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High IF Sampling Puts Wideband Software-Defined Radio Within Reach

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Introduction

Multiband radar and electronic warfare (EW) applications put a high value on wideband, high dynamic range, agile spectral monitoring. Increasingly higher sample rate data converters are allowing architecture changes to the radio front end that shrink size, weight, power, and cost (SWaP-C), maintain performance, and evolve toward software programmable common hardware. We'll explain the technology advancements enabling this age of wideband software-defined radio expected to transform EW and multiband radar architectures.

The discussion follows a series of frequency planning figures that show the progression of improved wideband spectral scanning methods enabled by advancing data converter technology. The example carried through is a 500 MHz to 18+ GHz EW digital receiver. The annotated figures show for a given approach why the frequency planning is necessary and what allows successive improvements to SWaP-C and flexibility while maintaining dynamic range. In the progression of improving schemes, you'll see the receiver RF image gets easier to address, which allows software-defined flexibility. The need for tunable preselection to kill multitone IMD2 doesn't change with the approach and will remain a critical need into the future even as direct sampling grows ever wider.

Spectral Sensing in Days of Yore

Not too long ago, industry-leading digital receivers employed digital data converters like AD9467 and covered up to a few hundred MHz instantaneous bandwidth (iBW) at a high dynamic range. They sampled at much less than 1 GSPS, and the bandwidth centered around DC (zero IF, also known as ZIF) or centered around an IF offset (RF direct sampling). ZIF requires IQ modulators and demodulators as well as quadrature error correction (QEC) to achieve image rejection.[1,2] Radar and EW applications often require wide iBW and high image rejection. It is difficult to implement QEC that achieves acceptable image rejection as iBW exceeds several hundred MHz, a modest iBW requirement by today's EW and radar standards. This is why high performance, bandwidth-hungry multiband radar and EW prefer the latter RF direct sampling of wide iBW in the first and second Nyquist zones.

To cover spectrum outside the Nyquist zones, an RF tuner uses a swept local oscillator (LO) mixer to frequency translate a sliding block of iBW into the fixed IF that matches up with the data converter direct sample zone. Figure 1 is a block diagram of a typical dual-frequency translation low IF receiver feeding a low sample rate data converter. These receivers are capable of a high dynamic range.

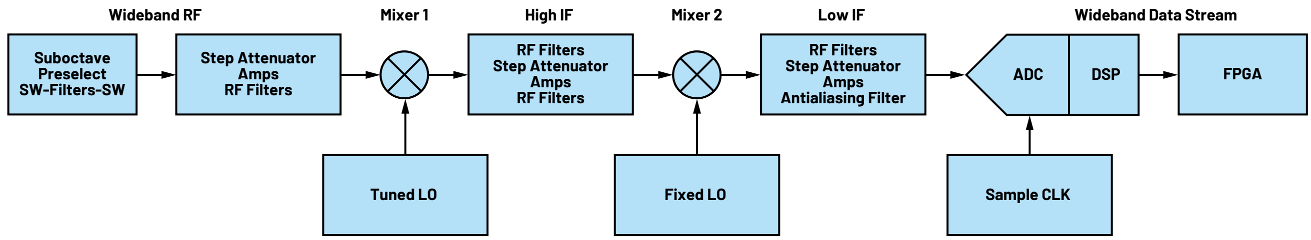

Figure 1. Dual-mixer frequency conversion used in low IF digital receivers.

Figure 2 is the frequency plan employed using the low IF scheme in Figure 1. Just like the digital data converter, the RF tuner requires high RF image rejection to avoid signal ambiguation, spurs, and noise. The single-RF mixer tuner method (red x) does not meet image rejection requirements because the IF frequency is too low to allow enough spacing between the desired band (green) and image band (red). The inadequate separation makes the required RF input filter impossible (or impractical—that is, too large and/or expensive). Thus, a dual-mixer two-stage frequency translation is employed, often called the superheterodyne receiver. The input RF is frequency translated to an intermediate high IF that is several GHz higher than the final direct sample IF. The high IF is RF filtered and frequency translated again to the final IF where it is direct sampled. This method allows realistic high performance RF filters to meet the image rejection requirement. These RF filters are high in the system SWaP-C Pareto.

The RF preselector filtering (Figure 2, yellow) is required to mitigate multiblocker induced IMD2 spurs (that is, F2 – F1 and F2 + F1). The requirement for IMD2 mitigation is independent from the image problem, but the front-end filtering often works to address both.

Spectral Sensing Today (MxFE)

Today's wideband spectral sensing approach improves on days of yore. Thanks to Analog Devices' mixed-signal front end (MxFE®), the ADC sample rate is high enough that you can direct sample the intermediate high IF following that first mixer mentioned previously. Thus, in today's wideband receivers employing MxFE, the RF tuner often doesn't require dual-mixer stages. The second Nyquist IF direct sampling is high enough in frequency to allow adequate frequency spacing of the desired input RF band and image band so that an attainable RF filter can do the job. Figure 3 shows today's single-mixer approach, and the frequency plan is shown in Figure 4.

Today's biggest SWaP-C savings come from eliminating an entire frequency translation stage with mixer, RF amps, filters, and other components. Another SWaP-C benefit of today's higher IF capability is that the direct sample now covers most of LF to 5.5 GHz. So, you don't always need an RF tuner covering all the way down to 2 GHz. In a lot of cases, you could get away with a 5 GHz to 18 GHz RF tuner. Shifting the low limit of the tuner from 2 GHz to 5.5 GHz seems

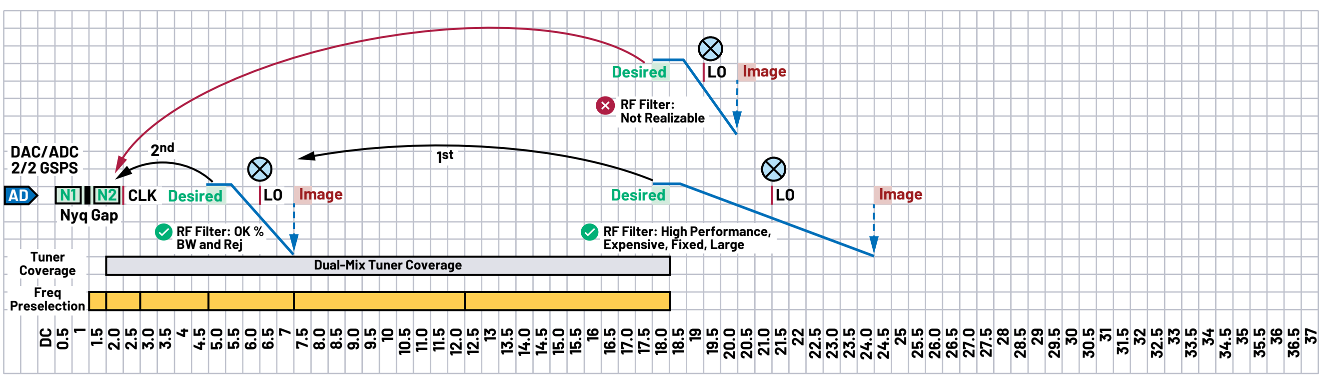

Figure 2. Old spectral scanning with narrow-band superheterodyne tuning.

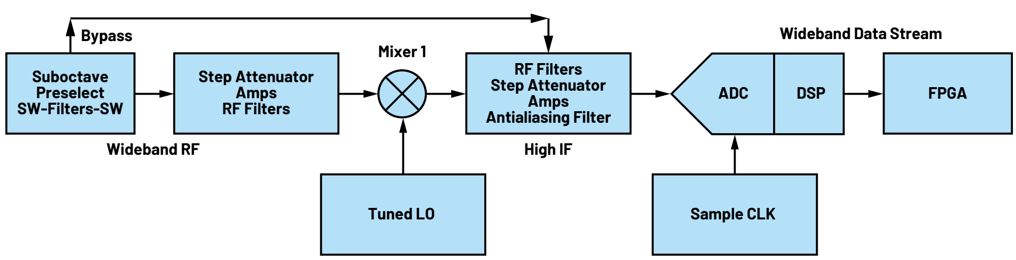

Figure 3. Single-mixer frequency conversion used in high IF digital receivers.

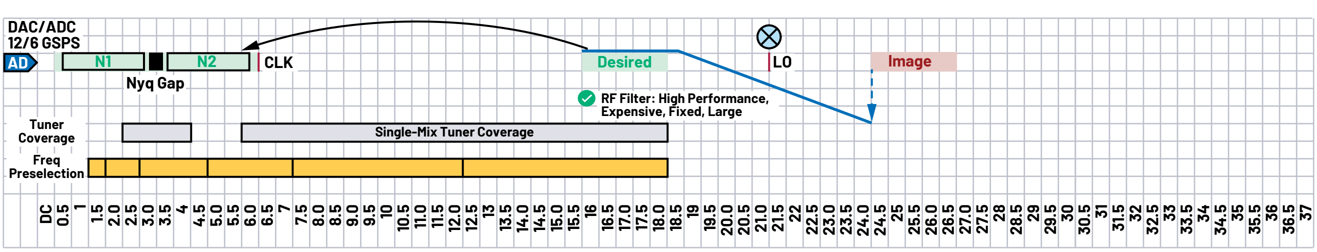

Figure 4. Today's spectral scanning approach, with wideband single-mixer tuning into MxFE sampling at 6 GSPS ADC. Mixer low sideband flips into the direct sample band and sweeps with LO.

minor but is quite significant as it eases filtering, frequency planning, and required LO range. The caveats are you still need to figure out how to cover the gap between the first and second Nyquist, which in the 6 GSPS ADC is roughly 2.7 GHz to 3.3 GHz. Another consideration is the need for switched or tunable ADC antialiasing RF filters that let you toggle between the first and second Nyquist operations.

The RF filters remain high in the system SWaP-C Pareto because they're:

- High performance, requiring low IL, flat pass band, and steep rejection skirts
- Large, using distributed planar geometries on high Q ceramics like alumina
- Lots of them are still required

The suboctave RF preselector is still required, but the requirements may ease allowing less aggressive filtering. The benefit comes from the direct signal chain not using an RF mixer, which should improve IP2.

To summarize today's scheme, wideband Nyquist sampling at high IF improves SWaP-C and iBW by eliminating an entire RF mixer stage. However, it still requires a high part count of discrete MMICs arranged in application-specific line ups and lots of high Q planar filters and structures. Thus, expensive, complex tuners that drive painful SWaP-C trades are still required (see Figure 8). SWaP-C is still looking for a transformative leap forward and it's coming.

Spectral Sensing in the Near Future

Looking ahead, even higher sample rate digital data converters get us over the tipping point to fully software-defined wideband radio at smallest SWaP-C. Today, plenty of companies already market high speed data converters at many 10s of GHz, but buyer beware: pay close attention to the multiblocker dynamic range. In order for high RF direct sample data converters to transform radar and EW, the excellent dynamic range of their narrow-band predecessors must be maintained. As sample rates and iBW push higher, maintaining excellent noise and linearity (that is, the dynamic range) is difficult and relies on countless architectural considerations. This is where ADI differentiates from the competition.

Next-generation higher sample rate data converters will allow many architecture improvements over today's MxFE scheme that is mentioned previously. We see the following three factors as the most significant:

- Direct RF sample higher IF, separating the desired and image band far enough that lower Q tunable MMIC filters are adequate. The MxFE ability to direct sample in the second Nyquist maxes out around 6 GHz. ADI's next-generation high speed digital data converters will significantly extend this coverage, and the resulting benefits are enormous.[3]
    - Now, you've finally eliminated planar high Q ceramic filters, which is a big SWaP-C savings.
    - The RF filters go from fixed (every use case has a custom set of filters) to tunable. This means a single-wideband hardware configuration can be software programmed to optimize the right performance trade for many customer frequency schemes across many use cases.
- Direct RF sample from low frequency up toward millimeter wave (mmW), except the Nyquist gap. Across this direct sample zone, you're digitally tuning while steering an RF tunable filter to knock down IMD2 inducing blockers. Noncontinuous multiband systems, common in radar, can likely eliminate the RF mixer and avoid the gap between Nyquist zones. In this case, the block diagram simplifies further to what is shown in Figure 5, and direct RF sample radar and digital beamforming take off. Systems that require continuous spectral coverage, common in EW, will still need an RF mixer stage to cover the gap between the first and second Nyquist zones and thus the block diagram looks more like Figure 3. Still, SWaP-C reduction is realized for the reasons previously mentioned.
- Extensive on-chip programmable digital signal processing (DSP) features to process the high speed wideband data stream.[4,5] The downstream FPGA responsible for processing the digital converter data payload is the worst size, power, and cost bottleneck in the system. Implementing diverse, flexible DSP on the data converter chip is more power efficient and frees up external FPGA resources for higher level mission-specific algorithms or allows a smaller, cheaper, cooler class of FPGA.

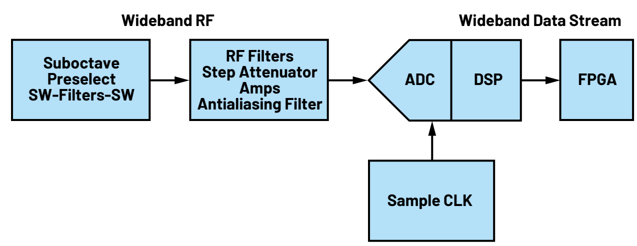

Figure 5. Direct RF sample digital receiver.

To illustrate the frequency planning advantage, Figure 6 and Figure 7 show an EW scheme providing continuous spectral coverage up to 44 GHz with the ADC clocked at 18 GSPS. First Nyquist RF direct sampling covers low frequency—8 GHz. The Nyquist gap is at 8 GHz to 10 GHz, and second Nyquist RF direct sampling covers 10 GHz to 16 GHz. The RF tuner covers the Nyquist gap plus band overlap by flipping 7 GHz to 11 GHz to an IF at 2 GHz to 6 GHz. A tunable band-pass is required at the input to the frequency mixer. The LPF rejects the image, and the HPF rejects IF feedthrough.

The RF tuner also covers higher frequencies outside the ADC RF direct sample range, shown in Figure 7. In this example, the high IF sampling at 10 GHz to 14 GHz pushes the image band far enough away so that lower Q MMIC tunable filtering is capable of achieving the required image rejection. High SWaP-C fixed filtering is eliminated from the signal chain.

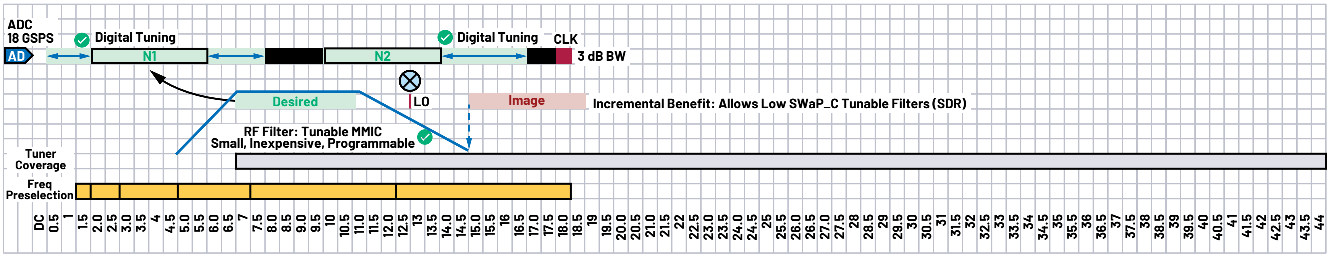

Figure 6. Tomorrow's spectral scanning covering the gap between Nyquist 1 and Nyquist 2.

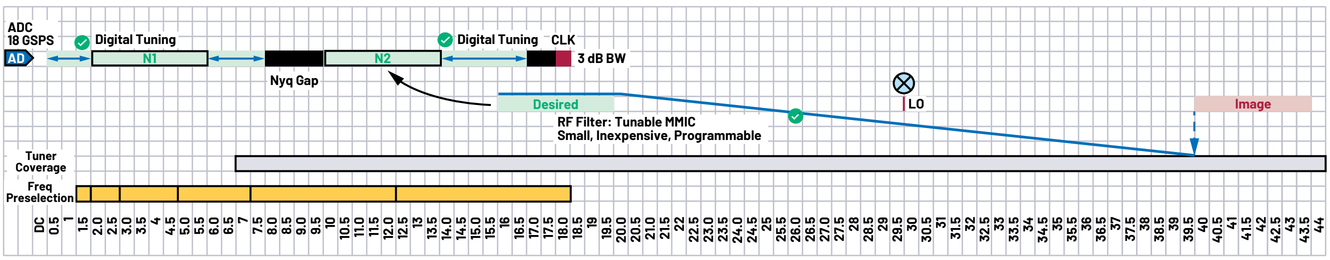

Figure 7. Tomorrow's spectral scanning using a tuner to cover mmW.

Another advantage in using the RF tuner is added flexibility. It is possible that the ADC has degraded noise and linearity the higher you try to direct sample, or you may prefer certain ADC frequency zones that are free of HD2 and/or HD3. If better performance can be attained using the RF tuner vs. direct RF sampling, a run-time software decision can toggle modes on-the-fly.

Despite the simplifications to the frequency planning and filtering, the need for preselect suboctave filtering carries through unchanged into the future and is only helped by IP2 improvements to the data converter and RF conditioning path. For example, wideband RF amplifiers continue to improve IP2 performance and will approach OIP2 = 50 dBm from several hundred MHz to 20 GHz.

Size Comparison

What size advantage can we expect to realize going to tomorrow's receiver front end? We estimate the typical receiver RF chain goes from the size of a business card today to a postage stamp tomorrow. This is a 90% reduction in size.

To get to this size assertion, we sum the component area needed for a typical receiver and add a 50% to 65% component fill factor to account for passive components, traces, walls, and keep outs. We do the same for the next-generation receiver front end that integrates all functional blocks on chip into an integrated downconverter. The tunable LO feeding the mixer is the same for each. The assumptions are shown in Table 1, Table 2, and Table 3.

Table 1. Today's Receiver Front-End Component and Total Area

RF Chain	L (mm)	W (mm)	Area (mm^2)
Preselector, Suboctave	40	25	1000
Digital Step Attenuator	4	4	16
RF Amp	4	4	16
BPF	5	10	50
Mixer	4	4	16
BPF	5	10	50
RF Amp	4	4	16
RF Amp	4	4	16
BPF	5	10	50
Mixer	4	4	16
BPF	5	10	50
RF Amp	4	4	16
Digital Step Attenuation	4	4	16
RF Amp	4	4	16
Antialiasing BPF	5	10	50
LO1			91
LO2			91
Total Components			**1576**
Fill Factor			0.35
Total RF Front End			**4503**

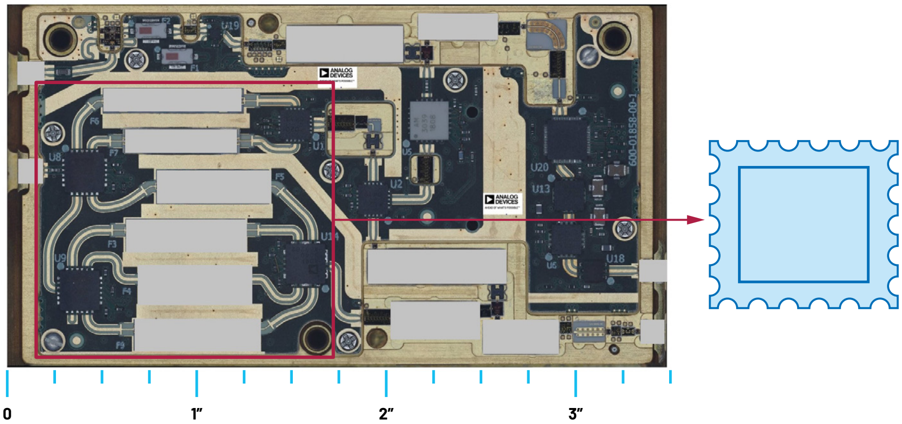

Figure 8. An example of a 2 GHz to 18 GHz receive tuner at high IF meant for an AD9082 MxFE. The need for many high Q planar RF filters (gray) drives up complexity, size, and cost. Suboctave preselection is shown in the red box. The future SDR chipset size is expected to be no larger than a stamp, as shown on the right.

Table 2. Tuned LO Component Area

RF Chain	L (mm)	W (mm)	Area (mm^2)
PLL-VCO	7	7	49
TBPF	5	5	25
RF Amp	4	4	16
LPF	1	1	1
Total LO Chain			**91**

Table 3. Tomorrow's Receiver Front-End Component and Total Area

RF Chain	L (mm)	W (mm)	Area (mm^2)
Preselector, Suboctave	14	10	140
Integrated Downconverter	10	10	100
Antialiasing TBPF	6	3	18
LO			91
Total Components			**258**
Fill Factor			0.5
Total RF Front End			**516**

Conclusion

As ADI's high speed data converter Nyquist sample rate and iBW push higher while maintaining leading dynamic range, frequency planning benefits allow converged, simplified RF front-end architectures. In the past, high performance integrated frequency translation ICs employing suboctave RF filtering and gain control were hard to nail down because everybody's use case, frequency plan, and resulting RF/IF filtering were different. Things are about to change drastically.

New monolithic radio tuners will be natively wideband with on-chip adaptive RF filtering capability and AGC. The vast, fragmented application realm of wideband tuning will converge to common hardware blocks within application-specific adaptive software loops. The system developer realizes time to market and cost benefits as application-specific advantage shifts away from unique hardware toward differentiated software algorithms on common flexible hardware platforms. All this at shrinking SWaP-C.

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About the Author

Benjamin Annino is the applications director for the Aerospace and Defense Business Unit at Analog Devices. He joined Hittite Microwave in 2011 before transitioning to Analog Devices in 2014. Prior to that, he worked at Raytheon on various radar technologies. He has a B.S.E.E. from Dartmouth College, an M.S.E.E. from University of Massachusetts-Lowell, and an M.B.A. from University of Massachusetts-Amherst.