Optimize RF Sampling Receiver Performance using Frequency Planning

Created by Thomas Neu

Presented by Thomas Neu

Frequency Planning

1. ADC SFDR
   - Low order spurs H2-H5
   - Interleaving spurs
   - High order harmonics
   - SFDR vs amplitude/frequency?
   - Nyquist zones and aliasing

2. Concept of frequency planning
3. Evolution from Traditional IF sampling to Modern RF sampling

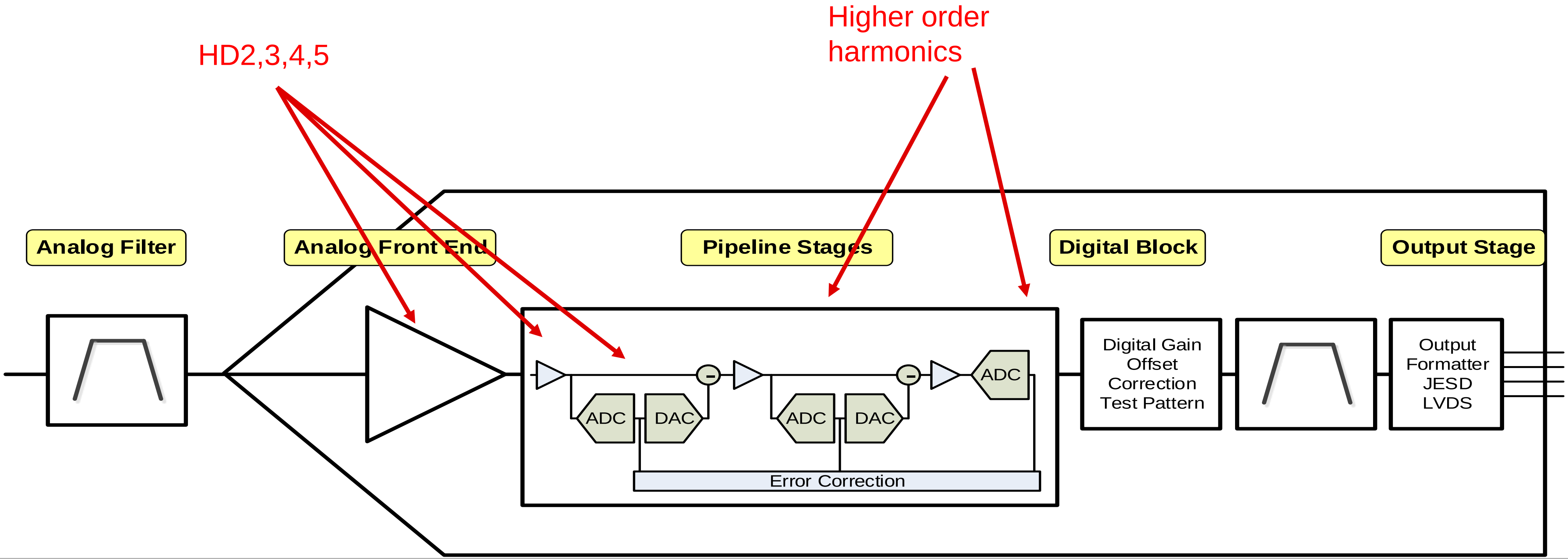
Introduction

- High-speed ADCs (> 100Msps) are used in wide range of different applications.
- In frequency domain applications (such as communications or radar), the ADC spur free dynamic range (SFDR) is a key receiver performance differentiator.
- ADC manufacturers spend a lot of time and power to improve spurious performance.

SFDR – Where do the spurs come from?

Pipeline design is one of most commonly used architectures for high-speed ADCs

- Input buffer, amplifiers and other “non-ideal” analog blocks have non-linear behavior
- Large input signal amplitudes make degradation worse
- Later stages and digital noise coupling are responsible for higher order harmonics



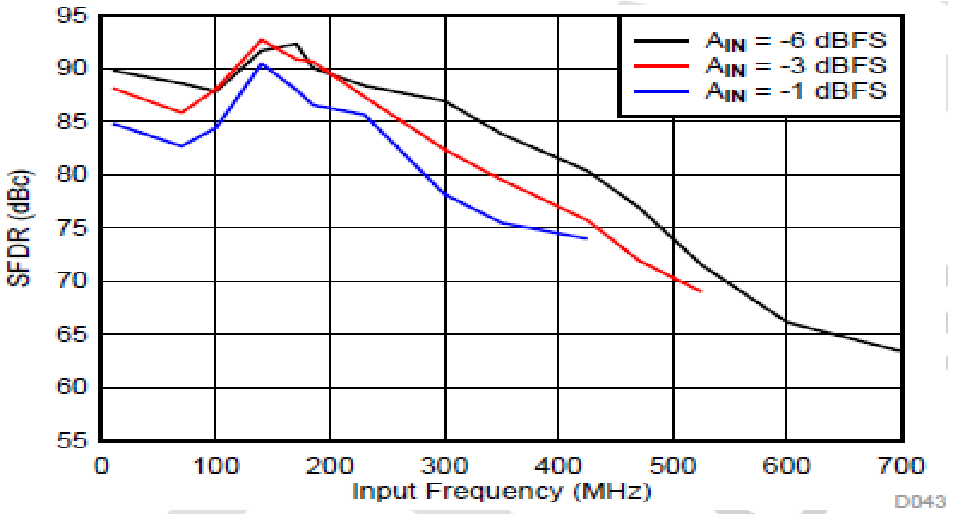
Additional SFDR Impairments

SFDR gets worse with higher input frequencies

- Layout and matching gets harder as frequencies increase
  - Fin = 100MHz => HD2 = 200MHz
  - Fin = 1GHz => HD2 = 2GHz

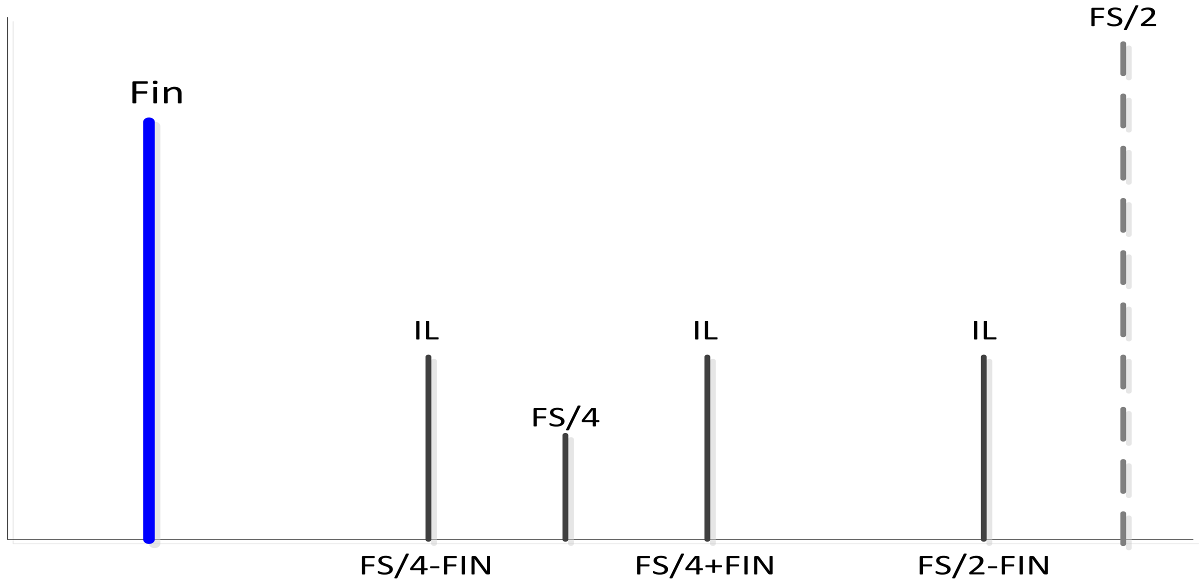
Low order harmonics (HD2…HD5) tend to improve with backoff (ie lower amplitude)

- Amplifier drives smaller swing at higher frequencies



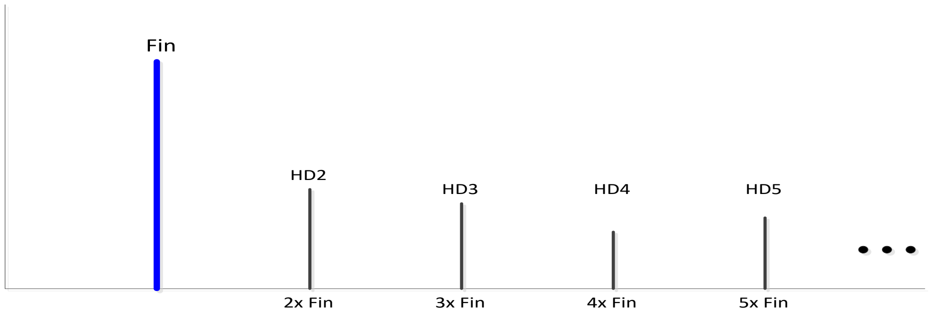
Additional SFDR Impairments (2)

- Fast Gsps ADCs are often times interleaved ADCs
- Interleaved ADCs have additional spurs originating from gain, offset, bandwidth and timing mismatch
- A 4x interleaved ADC (e.g. ADC12J4000, ADC32RF45) will have spurs at:
  - Fs/4
  - Fs/4 +/- Fin
  - Fs/2 – Fin

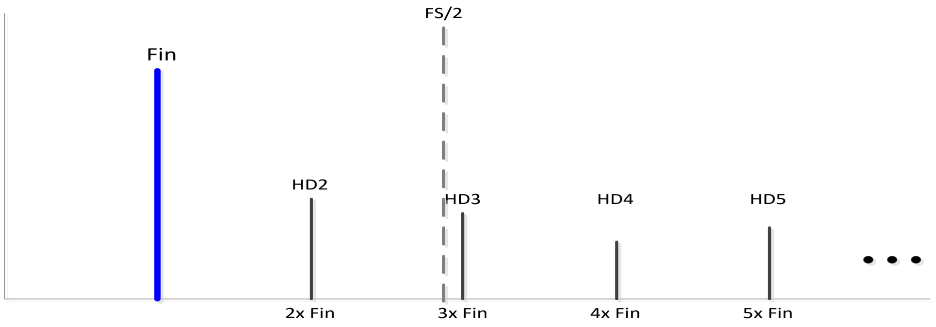


ADC Frequency Spectrum

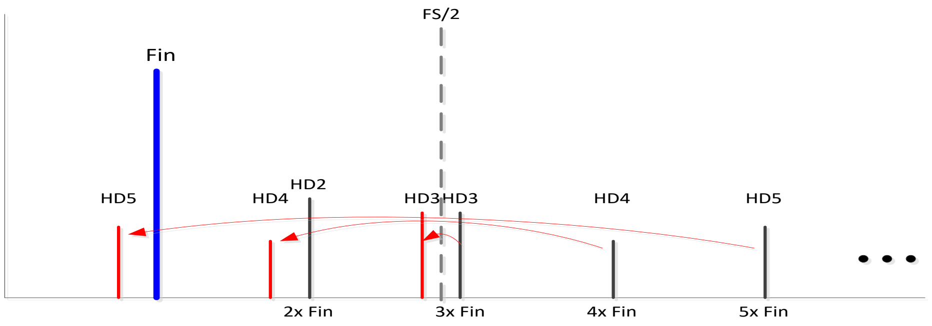
How does spectrum look like??



Adding ADC clock rate



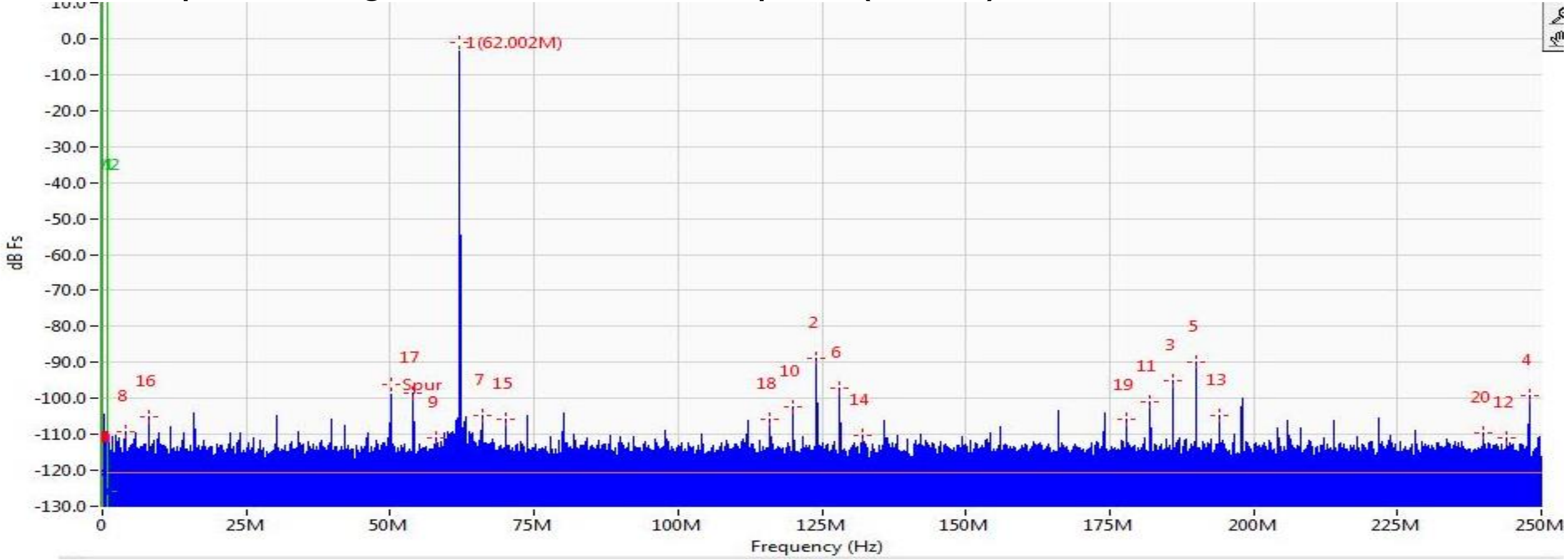
Now harmonics/spurs fold back into 1st Nyquist zone



Typical HS-ADC FFT Plot

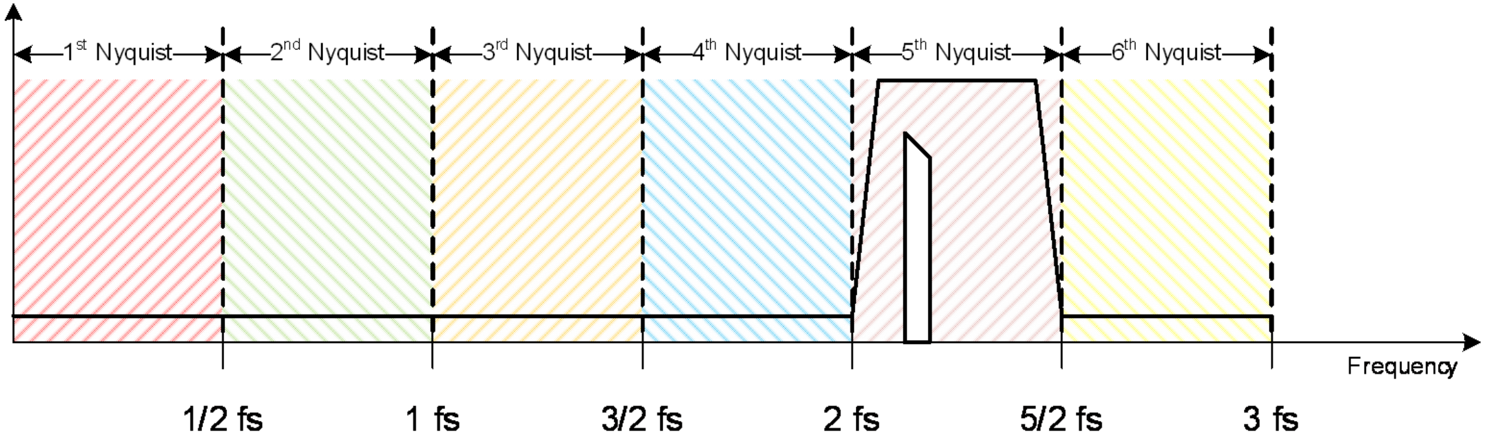
Sampling Rate FS = 500Msps, Input Signal at 62MHz

- Nyquist zone = 0…250MHz (FS/2)
- Larger amplitude low order harmonic spurs (HD2… HD5)
- Lower amplitude high order harmonic spurs (HD6+)



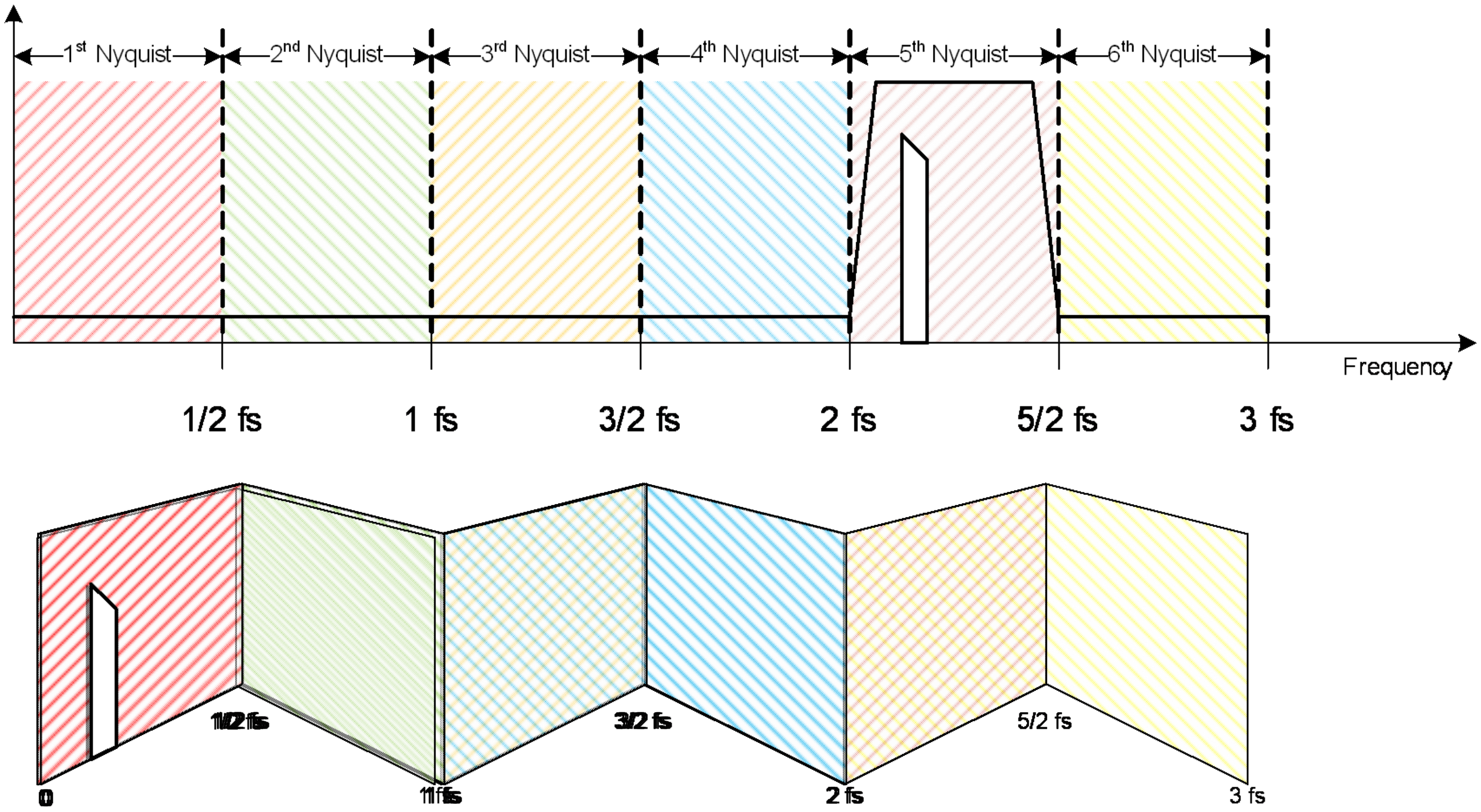
Nyquist Sampling vs. Undersampling vs. RF Sampling

- Nyquist theorem dictates that fs > 2 * fin,max to avoid aliasing
- Beyond Nyquist, if fs > 2 * Δf (signal bandwidth) and with careful frequency planning, spectral overlap can be avoided as signal folds back to 1st Nyquist zone
- With RF sampling, the undersampling concept gets expanded to higher Nyquist zones and offers more benefits and flexibility

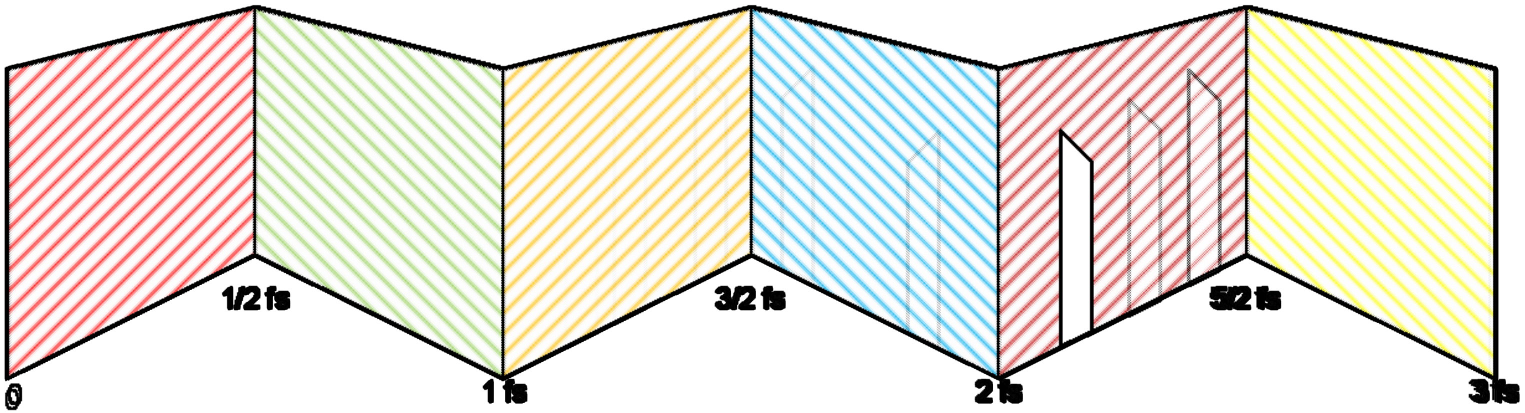


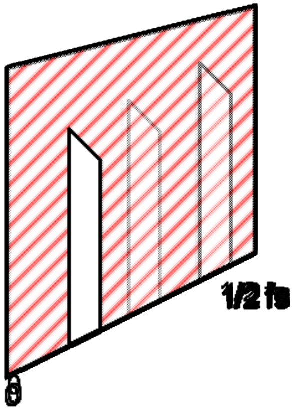
Adopted from: TIPL ADCs – Bandwidth vs. Frequency (Sub-sampling concepts), https://training.ti.com/ti-precision-labs-adcs-bandwidth-vs-frequency

Practical Aliasing Example - Undersampling



Practical Aliasing Example - Undersampling





Are all ADCs suitable for undersampling / RF Sampling?

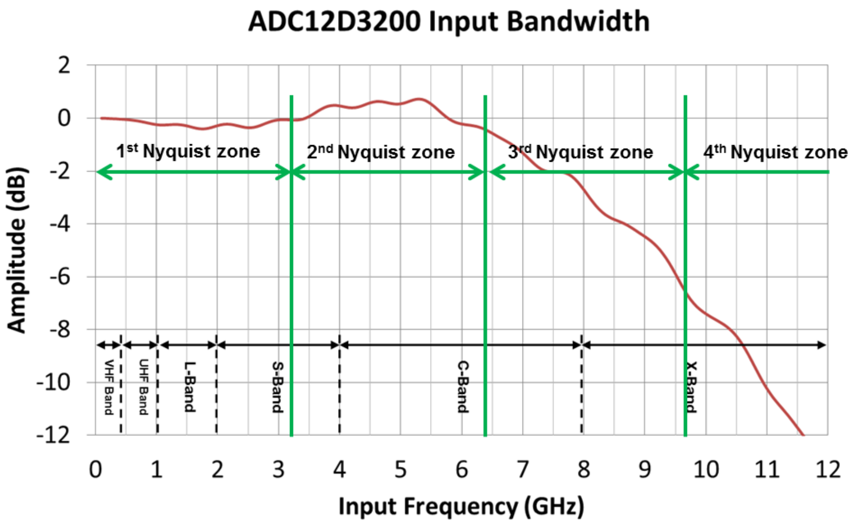
- Analog Input Bandwidth is key parameter determining undersampling capability
- Recent RF sampling ADCs have pushed usable input bandwidth up as high as 10GHz
- Trend continues to provide >> 10GHz direct sampling capability for microwave and millimeterwave systems

TEXAS INSTRUMENTS

ADC12DJ3200 6.4-GSPS Single C
12-bit, RF-Sampling Analo

1 Features

- ADC Core:
  - 12-bit Resolution
  - Up to 6.4 GSPS in single channel mode
  - Up to 3.2 GSPS in dual channel mode
- Buffered Analog Inputs with V_{CMI} of 0 V
  - Analog input bandwidth (-3 dB): 8.0 GHz
  - Usable input frequency range: >10 GHz
  - Full-scale input voltage (V_{FS}, default): 0.8 V_{PP}



Concept of Frequency Planning

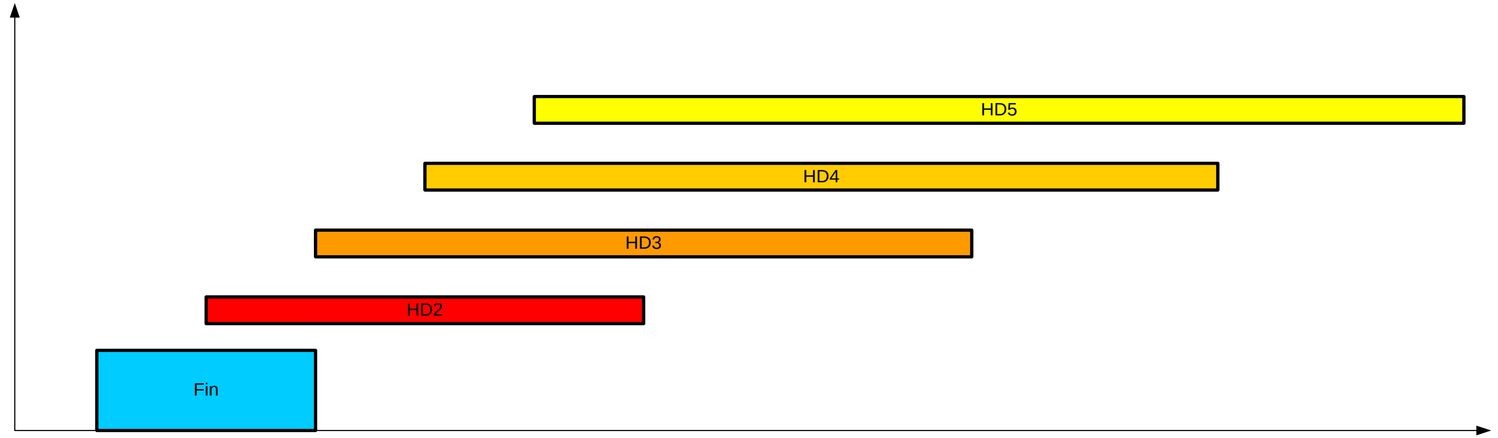
Frequency Planning Concept

- Until ~ 2010 the primary path to achieving highest SFDR was to spend more power on the ADC.
- As sampling rate requirements increased quickly that direction got more and more impractical

Let’s look at an example:

Input frequency band Fin

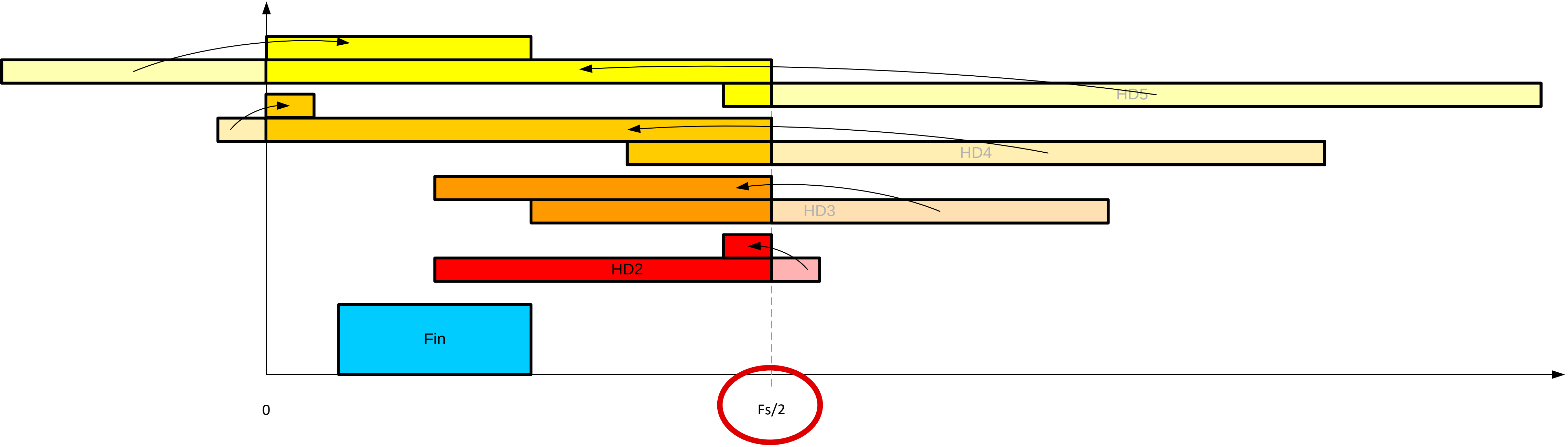
=> ADC generates primary harmonic bands HD2 to HD5 (remember HD2 = twice as wide as Fin etc)



Frequency Planning Concept (2)

Now let's add the Nyquist zone boundary of the ADC

=> Bands of harmonic frequencies wrap around Nyquist zone edges

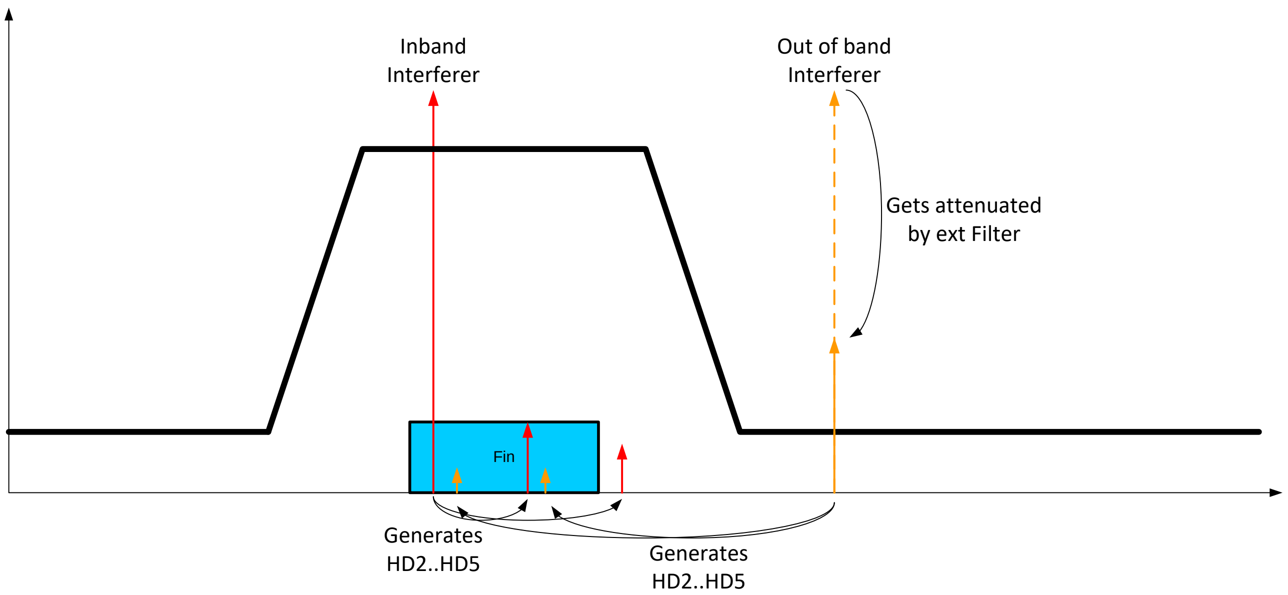


Frequency Planning Concept (3)

In receiver application there are 2 different types of interferer signals:

- In-band: within the pass-band of the external filter – experience no attenuation
  Harmonic distortions in ADC from this interferer will be larger
- Out-of-band: get attenuated by external filter
  Harmonic distortions in ADC will be much smaller as ADC SFDR improves with backoff

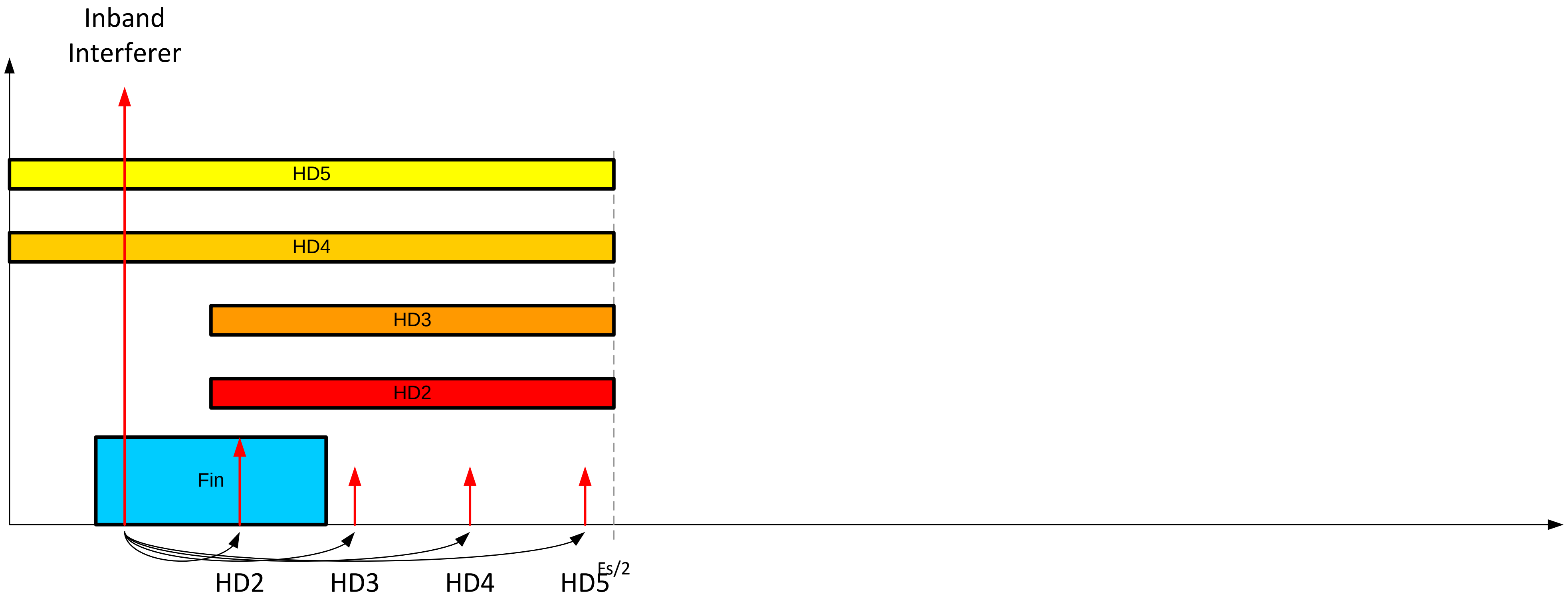
=> Frequency planning concept focuses on in-band interferer



Frequency Planning Concept (4)

Wanted band Fin has partial overlap with HD2/HD3 and full overlap with HD4/HD5

=> The harmonic distortions of In-band Interferer fall on top of wanted signal



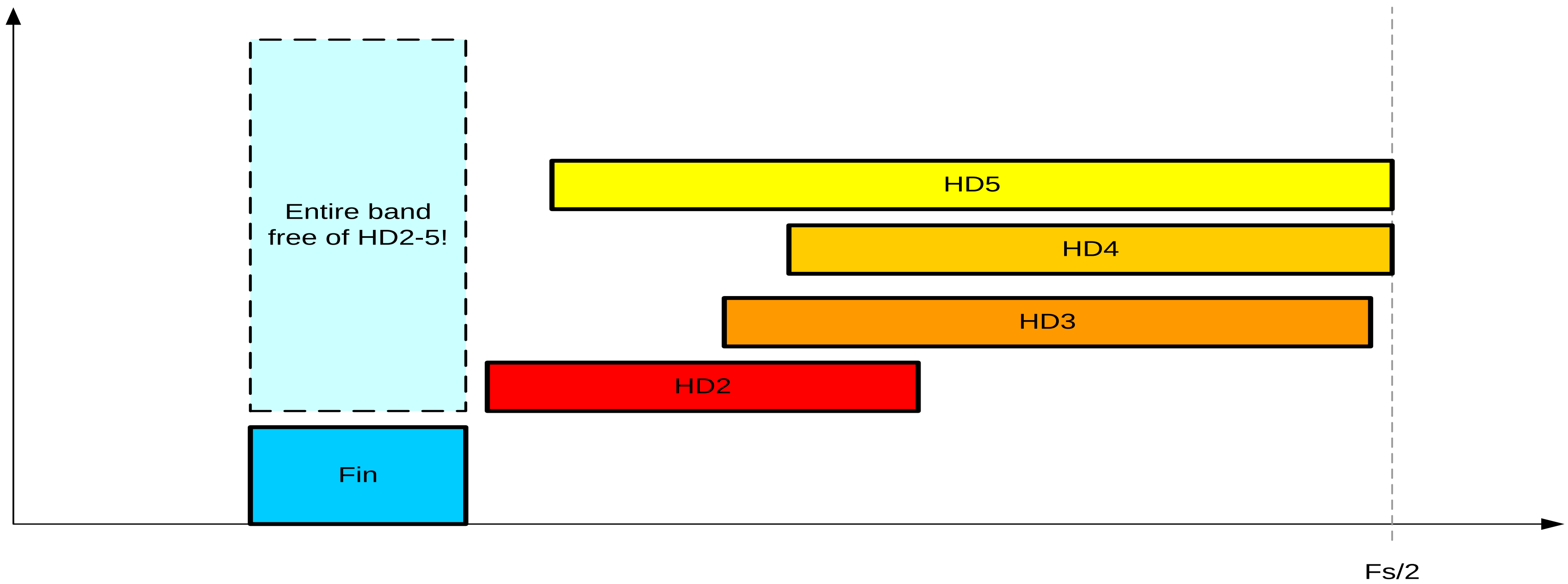
Frequency Planning Concept (5)

By increasing Nyquist zone (faster ADC sampling rate), the input band can be placed such that all low order harmonics from In-band Interferer fall out of band

Rule of thumb: ADC Sampling Rate needs > 10x of Signal Bandwidth

Digital Decimation Filter is often used to reduce output data rate

=> Oversampling + decimation (similar to ΔΣ ADC)



Frequency Planning Concept (6)

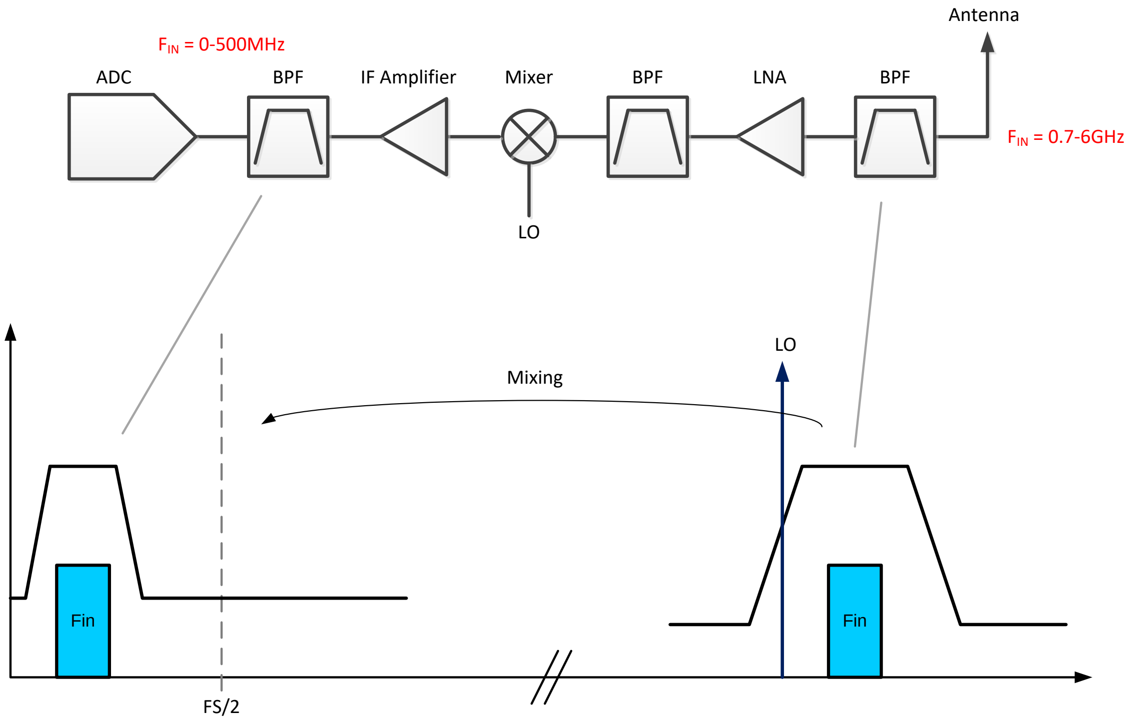
Summary

- Concept of frequency planning has been successfully used in last several years to achieve extraordinary SFDR performance with the ADC
- Nothing specific to RF sampling
- System Designer picks the IF center frequency and sampling rate such that the ADC dominant harmonics fall outside band of interest
  - Change input frequency range to plan around hd2, hd3 and dominant spurs.
  - **Increase** sampling frequency to work around fixed input frequency bands
  - Optionally use decimation filter to reduce data rate again

Evolution to RF sampling

Traditional IF Sampling

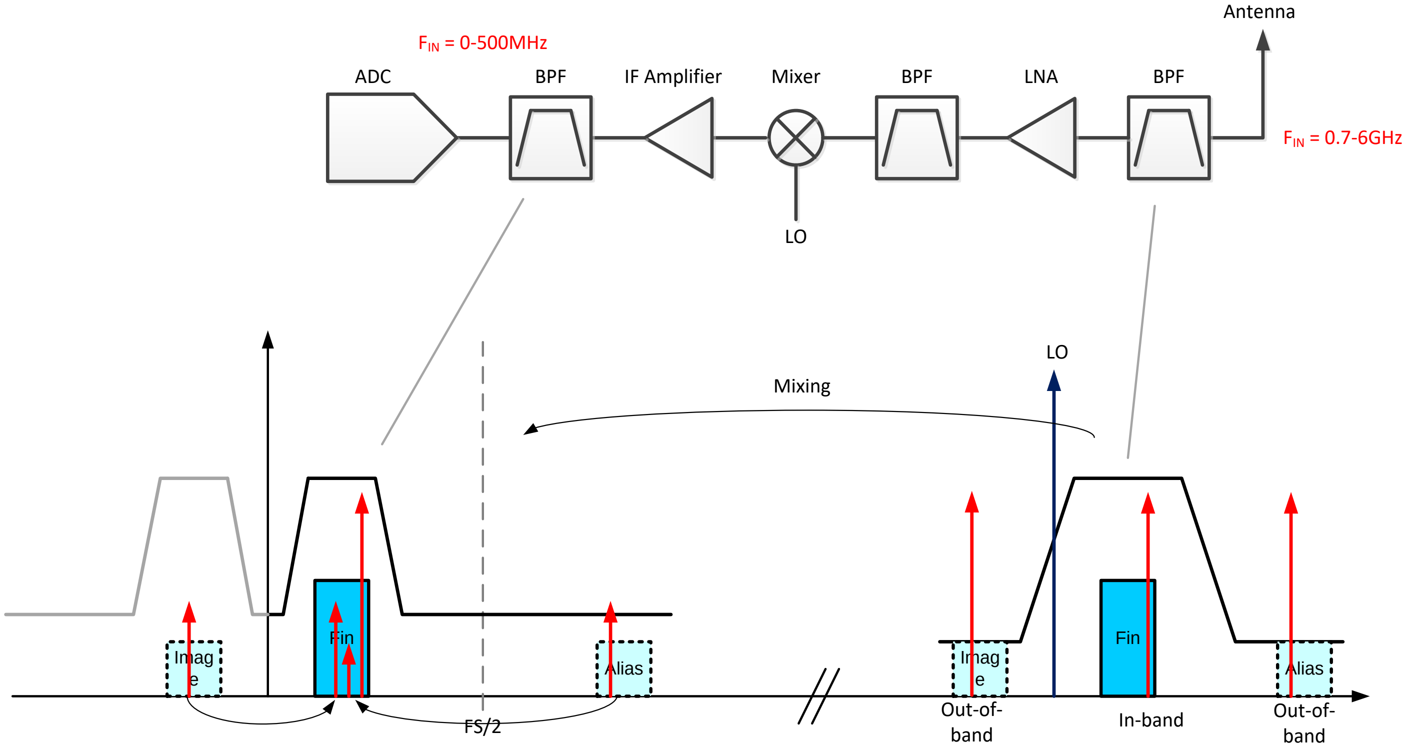
- Desired signal at some RF frequency anywhere from 700M to 6GHz
- Gets filtered and mixed to intermediate (IF) frequency (0-500MHz)
- Additional amplification and filtering is needed



Traditional IF Sampling (2)

- In-band interferer at RF can't be filtered out
- Mixer down converts Image and ADC Alias, which fall on top of wanted signal after sampling

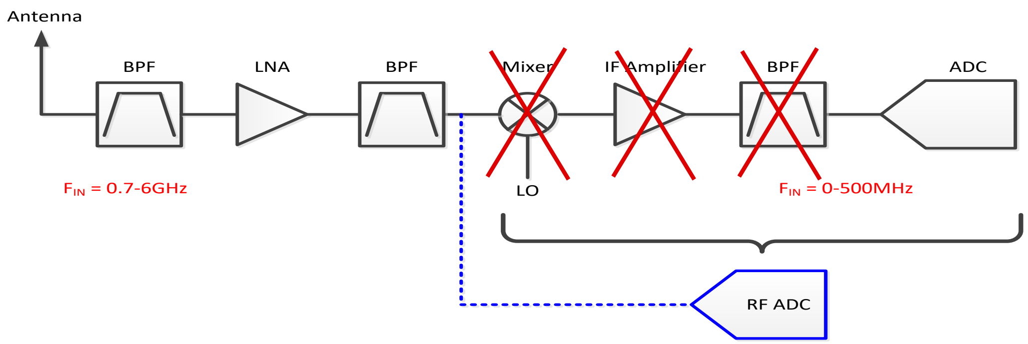
=> Both can contain out-of-band interferer which needs to be <u>filtered out primarily at RF</u>



Evolution to Direct RF Sampling

Remove an IF sampling stage

- Less components (higher integration)
- Less power consumption
- Higher overall channel count possible
- Relax RF Filtering (no close Image to filter)
- RF ADC can replace multiple IF chains
- Can use frequency planning



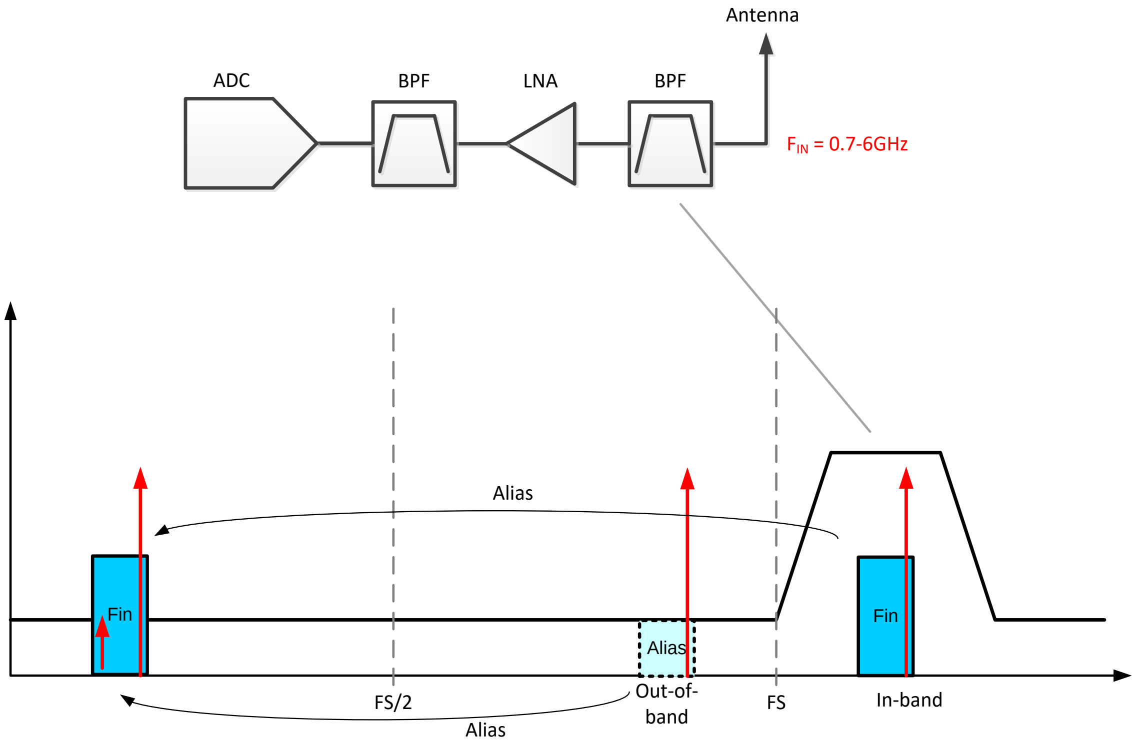
Super wide BW signal (500+MHz BW ultra wideband)

- Like traditional IF sampling, just at RF.
- Limited possibility of frequency planning

Direct RF Sampling

- In-band interferers still can't be filtered out. Need frequency planning to avoid its harmonics
- Out-of-band interferers get attenuated by filter.

  => Filtering gets little more relaxed as no close by Image to filter out



Tools for RF Sampling Receiver Designs

1. Frequency Planning Tool
    - Quick analysis for in-band interferer

2. Analog Filter Design Tool
    - External RF Filter design

3. Decimation Filter Spur Calculator
    - Tool to trace back spur origin when using decimation filter

Frequency Planning Tool

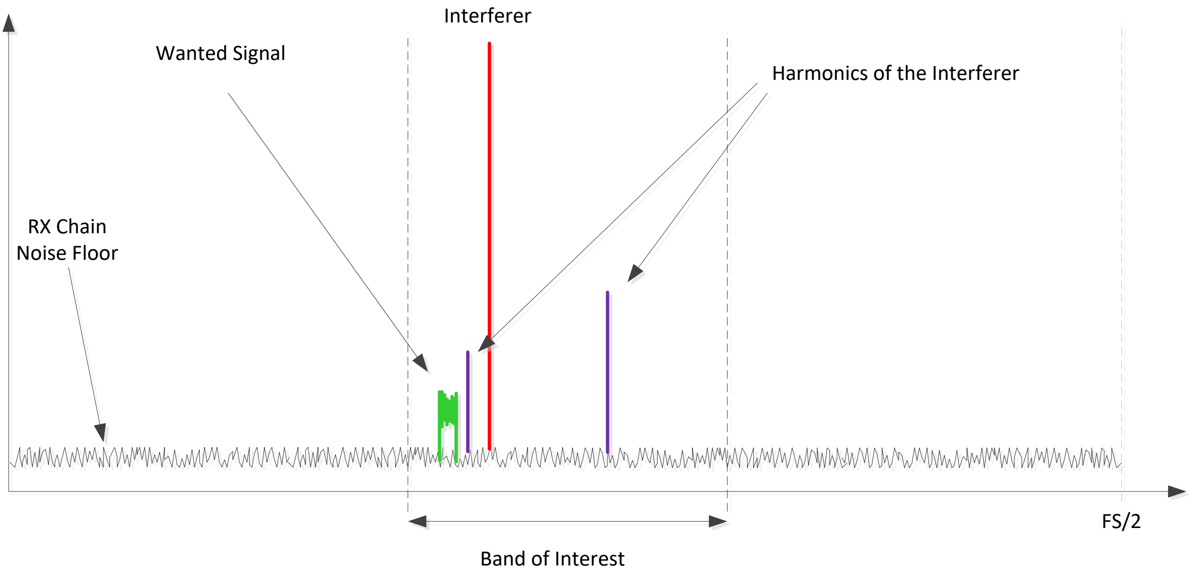
Basic Idea:

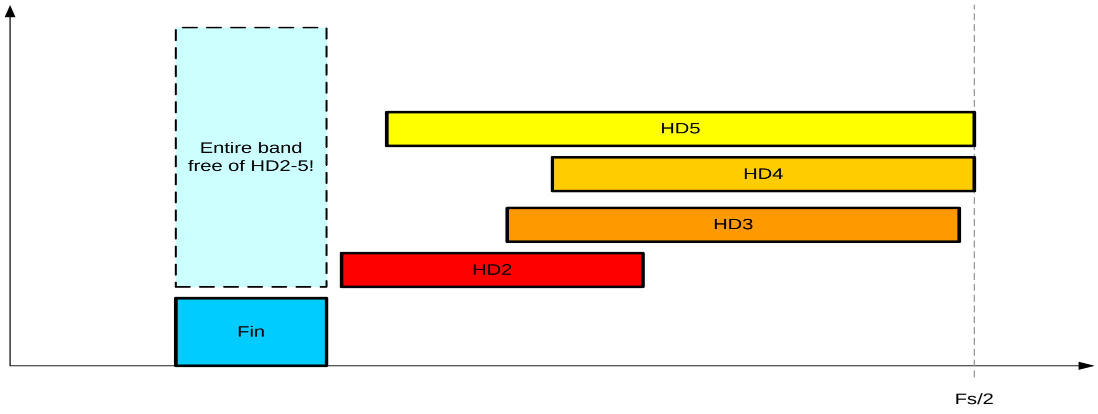
Develop a tool that shows location of unwanted spurs in frequency domain

Main parameters to adjust:

– ADC Sampling Rate

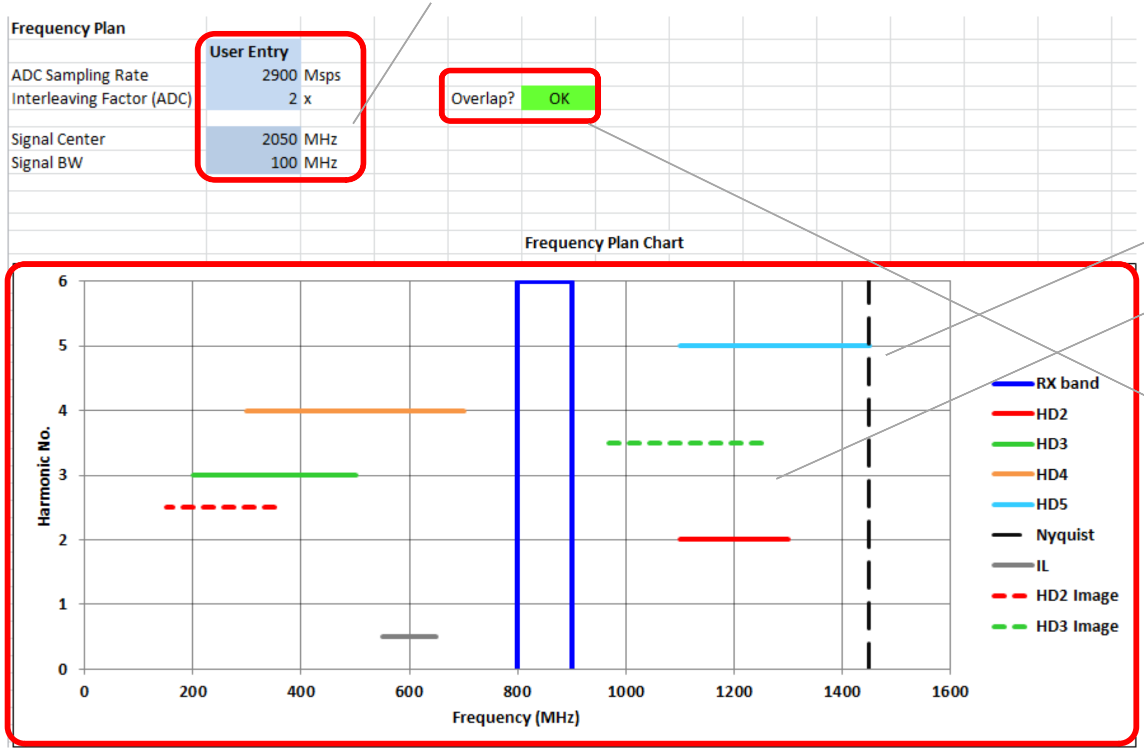
– Frequency band of interest (center frequency and bandwidth)





Frequency Planning Tool

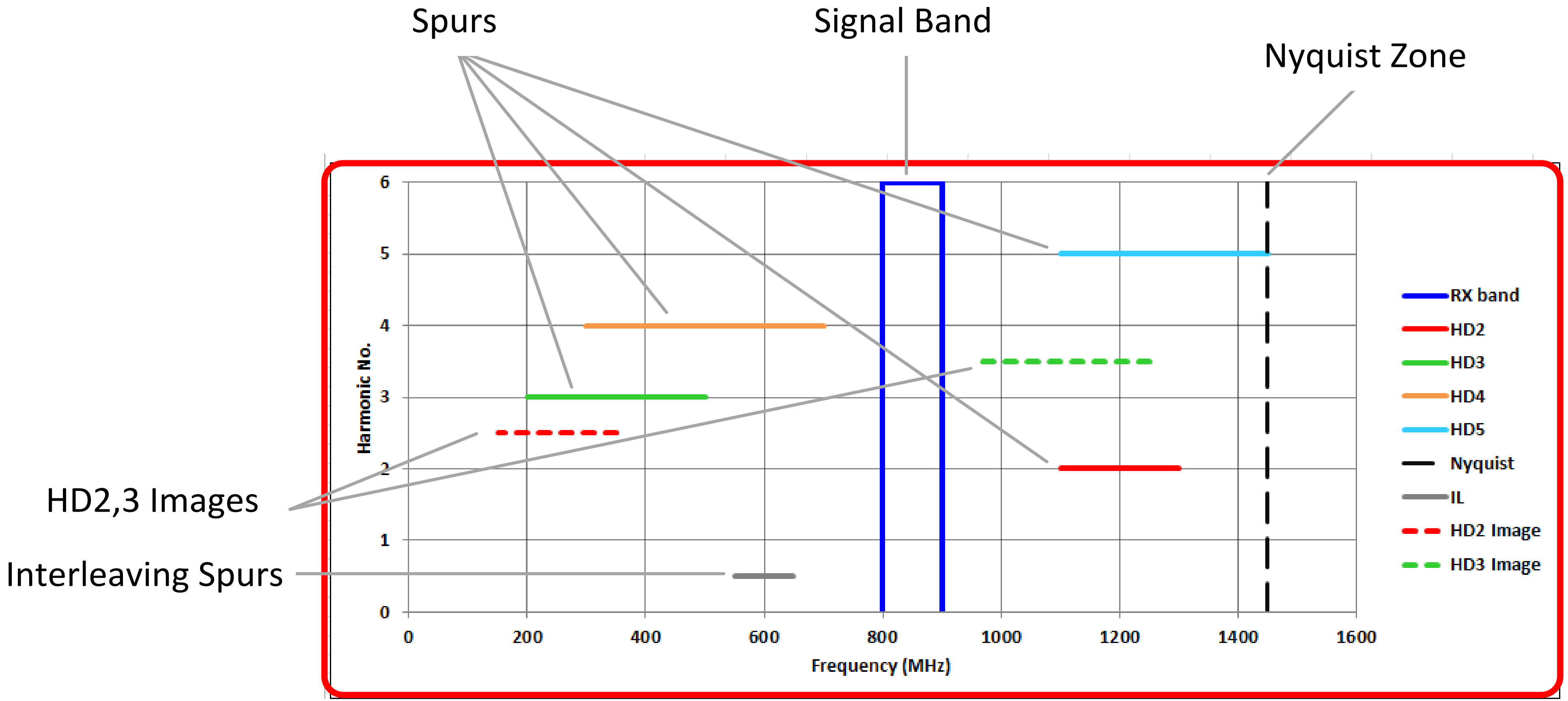
1. Enter ADC sampling rate
2. Enter ADC interleaving factor (e.g. ADC32RF45, ADC12J4000 = 4x)
3. Enter Signal Center Frequency and Bandwidth



<u>Tool calculates:</u>

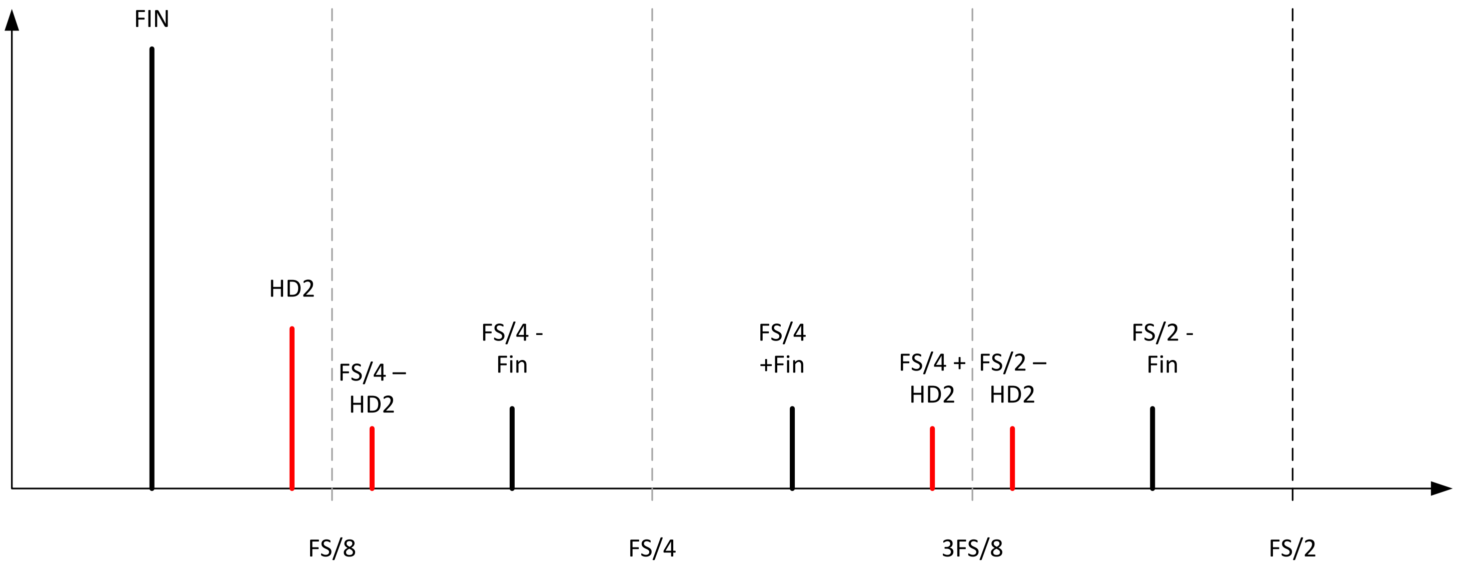
- ADC Nyquist Boundary
- Locations of dominant spurs in frequency domain
- Displays if there is overlap with input signal

Frequency Planning Tool (2)



What is HD2/3 Image?

- In interleaved ADCs, the low order harmonics (HD2-HD5) are mixing with the internal, interleaved clock frequencies.
- This creates images of low order harmonics, just like interleaving spurs with amplitudes significantly better than the harmonics but possibly worse than spur noise floor.
- For example: A 4x interleaved ADC would have HD2 image at Fs/2-HD2 and FS+/- HD2



Good vs bad frequency plan – fixed RF frequency

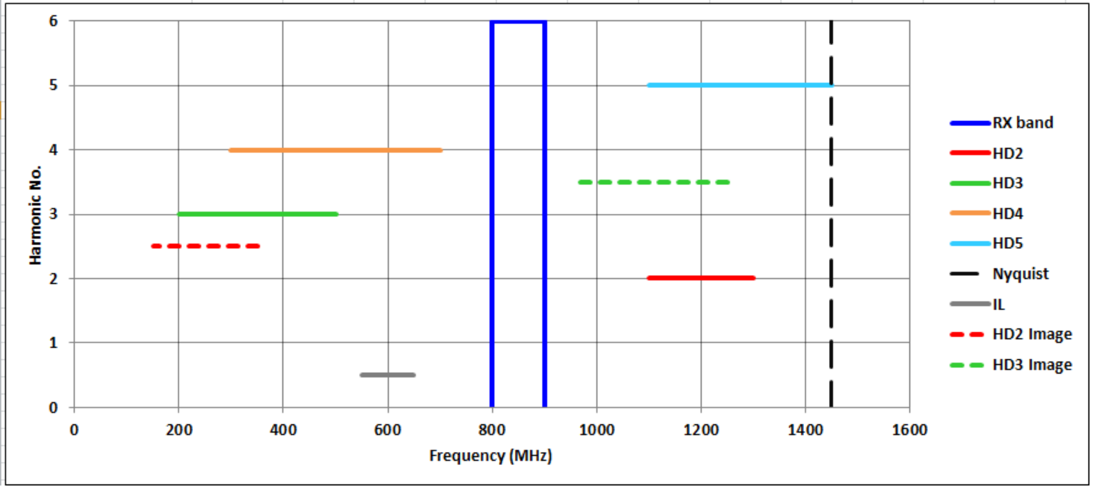
Fixed RF input frequency: 100MHz RX band centered at 2050MHz

Good Frequency Plan

Frequency Plan

	User Entry			
ADC Sampling Rate	2900	Msps		
Interleaving Factor (ADC)	2	x	Overlap?	OK
Signal Center	2050	MHz		
Signal BW	100	MHz		

Frequency Plan Chart

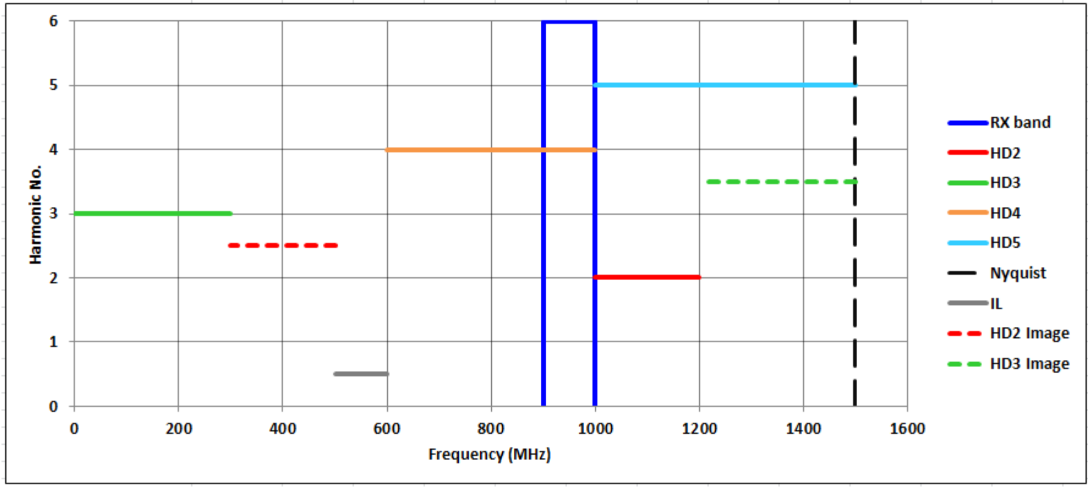


Bad Frequency Plan

Frequency Plan

	User Entry			
ADC Sampling Rate	3000	Msps		
Interleaving Factor (ADC)	2	x	Overlap?	HD2
Signal Center	2050	MHz		
Signal BW	100	MHz		

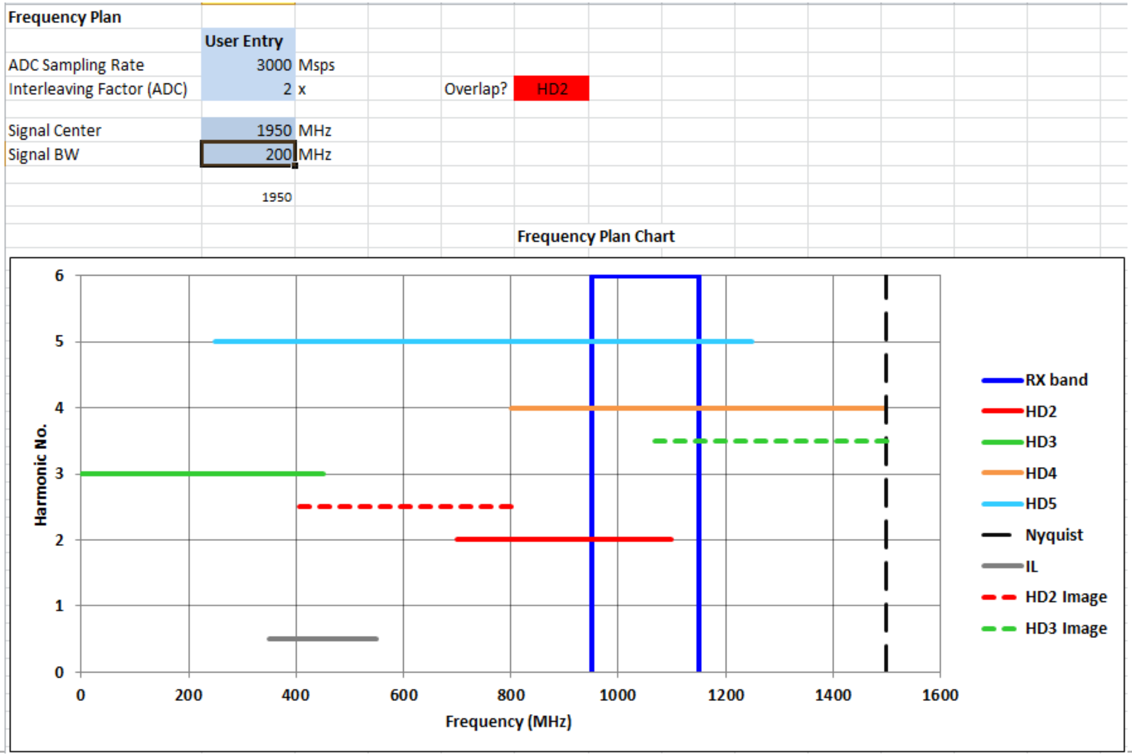
Frequency Plan Chart



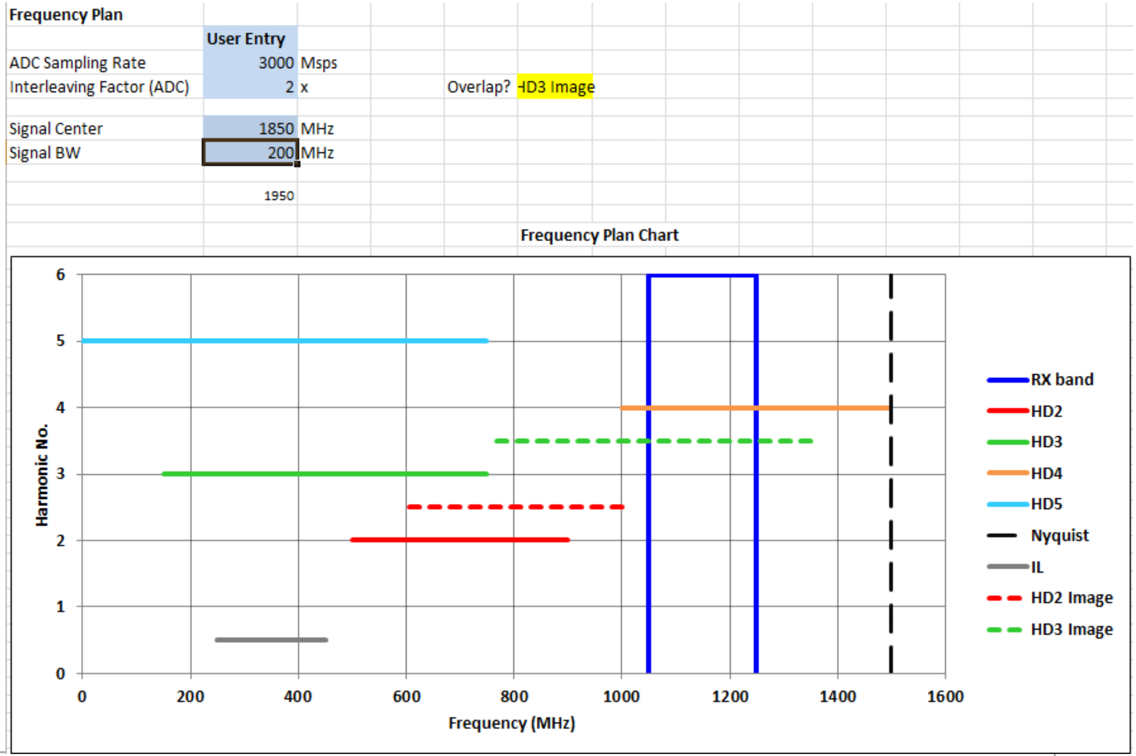
Good vs bad frequency plan – fixed ADC clock rate

Fixed ADC clock rate of 3Gsps and 200MHz RX band

Bad Frequency Plan



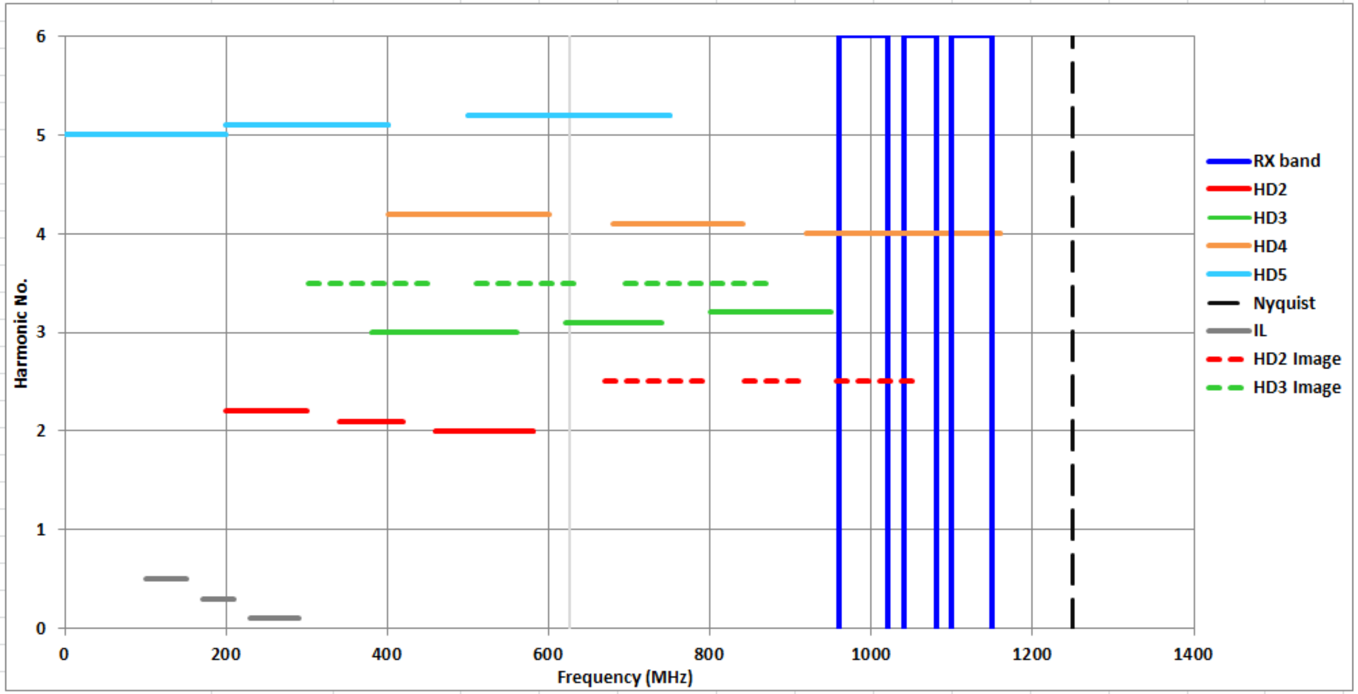
Good Frequency Plan



Multiband Option

Frequency Plan - Multi Band

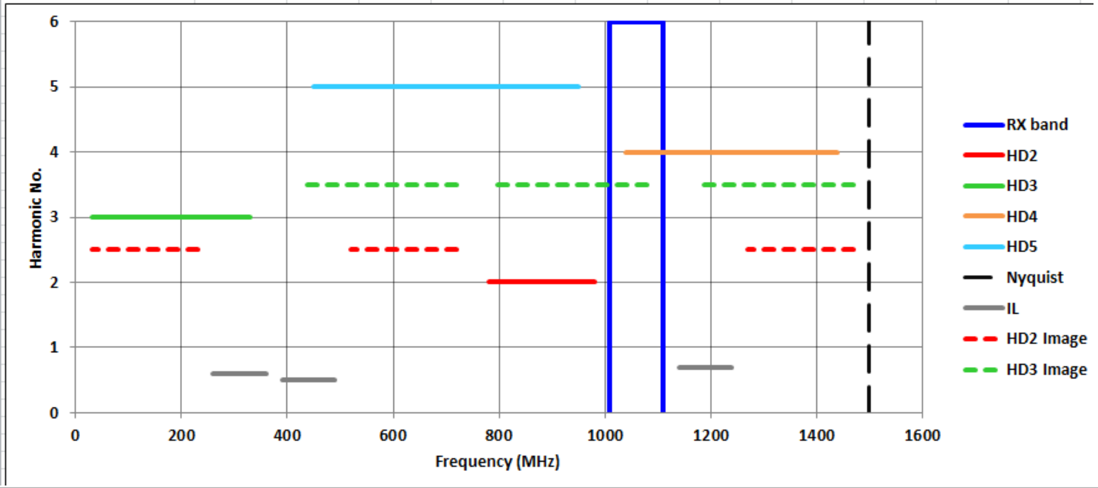
	User Entry				
ADC sampling rate	2500	Msps		Overlap	HD4
Interleaving Factor (ADC)	2	x			
	Band Low End	Band High End			
Band 1	960	1020	MHz		
Band 2	1040	1080	MHz		
Band 3	1100	1150	MHz		

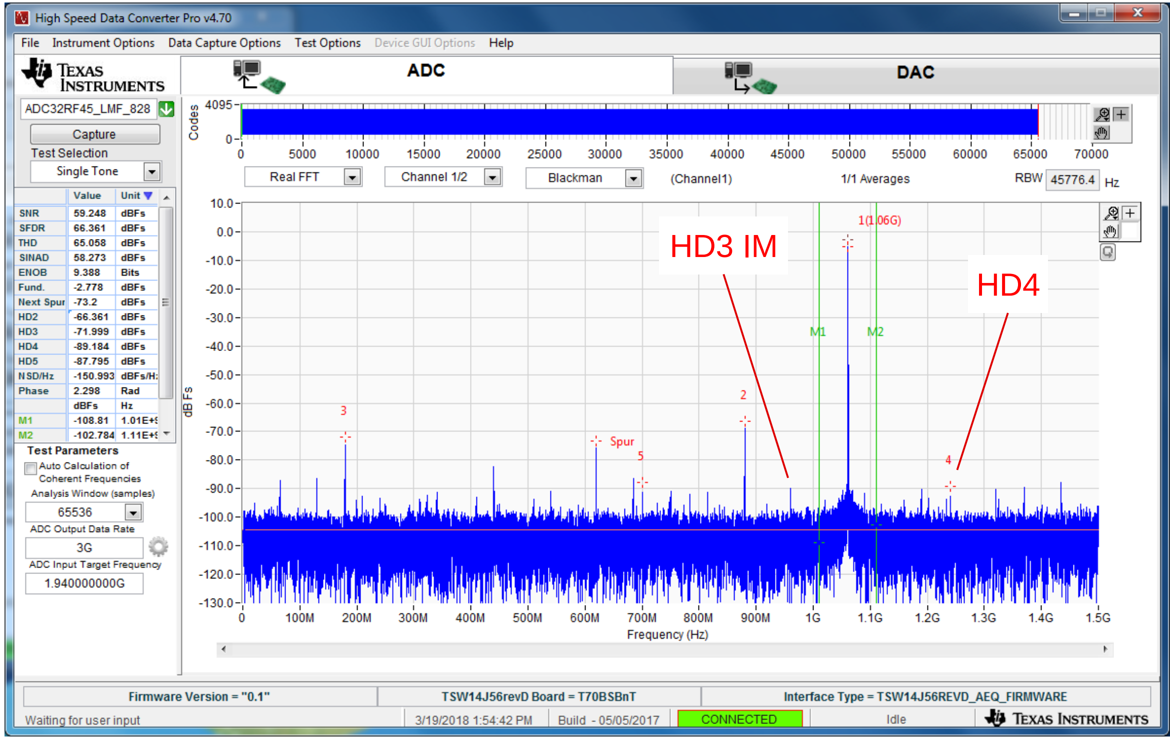


ADC32RF45 – Good Frequency Plan

- Fs = 3Gsps, Fin = 1940MHz with 100MHz BW
- Overlap with HD3 image and HD4

Frequency Plan				
	User Entry			
ADC Sampling Rate	3000	Msps		
Interleaving Factor (ADC)	4	x	Overlap?	HD3 Image
Signal Center	1940	MHz		
Signal BW	100	MHz		





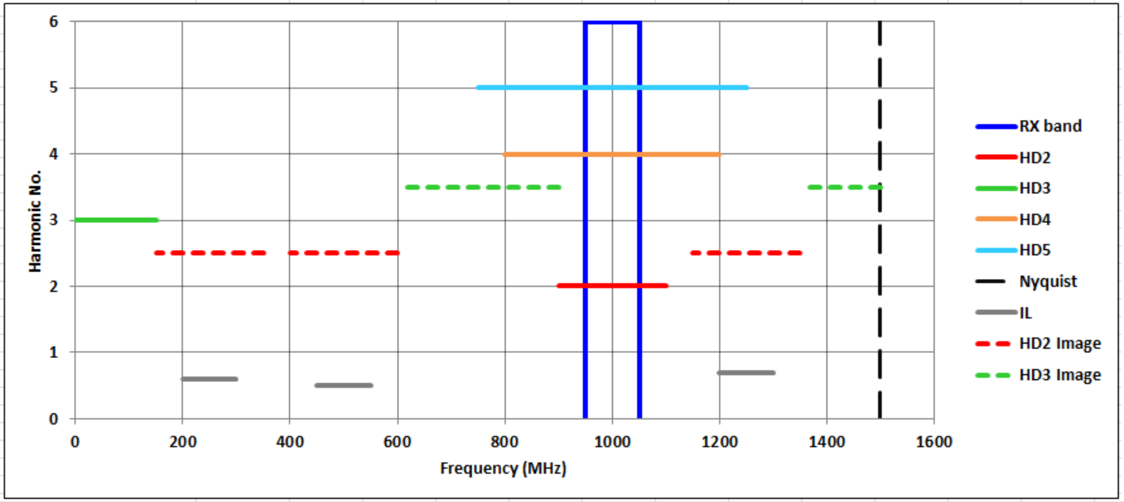
ADC32RF45 – Bad Frequency Plan

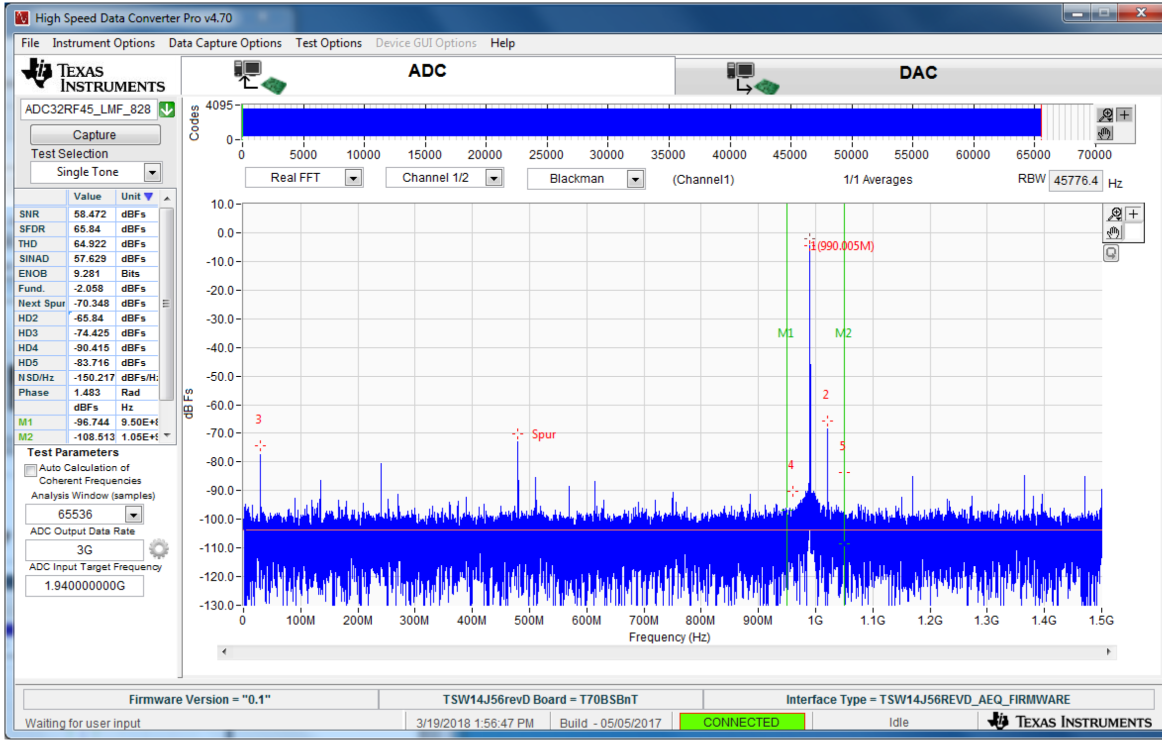
- Fs = 3 Gsps, Fin = 2000 MHz with 100MHz BW
- Overlap with HD2, HD5

Frequency Plan

	User Entry			
ADC Sampling Rate	3000	Msps		
Interleaving Factor (ADC)	4	x	Overlap?	HD2
Signal Center	2000	MHz		
Signal BW	100	MHz		

Frequency Plan Chart

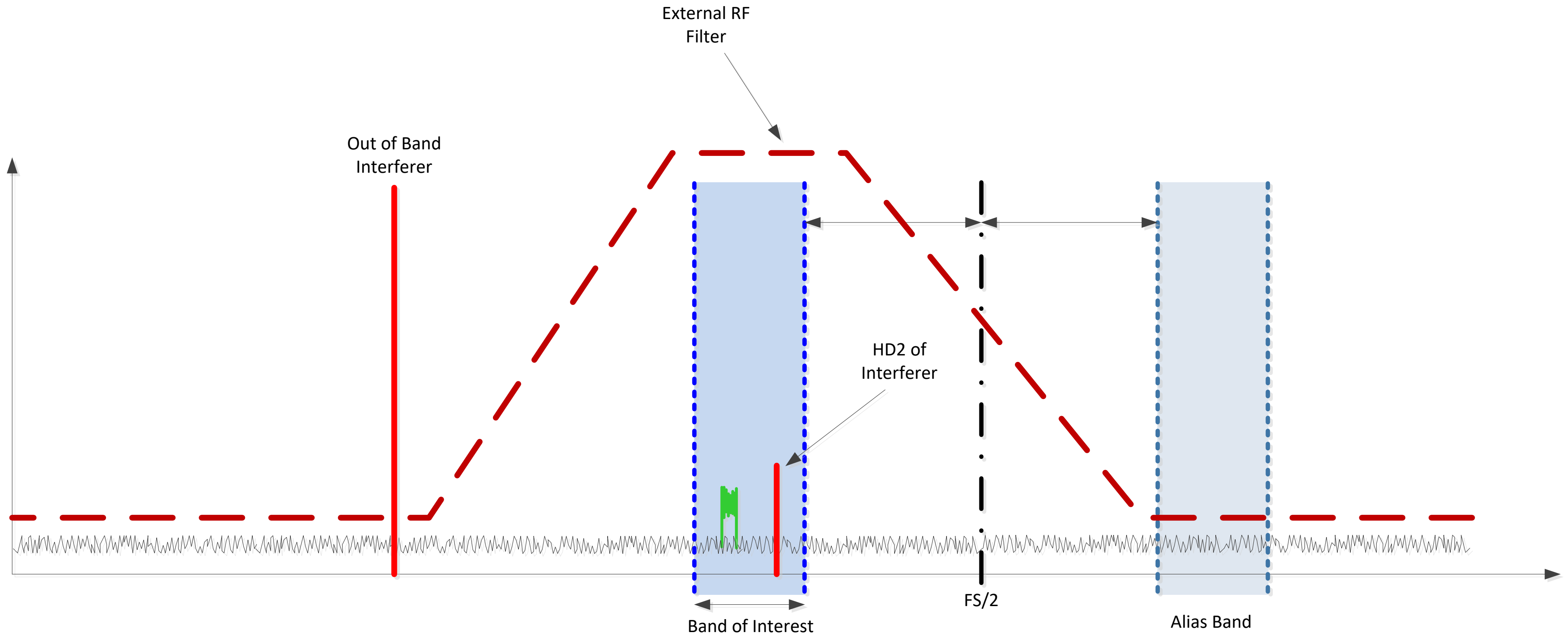




RF Filter Design Tool

Background

- Out-of-band interferers can generate large harmonic spurs that fall inside signal band
- Need to attenuate out-of-band signals sufficiently
- Also need to consider ADC alias bands

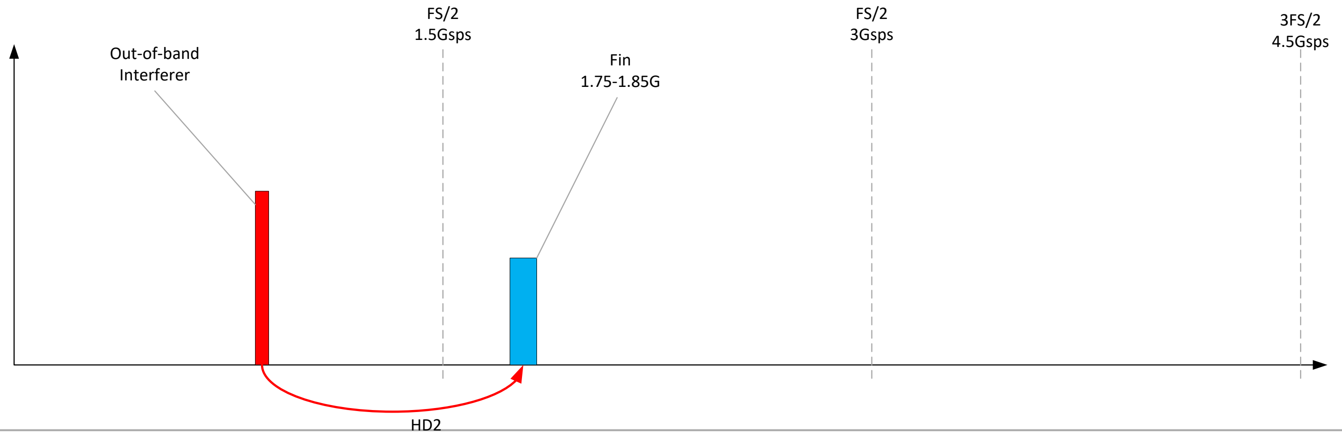


RF Filter Design Tool (1)

Let's look at the following example:

ADC Sampling Rate	3 Gsps
RX Band:	100MHz centered at 1800MHz (1750 to 1850MHz)
In-band SFDR Requirement:	100 dB
HD2 of the RF ADC is:	65 dB
=> Filter attenuation for HD2 is:	35 dB (100 dB – 65 dB)
At primary frequency location:	875 to 925 MHz (1750/2 to 1850/2)

=> Remember HD2 of interferer is twice as wide as interferer itself



RF Filter Design Tool (2)

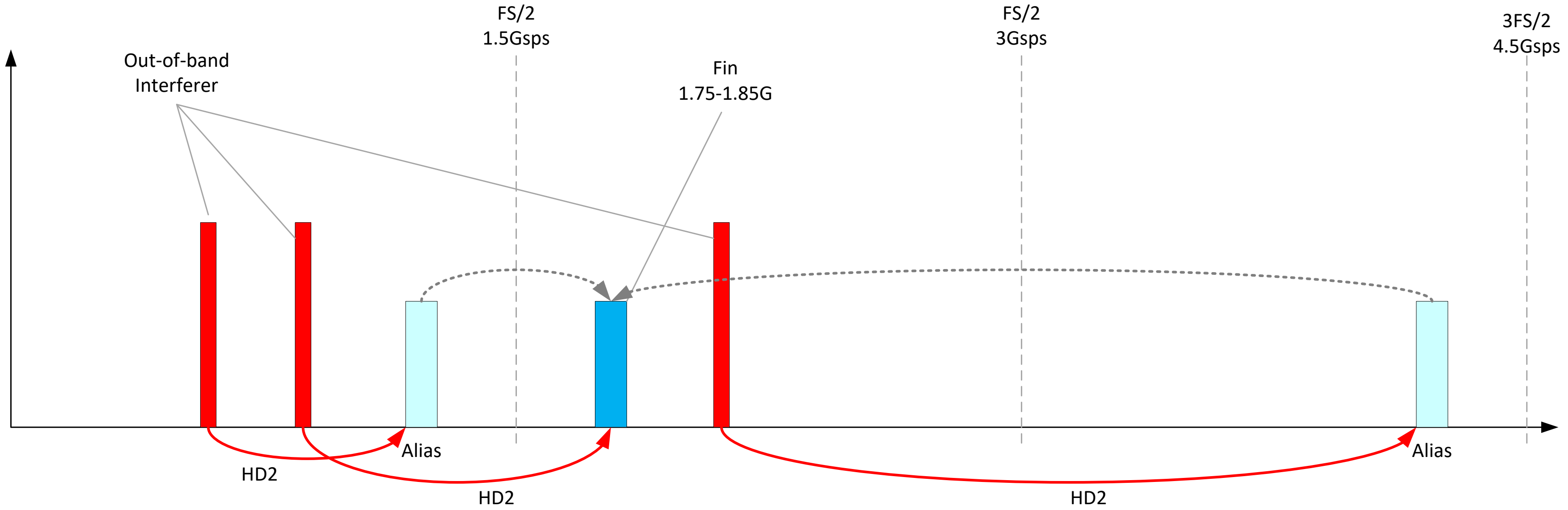
There are 2 other Nyquist zones with signal aliases we need to consider for filter design.

1st Nyquist zone: Alias = 1150-1250 MHz

=> Filter for out-of-band interferer at 575-625 MHz

3rd Nyquist zone: Alias = 4150-4250 MHz

=> Filter for HD2 of out-of-band interferer at 2075-2125 MHz



RF Filter Design Tool (3)

User Entry:

- ADC setup (sampling rate, interleaving factor, signal bandwidth and center)
- SFDR limit for out-of-band interferer
- Information about ADC SFDR Performance

The RF Filter Tool performs a frequency spectrum sweep from 0 to 4 GHz and returns:

- Table with required filter attenuation needed for each dominant spur and filter offset from input signal.
- A filter mask indicating required out-of-band filter attenuation vs frequency

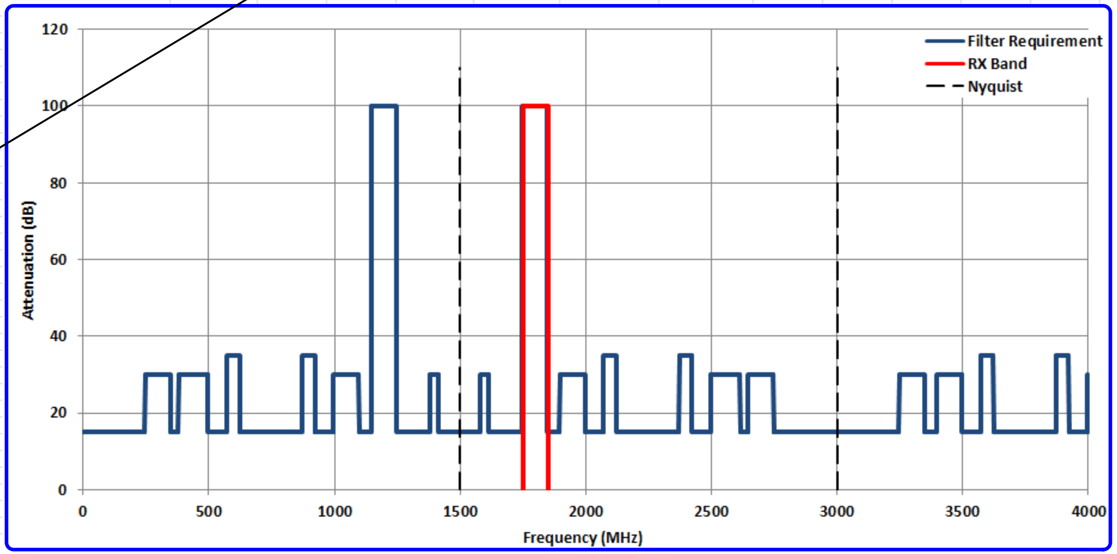
Analog Filter

User Entry

Sampling Rate	3000	Msps	Center	1800	MHz
Interleaving Factor (ADC)	4	x	Signal BW	100	MHz
Out of Band SFDR Limit	100	dB	Overlap?	HD4	

ADC SFDR Info		
HD2	65	dB
HD3	70	dB
Non HD23	85	dB
FS/2 IL Spur	70	dB
FS/4 IL Spur	70	dB

Attenuation Needed	Offset (MHz)	Amount (dB)
HD2	225	35
HD3	133	30
FS/4 IL Spur	50	30
FS/2 IL Spur	800	30
Alias	500	100



RF Filter Design Tool (4)

A few other points to note:

- High order spurs (non HD23) require broad band filtering
- Band alias in other Nyquist zones requires full out-of-band attenuation as interferer directly falls on top of wanted signal
- This is a simple tool for first hand check. Signal backoff due to filtering is not taken into account. As interferer amplitude is reduced (due to filtering), HD2-HD5 will further improve.

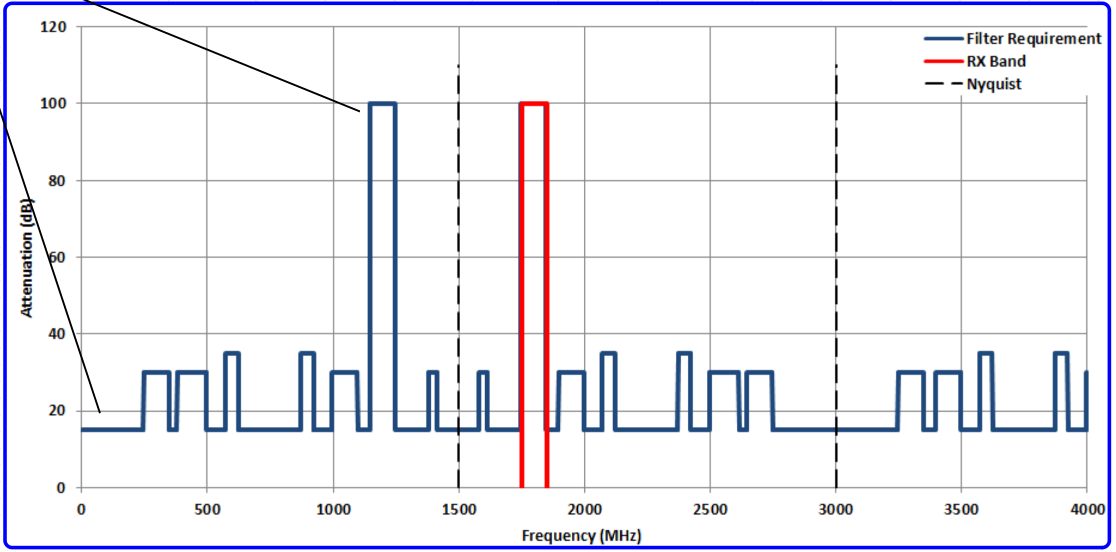
Analog Filter

User Entry

Sampling Rate	3000	Msps	Center	1800	MHz
Interleaving Factor (ADC)	4	x	Signal BW	100	MHz
Out of Band SFDR Limit	100	dB	Overlap?	HD4	

ADC SFDR Info		
HD2	65	dB
HD3	70	dB
Non HD23	85	dB
FS/2 IL Spur	70	dB
FS/4 IL Spur	70	dB

Attenuation Needed	Offset (MHz)	Amount (dB)
HD2	225	35
HD3	133	30
FS/4 IL Spur	50	30
FS/2 IL Spur	800	30
Alias	500	100



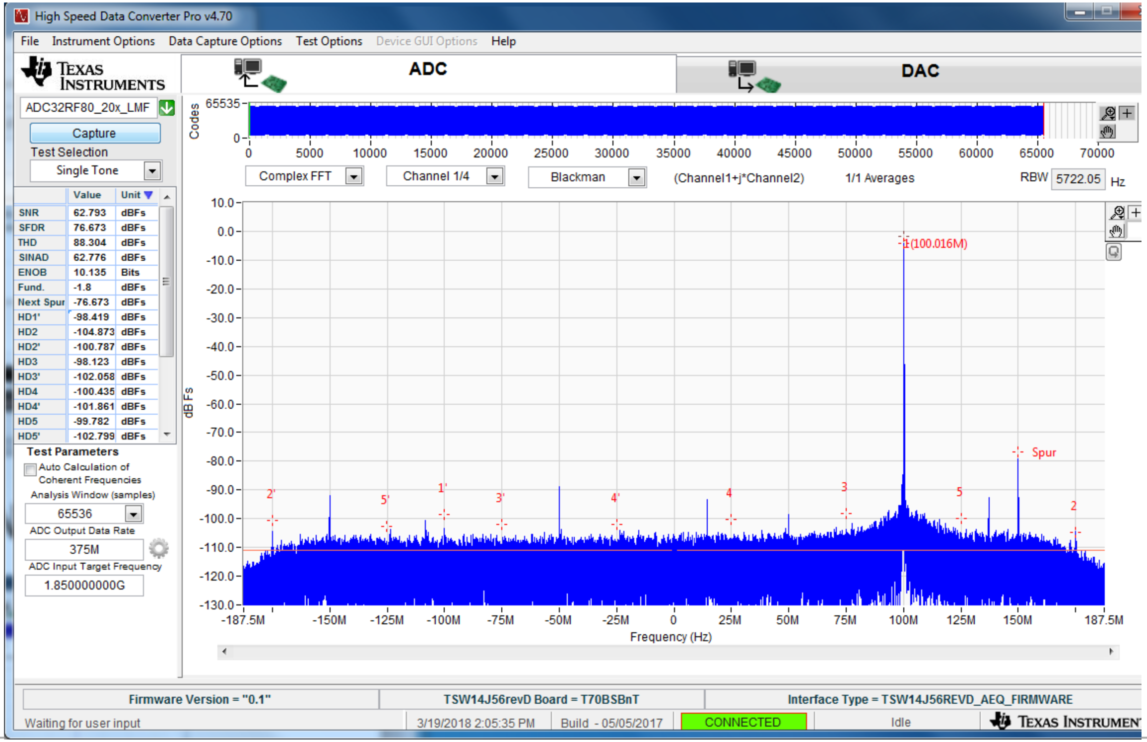
DDC Calculator Tool

Background

- With decimation it can be difficult to trace back spurs in FFT plots.
- FFT plot shows Fs = 3Gsps with 8x decimation

=> Few dominant spurs in FFT plot are not labelled

- F = 150 MHz
- F = 50 MHz
- F = 15 MHz
- F = -50 MHz
- F = -150 MHz



DDC Calculator

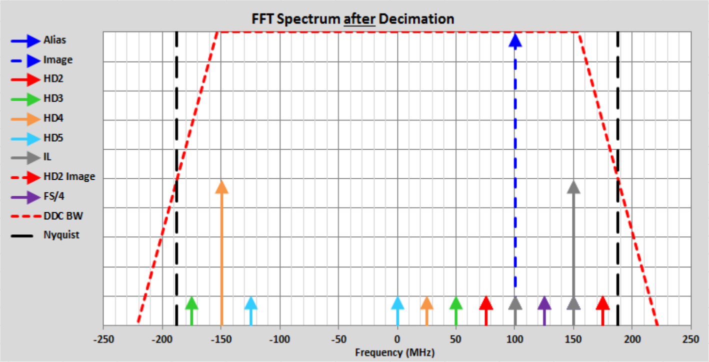
- Developed a tool that shows where dominant spurs are before and after complex decimation
- Requires ADC setup information (Sampling Rate, interleaving factor, input frequency, complex decimation factor and NCO frequency)

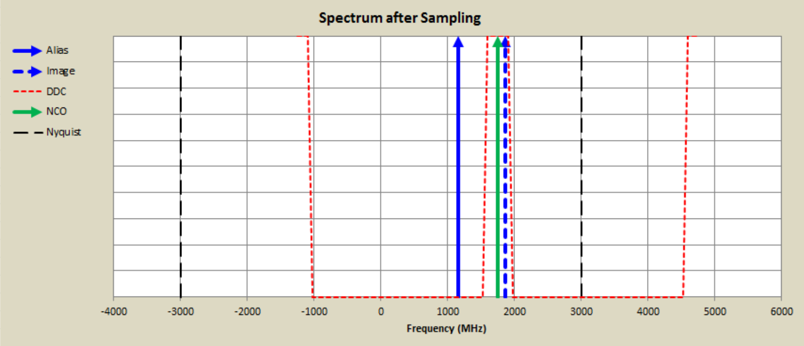
DDC

	User Entry	
ADC Sampling Rate	3000	Msps
Interleaving Factor (ADC)	4	x
Input Frequency	1850	MHz
Decimation by	8	x
NCO	1750	MHz

Spectrum after:	Sampling		shift by NCO		Decimation	
	Alias	Image	Alias	Image	Alias	Image
Input Frequency	**1150**	**1850**	-600	100	**150**	**100**
IL1 (FS/2 - FIN)	350	2650	-1400	900	100	150
IL2 (FS/4 - FIN)	400	2600	-1350	850	150	100
IL3 (FS/4 + FIN)	1100	1900	-650	150	100	150
HD2	700	2300	-1050	550	75	175
HD3	450	2550	-1300	800	-175	50
HD2 Image	800	2200	-950	450	175	75
HD2 Image	50	2950	-1700	1200	175	75
HD2 Image	1450	1550	-300	-200	75	175
FS/4	750	2250	-1000	500	125	125
HD4	1400	1600	-350	-150	25	-150
HD5	250	2750	-1500	1000	0	-125
HD3 Image	1050	1950	-700	200	50	-175
HD3 Image	1200	1800	-550	50	-175	50
HD3 Image	300	2700	-1450	950	50	-175
FIN + NCO	600	2400	-1150	650	-25	-100

Inside passband of DDC before decimation





Spectrum after Sampling

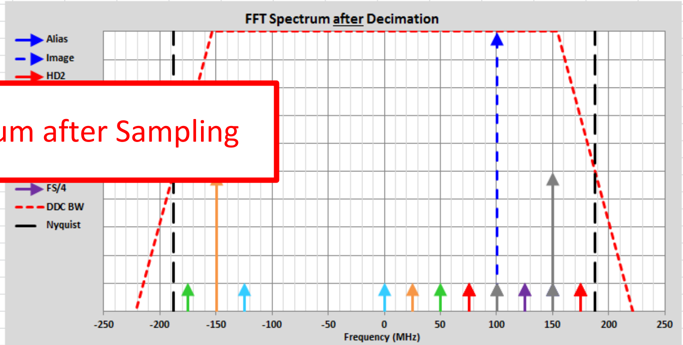
- This basically shows the full ADC Nyquist zone without any decimation applied.
- The plot shows input aliased to 1st Nyquist zone (and it's image in the negative frequency)
- Overlaid on top are the NCO frequency along with decimation filter response

DDC

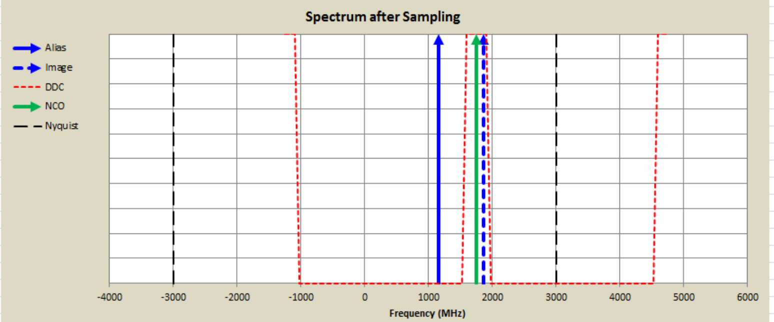
	User Entry	
ADC Sampling Rate	3000	Msps
Interleaving Factor (ADC)	4	x
Input Frequency	1850	MHz
Decimation by	8	x
NCO	1750	MHz

Spectrum after:	Sampling		shift by NCO		Decimation	
	Alias	Image	Alias	Image	Alias	Image
Input Frequency	**1150**	**1850**	-600	100	**150**	**100**
IL1 (FS/2 - FIN)	350	2650	-1400	900	[illegible]	[illegible]
IL2 (FS/4 - FIN)	400	2600	-1350	850	[illegible]	[illegible]
IL3 (FS/4 + FIN)	1100	1900	-650	150	[illegible]	[illegible]
HD2	700	2300	-1050	550	[illegible]	[illegible]
HD3	450	2550	-1300	800	[illegible]	[illegible]
HD2 Image	800	2200	-950	[illegible]	[illegible]	[illegible]
HD2 Image	50	2950	[illegible]	1200	[illegible]	[illegible]
HD2 Image	1450	1550	-300	-200	75	175
FS/4	750	2250	-1000	500	125	125
HD4	1400	1600	-350	-150	25	-150
HD5	250	2750	-1500	1000	0	-125
HD3 Image	1050	1950	-700	200	50	[illegible]
HD3 Image	1200	1800	-550	50	-175	[illegible]
HD3 Image	300	2700	-1450	950	50	[illegible]
FIN + NCO	600	2400	-1150	650	-25	[illegible]

Inside passband of DDC before decimation



Spectrum after Sampling



Spectrum after NCO Shift

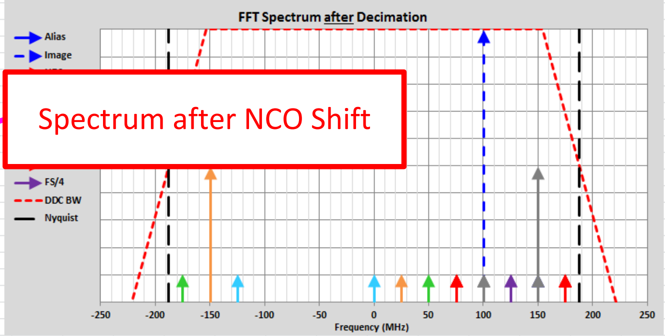
- Next, the location of input signal and all relevant spurs is calculated for both the alias and negative image. This is prior to decimation.
- Frequencies located within the passband of the DDC are highlighted in red. In this example we can see one interleaving spur (FS/4+Fin), HD4 and one HD3 image pass through the decimation filter.

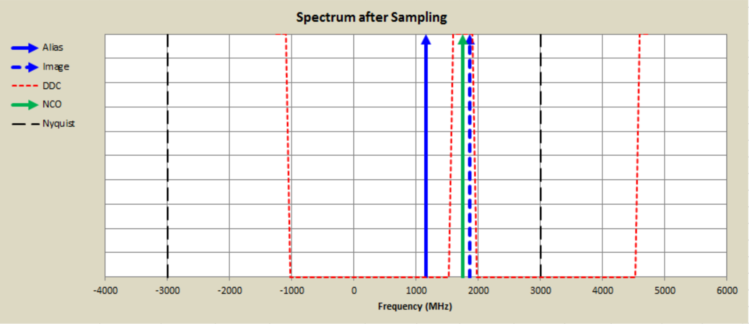
DDC

	User Entry	
ADC Sampling Rate	3000	Msps
Interleaving Factor (ADC)	4	x
Input Frequency	1850	MHz
Decimation by	8	x
NCO	1750	MHz

Spectrum after:	Sampling		shift by NCO		Decimation	
	Alias	Image	Alias	Image	Alias	Image
Input Frequency	**1150**	**1850**	-600	100	**150**	**100**
IL1 (FS/2 - FIN)	350	2650	-1400	900	100	150
IL2 (FS/4 - FIN)	400	2600	-1350	850	150	100
IL3 (FS/4 + FIN)	1100	1900	-650	150	100	150
HD2	700	2300	-1050	550	75	175
HD3	450	2550	-1300	800	-175	50
HD2 Image	800	2200	-950	450	[illegible]	75
HD2 Image	50	2950	-1700	1200	175	75
HD2 Image	1450	1550	-300	-200	75	175
FS/4	750	2250	-1000	500	125	125
HD4	1400	1600	-350	-150	25	-150
HD5	250	2750	-1500	1000	0	-125
HD3 Image	1050	1950	-700	200	50	-175
HD3 Image	1200	1800	-550	50	-175	50
HD3 Image	300	2700	-1450	950	50	-175
FIN + NCO	600	2400	-1150	650	-25	-100

Inside passband of DDC before decimation





Spectrum after Decimation

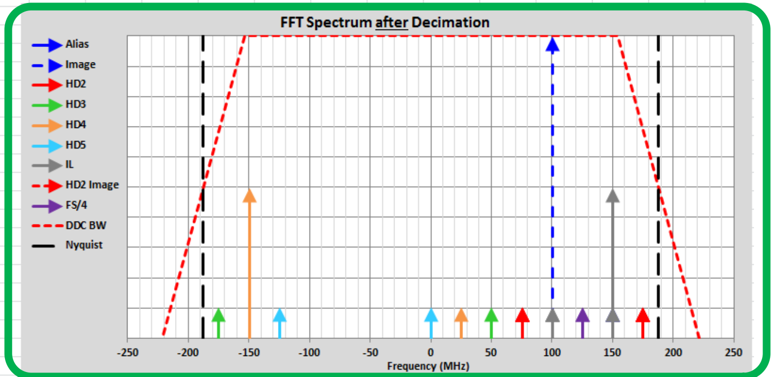
- Finally the frequency locations after decimation filtering are calculated. This is a little bit more complicated as in complex decimation frequencies wrap around instead of

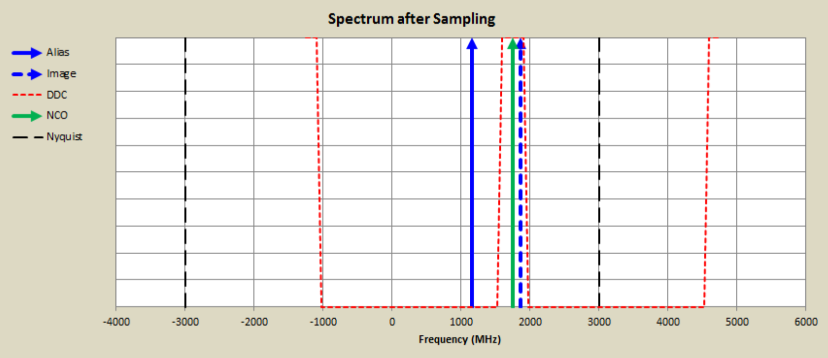
DDC

	User Entry	
ADC Sampling Rate	3000	Msps
Interleaving Factor (ADC)	4	x
Input Frequency	1850	MHz
Decimation by	8	x
NCO	1750	MHz

Spectrum after:	Sampling		shift by NCO		Decimation	
	Alias	Image	Alias	Image	Alias	Image
Input Frequency	**1150**	**1850**	-600	100	**150**	**100**
IL1 (FS/2 - FIN)	350	2650	-1400	900	100	150
IL2 (FS/4 - FIN)	400	2600	-1350	850	150	100
IL3 (FS/4 + FIN)	1100	1900	-650	150	100	150
HD2	700	2300	-1050	550	75	175
HD3	450	2550	-1300	800	-175	50
HD2 Image	800	2200	-950	450	175	75
HD2 Image	50	2950	-1700	1200	175	75
HD2 Image	1450	1550	-300	-200	75	175
FS/4	750	2250	-1000	500	125	125
HD4	1400	1600	-350	-150	25	-150
HD5	250	2750	-1500	1000	0	-125
HD3 Image	1050	1950	-700	200	50	-175
HD3 Image	1200	1800	-550	50	-175	50
HD3 Image	300	2700	-1450	950	50	-175
FIN + NCO	600	2400	-1150	650	-25	-100

Inside passband of DDC before decimation





Spectrum after Decimation

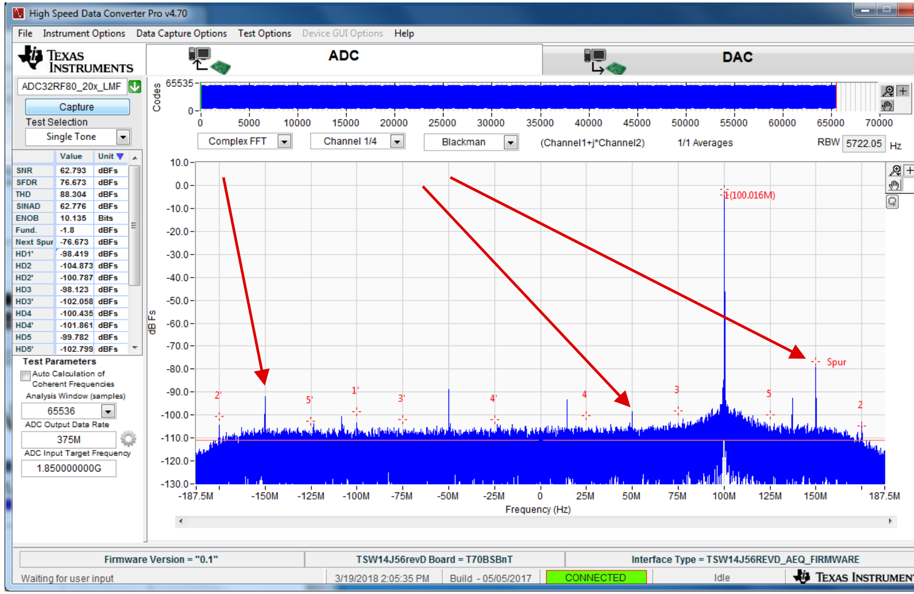
Comparison of FFT plots vs Calculation

Calculation correctly predicted spurs at

- F = 150 MHz
- F = 50 MHz
- F = -150 MHz

DDC									
	User Entry		Spectrum after:	Sampling		shift by NCO		Decimation	
				Alias	Image	Alias	Image	Alias	Image
ADC Sampling Rate	3000	Msps							
Interleaving Factor (ADC)	4	x	**Input Frequency**	**1150**	**1850**	-600	100	**150**	**100**
Input Frequency	1850	MHz	IL1 (FS/2 - FIN)	350	2650	-1400	900	100	150
Decimation by	8	x	IL2 (FS/4 - FIN)	400	2600	-1350	850	150	100
NCO	1750	MHz	IL3 (FS/4 + FIN)	1100	1900	-650	150	100	150
			HD2	700	2300	-1050	550	75	175
			HD3	450	2550	-1300	800	-175	50
			HD2 Image	800	2200	-950	450	175	75
			HD2 Image	50	2950	-1700	1200	175	75
			HD2 Image	1450	1550	-300	-200	75	175
			FS/4	750	2250	-1000	500	125	125
			HD4	1400	1600	-350	-150	25	-150
			HD5	250	2750	-1500	1000	0	-125
			HD3 Image	1050	1950	-700	200	50	-175
			HD3 Image	1200	1800	-550	50	-175	50
			HD3 Image	300	2700	-1450	950	50	-175
			FIN + NCO	600	2400	-1150	650	-25	-100

Spurs at F = +15 and -50MHz were not determined with the tool



Texas Instruments