Lo and behold, no LO!

Direct Sampling Techniques in SDR

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Chief Nyquist Zoner

Humble Beginnings of SDR

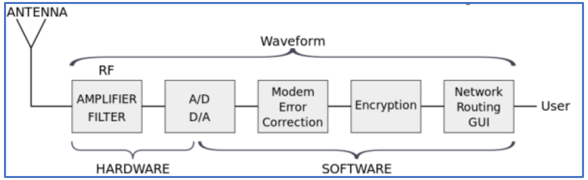
- What did young Martin B. learn about SDRs?
- "An ideal SDR would consist of just AD/DA converters and an antenna. All further processing would be done by a digital computer"
- "But in practice, RF circuitry will be used for selection and tuning"
- Converters in the 1990s/2000s/2010s were simply not fast enough to even consider this, except for niche applications (low frequencies, low selectivity requirements)

Ideal [Bearbeiten | Quelltext bearbeiten]

Der einfachste und ideale SDR-Empfänger würde aus einem Analog-Digital-Umsetzer mit Antenne bestehen. Die ausgelesenen Daten würden dann direkt nach der Analog-Digital-Wandlung von einem digitalen Rechner verarbeitet.

Der ideale Sender sähe ähnlich aus: Ein Rechner erzeugt einen digitalen Datenstrom über einen Digital-Analog-Umsetzer und eine nachfolgende Antenne versendet diesen.

[Source: Wikipedia, DE]



What do users really consider an ideal SDR?

[In this case, users == me. This is entirely subjective]

An ideal SDR is one that can produce or consume IQ data at any given frequency range and sampling rate, with minimal distortions.

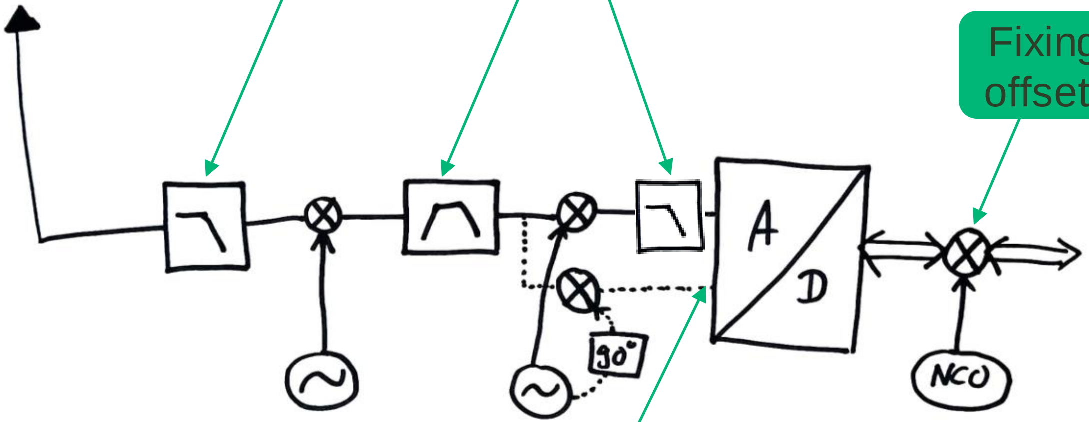
- Example: "Give me a 20 MHz wide spectrum (at 20 Msps) for a specific wifi band in the 2.4 GHz range"
- Minimize required knowledge on the hardware implementation
- Specify only rate, frequencies, and gains based on desired application
- "RF to software converter"

Zero-IF / superhet architectures: An excellent compromise

- Very well understood architectures
- Matches available converter's capabilities with required RF and software capabilities

Various filter stages remove spurs / aliases

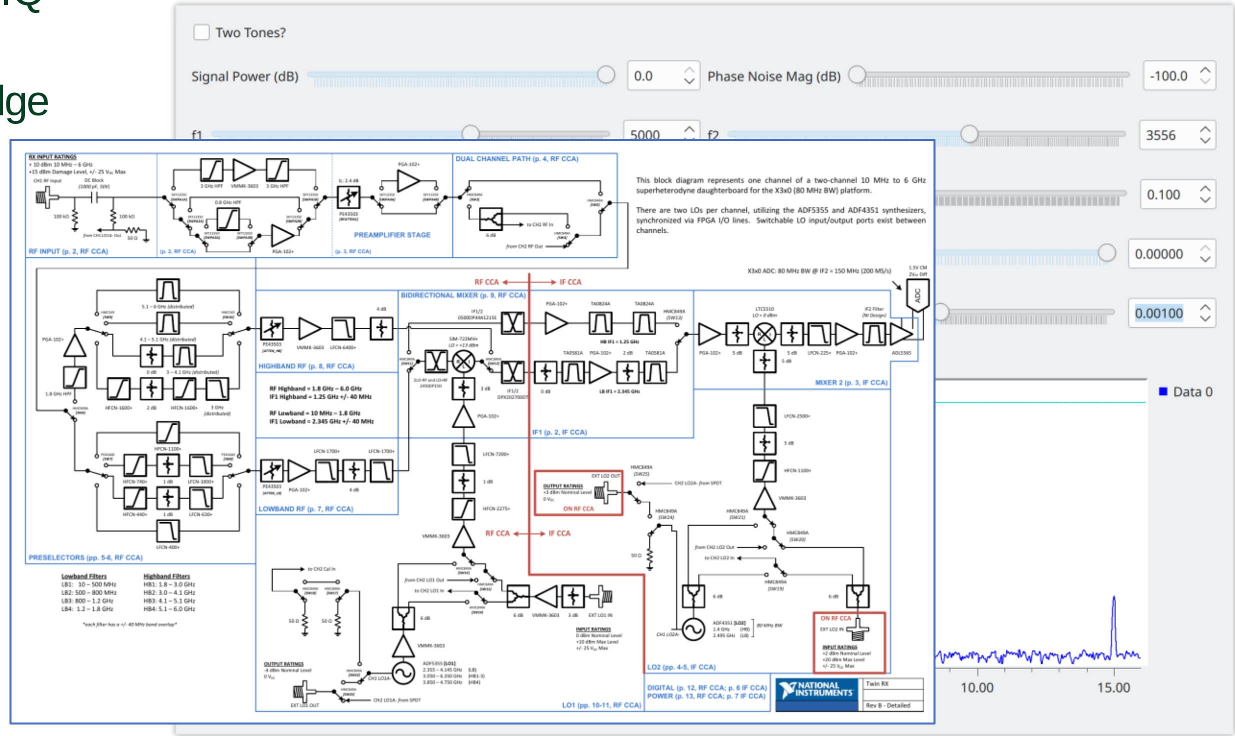
Fixing residual offsets is trivial



Sampling occurs at "optimal" frequencies

Zero-IF / superhet architectures: Some downsides, too

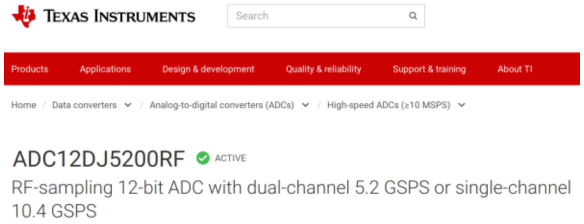
- Calibration required to avoid IQ imbalance issues
  - Extra effort, extra knowledge required
- LOs can cause LO leakage and add phase noise
- Mitigations available
- Complexity!
  (Software and Hardware)



2023: State of converter silicon

- Today's converter's are really fast!
- All major vendors of converter ICs offer multi-GHz converters
- Often, with integrated additional capabilities (FFTs, mixers, filters, full SoCs...)

Can we now build those "ideal" SDRs without RF components?



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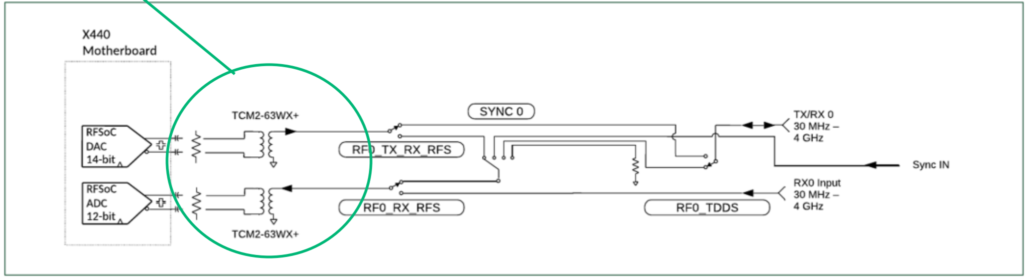
Did you say *without any* RF components?

- If there's an RF connector, that means you have RF components
- Typically, you'll need at least some baluns
- Like everything else that's actually a real part, these have a frequency response (e.g., 30 – 6000 MHz)
- High & low (close to DC) frequencies are attenuated



Sampling Theorem: Favourite source of confusion

Ever seen something like this?

Shannon Sampling Theorem

According to the sampling theorem (Shannon, 1949), to reconstruct a one-dimensional signal from a set of samples, the sampling rate must be equal to or greater than twice the highest frequency in the signal.
From: The Science of Color (Second Edition), 2003

[Source]

???

Theorem 1: If a function $f(t)$ contains no frequencies higher than W cps, it is completely determined by giving its ordinates at a series of points spaced 1/2 W seconds apart.

[C.E. Shannon, Communication in the presence of noise]

Wikipedia to the rescue!

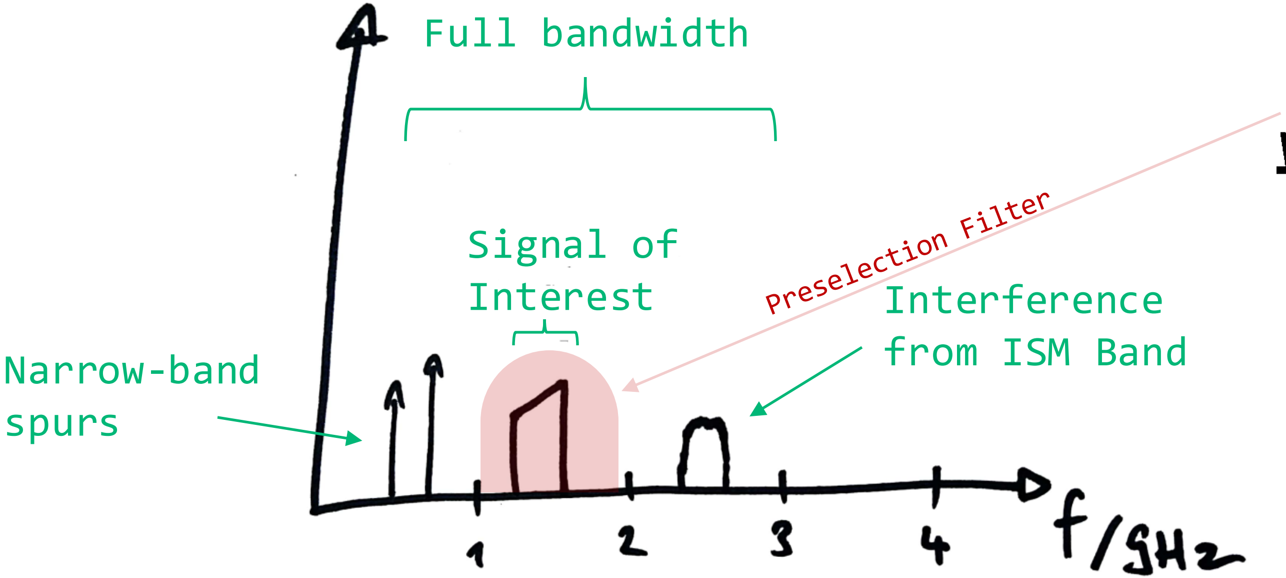
The **Nyquist–Shannon sampling theorem** is an essential principle for digital signal processing linking the frequency range of a signal and the sample rate required to avoid a type of distortion called aliasing. The theorem states that the sample rate must be at least twice the bandwidth of the signal to avoid aliasing distortion. In practice, it is used to select band-limiting filters to keep aliasing distortion below an acceptable amount when an analog signal is sampled or when sample rates are changed within a digital signal processing function.

[Source]

Problem 1: ~~Spectral garbage~~ Interference & Spurs

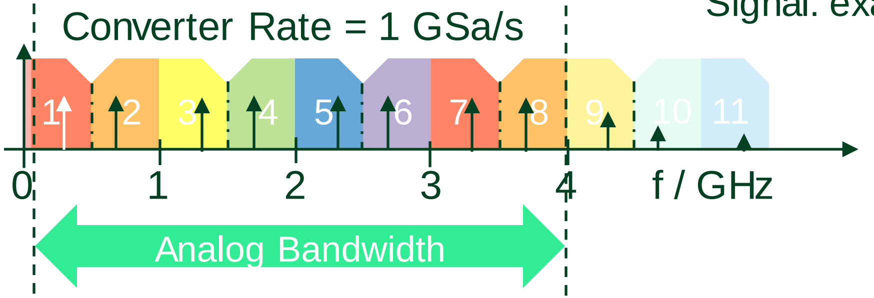
Any undesired signal content will (probably) violate the sampling theorem!

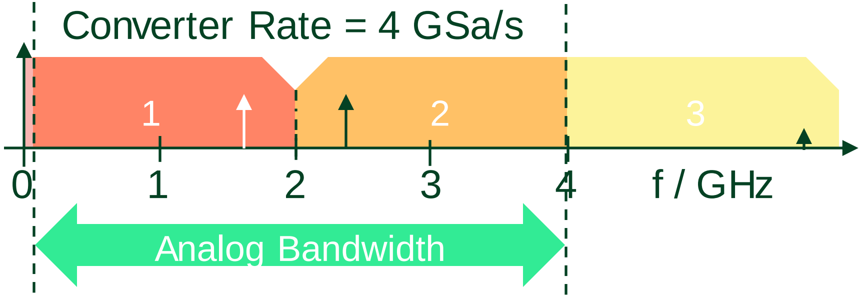
Example: ADC running at 2 GHz



OUT-OF-BAND INTERFERENCE AT THE RECEIVER

Nyquist Zones & Aliasing



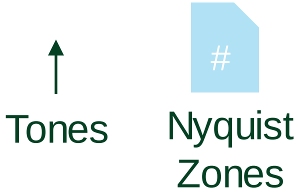


Signal: example is a CW tone at 0.4x Converter Rate

Converters will send/receive copies of a signal within their analog bandwidth

Copies = Aliasing in all Nyquist Zones
Width of each Nyquist zone is 0.5x converter rate

→ To cover a clean wide spectrum, you need high converter rates
→ You can't cleanly address the range between Nyquist zones due to aliasing
→ To transmit only desired signals, anti-alias filtering is required



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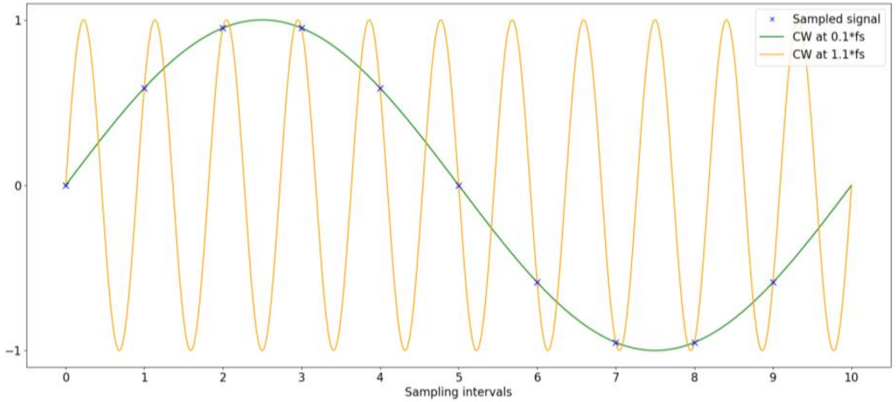
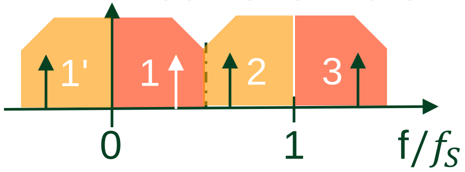
Where does aliasing come from?

The loss of information by time-discrete sampling causes an ambiguity:



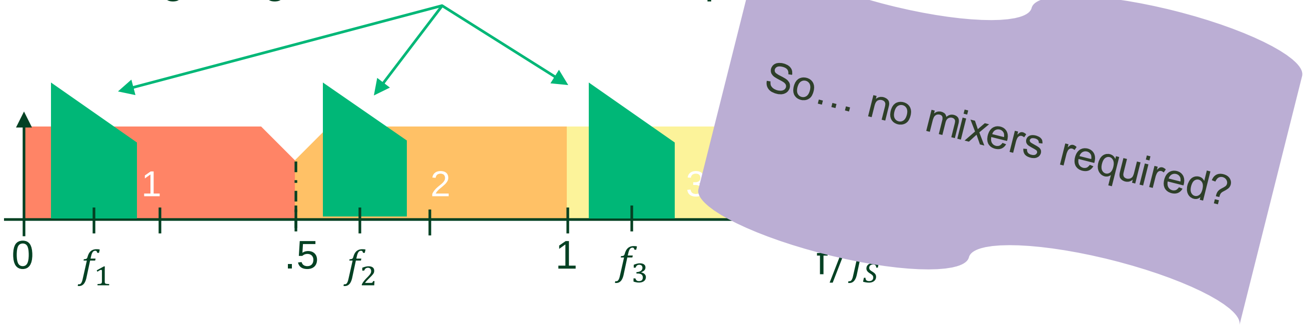
In real sampling, negative frequencies mirror their positive counterpart (`cos(x) = cos(-x)`)

Converter Rate = 1 GSa/s

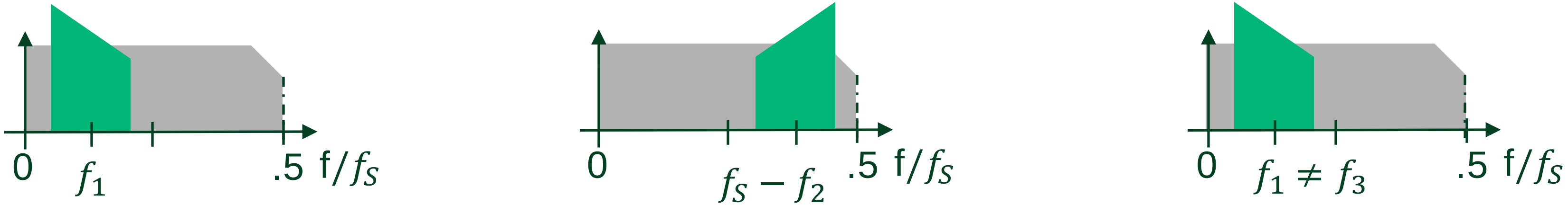


Using aliases: Undersampling

- Also known as “bandpass sampling”
- Example: Assume we are receiving a signal at one of three frequencies

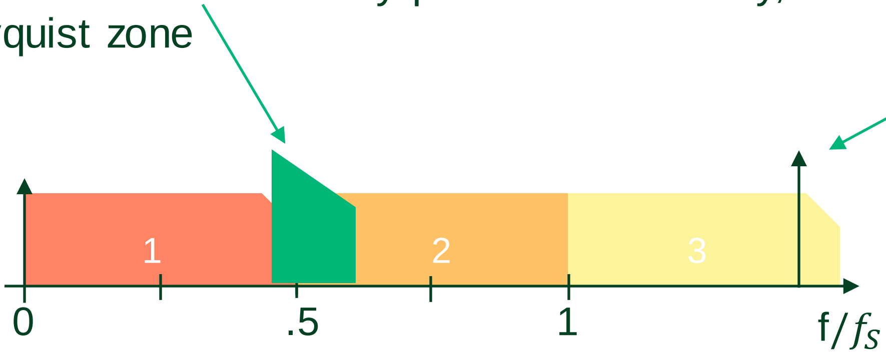


- What will the digital signal look like?



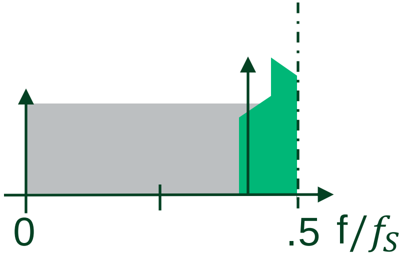
Problem 2: Unwanted aliases

Example: Assume our signal of interest is on a Nyquist zone boundary, and there is a narrow-band interferer in another Nyquist zone



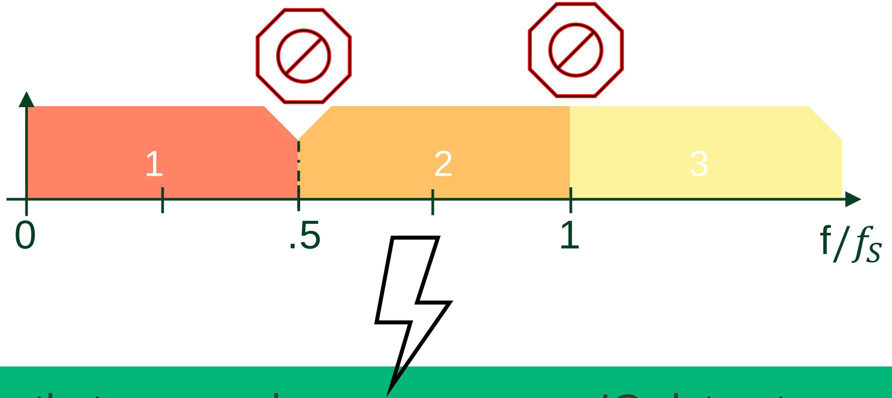
What will the digital signal look like?

- Signal of interest is garbled
- Interferer is aliased onto signal of interest



Unwanted correlation: Available frequencies, rates

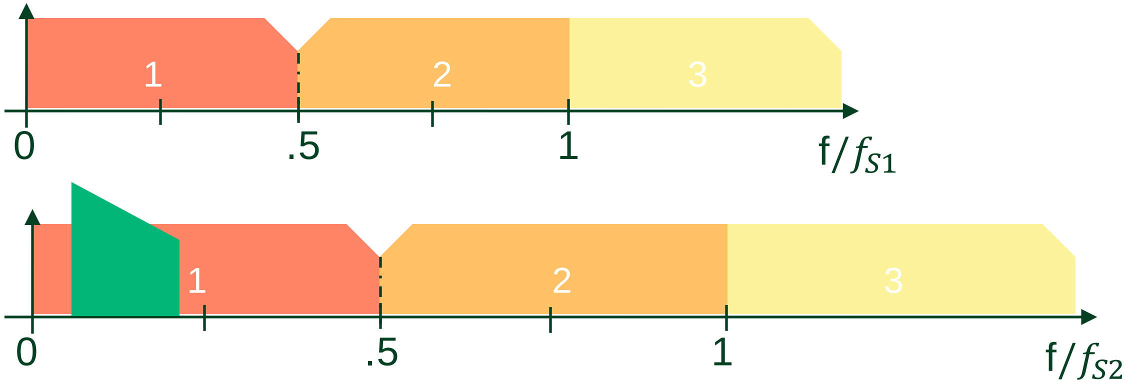
- RF operation near Nyquist zone boundaries is not possible
- To move the boundaries, change the sampling rate



An ideal SDR is one that can produce or consume IQ data at any given frequency range and sampling rate, with minimal distortions.

Potential solution: Combining different rates

- Combining two or more channels with different rates allows detection of signals at any frequency
- This might require digital resampling on at least one of the receivers to make chains "usefully identical"
  - Relationship of the two sampling rates should be chosen carefully
- For a dynamic approach, a single channel with variable rate will also work
  - (When receiving a single signal at variable center frequency)
  - Note: Many of these chips cannot quickly change rates!



Problem 3: Tx sinc-response

- Ordinary DACs have severe attenuation in all but first Nyquist zone!
  - Reason: Zero-order hold signal reconstruction
- Some chips offer a solution: Mix-mode
  - Improves response in 2nd Nyquist zone
- For residual distortion: Inverse sinc-filter
  - For higher Nyquist zones, DACs generally not a great option

Figure 73: **RF-DAC Nyquist Zone Operation**

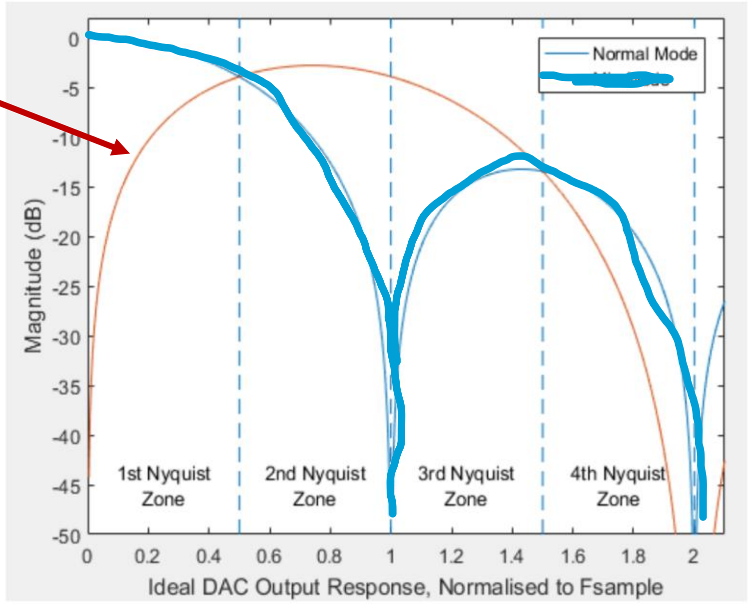
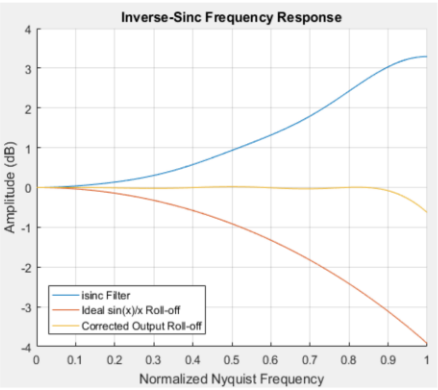


Figure 74: **Inverse Sinc Frequency Response**



[Source: Xilinx RFSoC]

"Problem" 4: Scalability

First-world problem of SDR:

- Increasing the frequency range of direct-sampling-only transceivers requires increasing the sampling rate
- Unsuitable for mmWave applications (FR2,3)

Apollo MxFE Product Details

Apollo MxFE's 4T4R product offers four 12-bit RF ADCs with a sample rate up to 20GSPS, four 16-bit RF DACs with a sample rate up to 28GSPS, an RF input bandwidth from DC to 18GHz (Ku Band), and an instantaneous bandwidth up to 10GHz. Apollo MxFE is the industry's first integrated radio that is capable of directly interfacing to the emerging 6G frequency bands from 7GHz to 15GHz.

Common DSP of high-speed converters

Most common operations available:

- Half-band/by-3 decimation/interpolation
  - Allows resampling by some integer values
- Digital mixers
  - Allows shifting remaining frequency offsets onto complex baseband

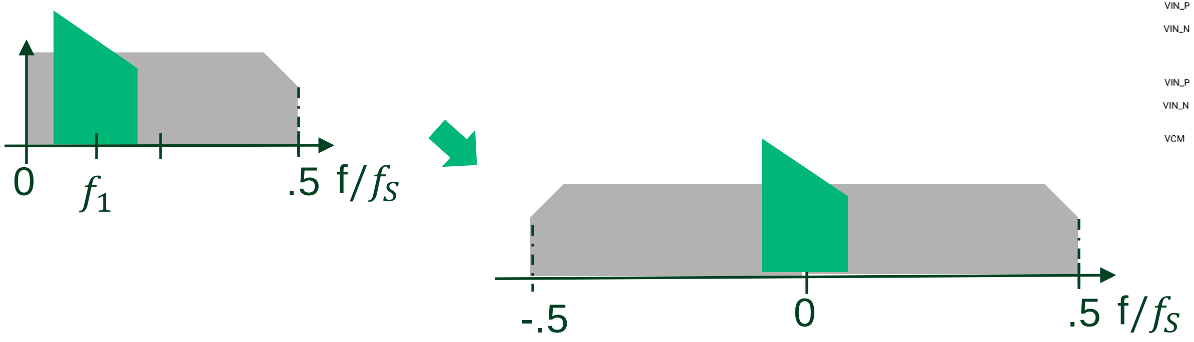
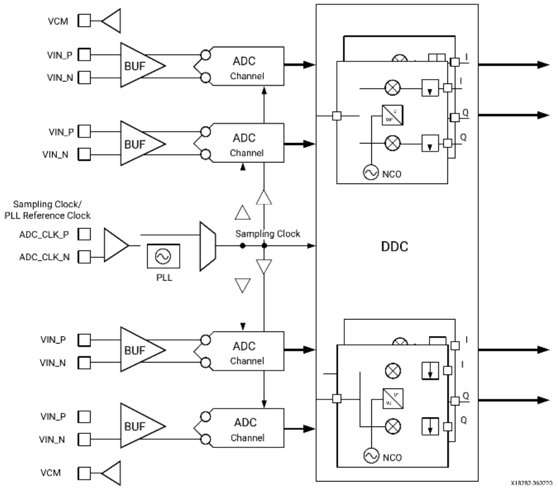


Figure 5: **Quad RF-ADC Tile Overview (Gen 1/Gen 2)**



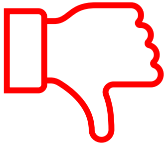
[Source: Xilinx RFSoC]

- Converter/SoC may support more complex operations (FFTs, fractional resamplers, …)

Summary: Direct sampling architectures

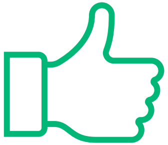
Cons:

- Default RF conditioning will likely not match use case
- Choice of rates directly affects available frequencies
- (Limited scalability)



Pros:

- Much simpler RF architecture
- Much simpler RF architecture
- Much simpler RF architecture



Thank you!