is co-location with multiple interfering bands. In this case, the designer has the option to:

- Frequency plan all blocker bands to alias outside of the wanted band.
- If this is not feasible, the designer can prioritize bands that would impact the filter design the most (such as co-locating bands closer to the wanted band).

The flexibility and high performance of the Zynq UltraScale+ RFSoC DFE device together with the readily available low cost, small footprint chip filters render the co-location requirements rather trivial. There are no additional burdens on the antenna filter to handle this versus the non-co-location scenarios regardless of ADC architecture design.

Receiver Architecture Choices/Tradeoffs for 5G Wideband Radios

The discussion so far has focused on the implications of transceiver design resulting from the additional 3GPP requirements for co-location deployment. These requirements are easily addressed when using RF sampling data converters such as those found in the RFSoC DFE together with widely available low-cost bandpass filters. In practice, there are other considerations and requirements that need to be addressed in addition to co-location. In particular for the receiver, the radio designer must take into account the in-band selectivity and blocking [REF 1, section 7.4] requirements when making design choices on the architecture.

The ZIF receiver has been a popular architecture for 3G and 4G due to the narrowband nature of these radios and the ease of addressing the RF image filter needs of ZIF. However, this is not as applicable for 5G as its wideband nature significantly impacts the key shortcomings of the ZIF transceiver architecture.

To realize the gigabit throughput of a 5G enhanced mobile broadband (eMBB) use case, the bandwidth of the component carriers has increased from 20 MHz in 4G LTE to 100 MHz for FR1 and to 400 MHz for FR2, with the radio RF operating bandwidth often covering 400 MHz in FR1 and 1600 MHz in FR2. Non-contiguous operating bands are also becoming more common due to these very wide RF radio bands or the need to support multiple bands for carrier aggregation. Consequently, the 3GPP compliance requirements for adjacent channel selectively and in-band blocking have become more difficult as the interfering signal is now as wide as 20 MHz [REF 1, section 7.4]. The following sections examine two of the most challenging aspects of using ZIF receivers when handling wideband signals.

Local Oscillator Leakage

Perhaps the most widely known issue with ZIF is the local oscillator (LO) leakage at the baseband output. The LO leakage includes a static component and a dynamic component. The static component does not change much during runtime but can vary from unit to unit. The dynamic leakage component is a function of many factors such as temperature, input signals, non-linear distortions, receiver component lineup variation, analog mixer, LO isolation, etc. In practice, the receiver must incorporate a non-trivial DC nulling algorithm for real-time reduction of the LO leakage power so that it does not degrade the signal to noise ratio (SNR) of the wanted signal. Due to the dynamic nature of the leakage power, the nulling algorithm must trade off tracking speed, nulling accuracy, and implementation cost, which makes it very difficult to remove the LO leakage to a level that does not degrade the receiver sensitivity. Reducing the LO leakage power in the vicinity of –109 dBm (reference to the antenna input) can be very difficult to achieve in practice.

This issue is less impacting in 4G LTE because LTE carriers do not have a sub-carrier located at the center of the carrier. As such, the radio designer can use a sub-par algorithm to achieve an acceptable level of performance. Component carriers for 5GNR do not have this characteristic. The entire occupied bandwidth of the carrier can have valid sub-carriers present. This further complicates the LO nulling algorithm as it is difficult to distinguish between the wanted signal and the LO leakage. Any non-zero integration loop bandwidth of the algorithm will be detrimental to the sub-carrier of the wanted signal centered around DC.

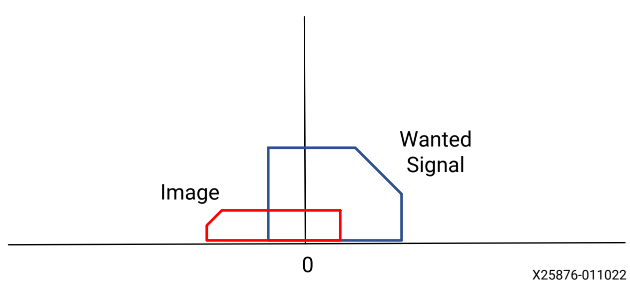
Another well understood artifact that impacts the 5G signal is the inherent 1/f flicker noise at DC generated by the LO and mixer. This noise cannot be reduced with the LO-nulling algorithm and will have meaningful impact on the sensitivity of the receiver in that region of the band.

Image Due to IQ Imbalance

The other well known challenge with the ZIF receiver is the image created by the gain and phase imbalances between the I and Q channels. The image mirrors the signal around DC and falls inside the wanted band as illustrated in the following figure. A 0.2 dB gain and 2-degree phase mismatch creates an image at 39 dBc from the main signal. Typically, an uncalibrated ZIF IQ receiver has 30 to 35 dB of image level. There are many components in the I and Q signal path that exhibit mismatches and contribute to the image level, including:

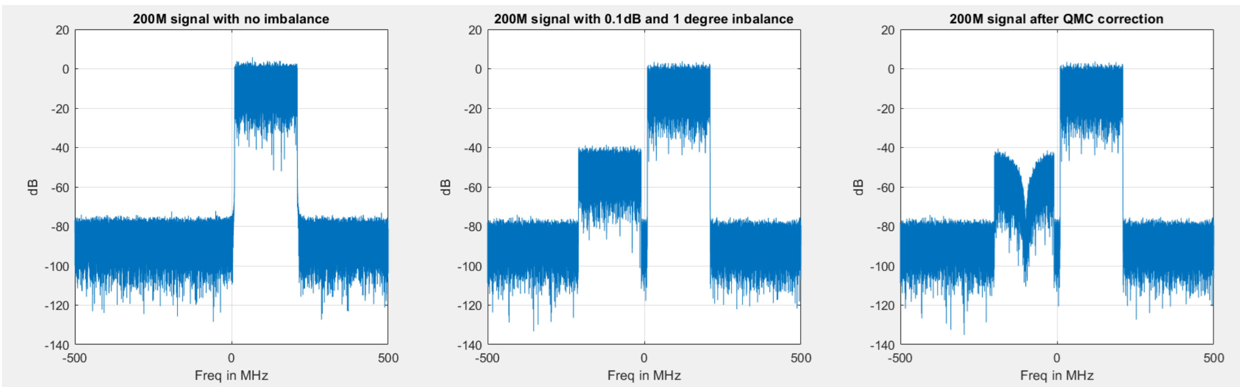
- ADC.
- Low-pass filter.
- Down-converter/mixer.
- I/Q independent gain stages.
- Digital step attenuator (DSA) for RX AGC function that adjust I and Q separately.
- LO 90-degree phase shifter.

Figure 12: **Image Due to IQ Imbalance**



The ZIF receiver design often employs an IQ calibration mechanism to reduce the image level. The process to calculate the IQ imbalance and provide the compensation is often non-trivial and requires additional hardware in the design to support the calibration. The quadrature error correction (QEC) block in ZIF RFIC devices might be designed with a single complex correction tap, suitable for correcting IQ imbalance at a single frequency point or for narrow instantaneous bandwidth (iBW). This tends to be enough for 4G systems with smaller carrier and operating bandwidth. For wider band 5G radios, the IQ mismatch has a larger frequency dependency as the gain and phase mismatch can vary across the band. As a result, the single point correction QEC is not enough. This concept is illustrated in the following figure. For ease of visualization, half of a 400 MHz band is populated with signal. The left plot shows the spectrum of a perfectly balanced I and Q path. The center plot shows the image at –40 dBc level when the I and Q paths differ by 0.1 dB in gain and 1 degree in phase. The plot on the right shows the image after a single point QEC correction. The QEC correction does a very good job around the center of the 200 MHz signal. However, the signal edges do not get much correction at all due to the frequency variation of the gain and phase mismatch. Mismatches caused by temperature variation further complicates the issue.

Figure 13: **IQ Correction with Single Frequency Point QMC (One Complex Tap)**

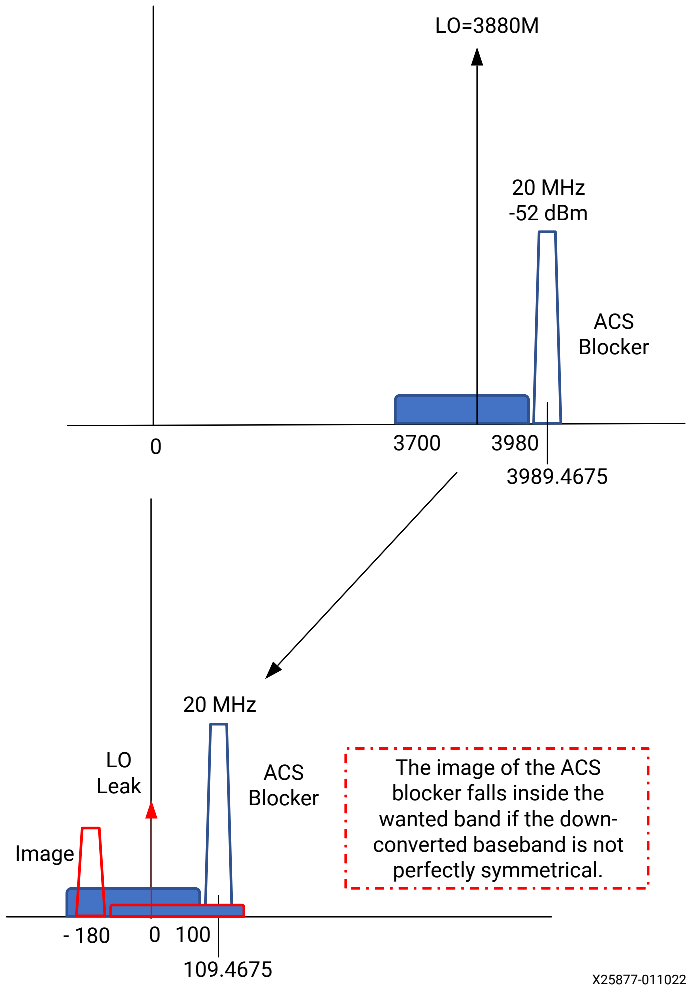


To reduce the image across the entire band, a more complex QEC filter is required. This leads to an increase in power, as well as computational complexity in the calibration mechanism. In practice, over operating conditions of temperature, signal dynamic range, and RAT types achieving a 50 dBc image level across 400 MHz or more of instantaneous bandwidth is a challenge.

Adjacent Channel Selectivity

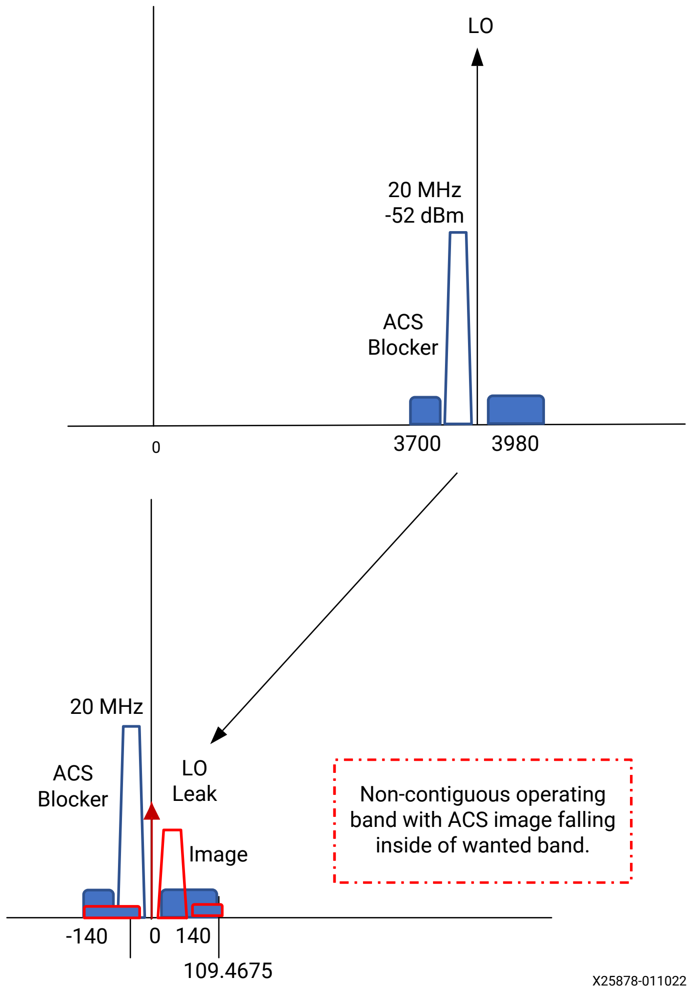
Due to IQ imbalance, the image falls on the same band as the wanted signal in a ZIF receiver. This impairs the sensitivity, particularly for situations where one carrier has a higher power than another in the same band. The adjacent channel selectivity (ACS) setup where a –52 dBm 20 MHz NR blocker is received at the antenna just adjacent to the operating band edge [REF 1, Section 7.4.1] is such an example. If the operating band is not perfectly centered around the DC when down-converted to the baseband, the image of the ACS blocker falls onto the wanted band, degrading the sensitivity of the receiver as shown in the following figure. From the previous calculation of keeping any in-band interferer at –109 dBm or less it means the IQ correction/rejection across the 280 MHz bandwidth must be 57 dBc or better.

Figure 14: **Image of ACS Blocker Falling onto Wanted Band**



Another operating scenario where the IQ image presents a problem is the ACS requirement for non-contiguous bands. In this situation, the ACS blocker is located in between the non-contiguous bands and its image falls onto one of the operating sub-bands as illustrated in the following figure. Situations like these can severely limit the designer's frequency planning options.

Figure 15: **ACS Blocker Image Falls onto Wanted Band for Non-contiguous Operating Bands**



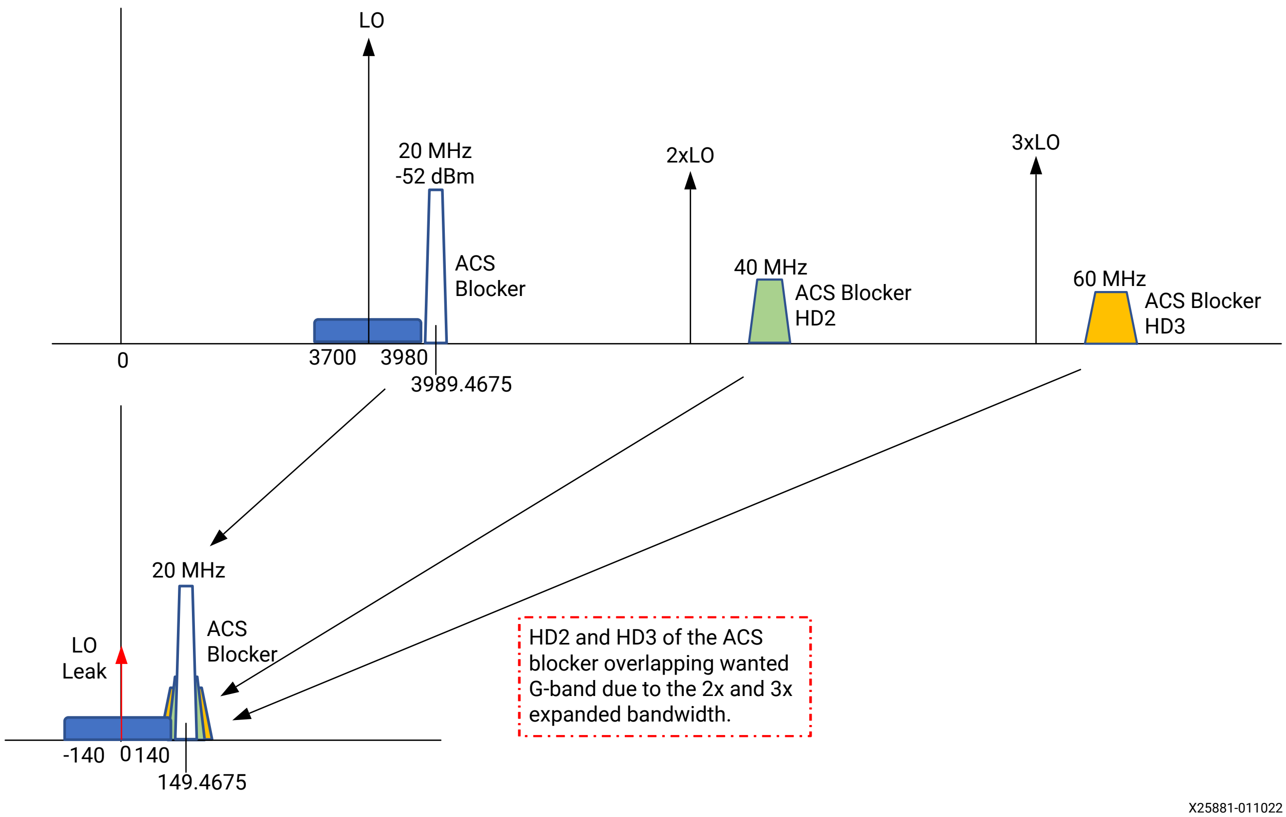
RF Image Filtering

An advantage of ZIF receivers is the lower requirements on RF image filtering due to the inclusion of a low pass filter between the IQ demodulator and the ADC. While this is still the case for 5G NR receiver design, the advantage is largely diminished due to the availability of low-cost miniature ceramic bandpass filters. Several companies now provide such parts as standard catalog filters for each NR band, including Johanson and Murata. The Murata equivalent of the Johanson C-band ceramic filter used in the analysis is the Murata LFB213G60CGUE234 [REF 3].

Although it is often claimed that the anti-alias RF filter in Figure 2 is not required in a ZIF receiver, it is generally used in practice. The main goal of the AAF there is to remove out-of-band HD2 and HD3 products generated by the amplifier stages to avoid any MxN mixing products in the demodulator that will eventually fall into the baseband and on top of the wanted C-band. For instance, 2xLO mixing with HD2 and 3xLO mixing with HD3 will all land at the same location as the wanted band.

The following figure illustrates the problem with the ACS blocker scenarios. In 5GNR, the ACS blocker is as wide as 20 MHz and sitting directly adjacent to the wanted band. The HD2 of the blocker is 40 MHz wide, and its HD3 is 60 MHz wide. As a result, the mixed down version of the HD2 and HD3 is wide enough to spill onto the wanted band even though the blocker itself does not (as shown in the figure). For this reason, it is important to have the RF AAF to clean up the RF spectrum prior to the mixer stage. However, this does not help with the HD2/HD3 generated by the active mixer in the ZIF demodulator.

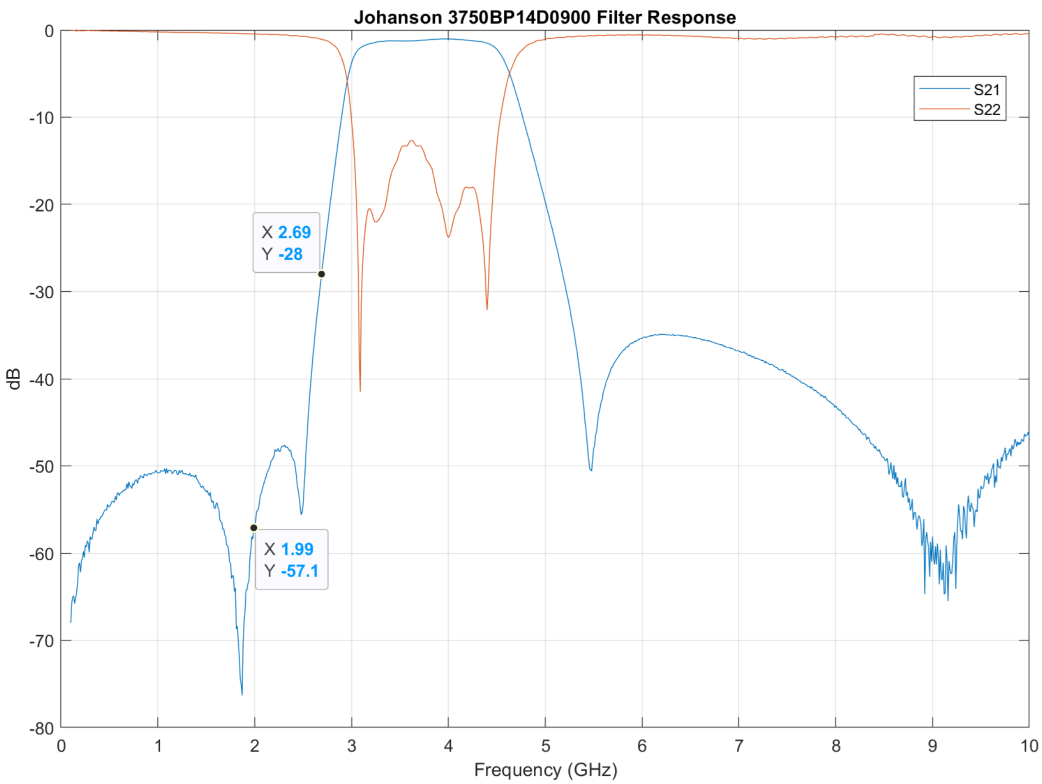
Figure 16: **Adjacent Channel Selectivity Blocker with MxN Mixing Products**



Filter Response of Johanson 3750BP14D0900

The filter response of the Johanson 3750BP14D0900 is shown in the following figure.

Figure 17: **Filter Response of Johanson 3750BP14D0900**



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Conclusion

This white paper provides a detailed analysis of the design implications of a 5G radio for the C-band in a co-location deployment. An example design using off-the-shelf components is presented to show that the additional 3GPP co-location requirements are easily met when designing the receiver with highly integrated and cost-effective RF sampling SoC devices such as the Zynq UltraScale+ RFSoC DFE. It is shown that the requirements on the antenna filter are not dependent on the choice of ADC/receiver architecture and there are no additional requirements for the antenna filtering specification.

In fact, widely available low-cost miniature ceramic bandpass filters provide enough rejection that can meet the co-location requirement with ample margin. This white paper also discusses the advantages of using RF sampling converters for 5G transceiver design from the perspective of frequency planning flexibility and overcoming some of the inherent drawbacks of the ZIF architecture. The Zynq UltraScale+ RFSoC DFE provides radio architects a highly integrated system on-chip solution that can be adapted for many use cases and deployment needs for the 5G network that also meet and exceed the 3GPP RF performance requirements.

For more information, see the Breakthrough Adaptive Radio Platform for Mass 5G Deployments website.

References

These documents provide supplemental material useful with this guide:

1. 3GPP, TS38.104 v16.7.0, *NR, Base Station (BS) radio transmission and reception (Release 16)*, April 2021
2. https://www.johansontechnology.com/datasheets/3750BP14D0900/3750BP14D0900.pdf
3. LFB213G60CGUE234.pdf (murata.com)

Revision History

The following table shows the revision history for this document.

Section	Revision Summary
01/11/2022 Version 1.0	
Initial release.	N/A

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