An Analysis Method for Comparing ADC Merit in Digital and Hybrid Phased Array

Ben Annino
Aerospace and Defense
Analog Devices, Inc
Chelmsford, MA
benjamin.annino@analog.com

Abstract- ***To meet unique mission objectives, a given phased array system must balance performance at a certain DC power limit. This paper uses RF-to-ADC cascade modeling to show dynamic range (linearity and noise) and sample rate trade-offs against DC power consumption in a multichannel system with varying channel summation in both the RF and digital realms. A framework for optimizing these criteria against DC power consumption is suggested. The popular Schreier and Walden ADC figures of merit (FOMs) are extended to a multichannel system to express a single system FOM portraying optimal dynamic range normalized for DC power expense.***

Keywords- phased array, radar, RF receiver, analog-to-digital converter (ADC), spur free dynamic range (SFDR), sensitivity, instantaneous bandwidth, linearity, noise, RF cascade, DC power, sample rate, digital beamforming, figure of merit (FOM), model

I. INTRODUCTION

Digital phased array is attractive because it enables multiple independent, simultaneous, software-configurable digital beams and shapes that improve detection and enable multifunction. [1] In practice, every element digital phased array has multiple challenges to overcome—the biggest being DC power consumption. [2] Choosing the optimal ADC bit resolution (ENOB) and sample rate, in the system context of RF performance, power consumption, and digital vs. analog beamforming capability is a complicated multidimensional puzzle for phased array system designers.

In elemental digital beamforming the digitizer node (DAC/ ADC) is distributed behind every single element and so must be lower power than what is available today, without sacrificing performance. Digitizer power burn is a direct function of dynamic range capability and sample rate.

Thermal limits and the size footprint are also big factors. Larger phased arrays often employ blades that put the electronics orthogonal to the antenna face, offering lots of thermal and size flexibility. However, some systems especially those at higher frequencies require the electronics to be planar with the antenna and fit within the element lattice spacing. This requires today's electronics to shrink and shed power—without giving up performance.

II. SYSTEM FIGURES OF MERIT

Spurious-free dynamic range (SFDR) is the most common RF receiver FOM and is a function of linearity and sensitivity. Confusingly, an alternate definition for SFDR shows up on ADC datasheets meaning the worst case spur level. This paper only uses the former definition. Receiver sensitivity is the minimum signal level that can be detected at some offset threshold from the noise floor (lower is better). Several considerations like waveform type and probability of detection determine the offset threshold, which is set to zero in this paper. Sensitivity does not consider linearity; it is solely a noise metric. A point of emphasis: radar and EW systems operate in blocker environments, so linearity (two-tone intermodulation) is as equally important as noise. Phased array is generally suboctave and cares mostly about IMD3 distortion, whereas EW is multi-octave and cares about IMD2 and IMD3 distortions. Usually, a radar or EW receiver is not optimized just for sensitivity. Linearity (that is, IP2 and IP3) is an important design goal, and receiver SFDR is a handy FOM because it considers both sensitivity and linearity.

SFDR is a single-point FOM that expresses the best-case signal to noise and distortion at a singular best-case RF input power. This occurs when the IMD spurs are at the same level as the noise. SFDR is derived in [5].

$$SFDR\ dB = \frac{2}{3}(IIP3\ dBm - Sensitivity\ dBm)$$

$$Sensitivity\ dBm = -174\frac{dBm}{Hz} + NF\ dB + 10Log(IFBW)$$

Where thermal noise spectral density is –174 dBm/Hz at T = 290 K and IFBW is the bandwidth of the noise channel, often set using a combination of IF and digital filtering.

SFDR and sensitivity are the system performance FOMs analyzed herein and are processing bandwidth dependent, as illustrated in Figure 1. To generalize, the processing bandwidth is set to IFBW = 1 Hz. To adjust for the specific processing bandwidth:

- Add 10log IFBW to sensitivity
- Subtract 2/3 × 10log IFBW from SFDR

A receiver often has simultaneous requirements for both sensitivity and SFDR. Low front-end NF helps both, and high IP3 helps SFDR, but gain helps sensitivity and hurts SFDR. So, an optimal RF front-end gain is high enough to meet sensitivity but low enough to meet SFDR.

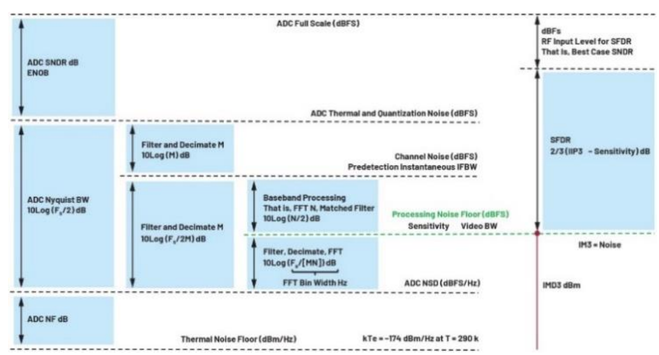

Figure 1 ADC SNDR, NF, proc. BW, IMD3, and SFDR.[3][6]

III. SYSTEM CASCADE MODEL

The goal is to determine the best combination of dynamic range and DC power burn using a model that allows swept RF: digital beamforming ratios, swept ADC ENOB, and DC power drawn from Murmann survey data [4]. The cascade model includes the RF front end, RF channel summation, ADC, and digital channel summation.

Figure 2 shows the modeled blocks and the notable cascade metrics at each node.

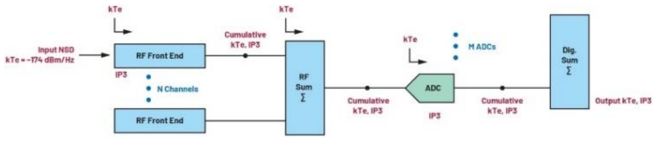

Figure 2 Cascade model of phased array with RF & digital ch summation.

The cascade model tracks device-additive and cumulative noise spectral density kTe at each node, and accounts for signal gain and noise gain separately [7]. The input SNR sums coherent signals and non-coherent noise across all N input channels as described in [9].

$$NF_{overall}\ dB = SNR_{in} - SNR_{out}\ dB$$

$$NF_{overall}\ dB = [signal_{in} - noise_{in}] - [signal_{out} - noise_{out}]\ dB$$

$$NF_{overall}\ dB = Gain_{signal} - Gain_{Noise}\ dB$$

$$Gain_{Noise}\ dB = NSD_{out} - NSD_{in}\ \frac{dBm}{Hz}$$

$$NSD\ \frac{dBm}{Hz} = 10\log_{10}(kTe)$$

$$k = 1.38 \times 10^{-23} \text{ and } T_e = k\ (F-1)$$

Where F is Noise figure (linear, not dB) and NSD is noise spectral density.

The model uses a subarray size of 64 channels. In many of the plots, the horizontal axis shows the model sweep from all-digital summation on the left (64-channel digital sum, no RF sums) to all-RF summation on the right (no digital sum, 64-channel RF sum). In between is a digital and analog summation blend (i.e. hybrid) increasing RF sum from left to right. These plots are in the results section. ADC ENOB is swept in the analysis and presented in the plots. Trends in DC power and performance (SFDR and SENS) are analyzed as these parameters are swept.

A. *Modeling the RF Front End*

The RF front-end model is an RF black box with attributes gain, NF, IP3, and DC power that are functions of swept attributes. As the system model sweeps the RF: digital sum ratio and ADC ENOB, the RF front-end attributes tune for the best cascade performance. Table 1 provides the equations behind each attribute function.

Attribute	Equation	Note
Gain	–4.2 × ADC_ENOB + 50 dB	
NF	5 dB	Nominal
OIP3	ADC_IP3 + 8 – 7 LOG10(N)	N = RF sum ports
DC power	(N = 1) m × OIP3 + b (mW) (N > 1) 2× (N = 1 case)	M = 0.14, b = 0.02

Table 1 RF Front-End Attribute Equations

The model sets RF front-end gain as a function of ADC_ENOB, a swept parameter, as shown in Table 1. The model uses a linear equation to set a minimum viable gain for reasonable system kTe while seeking to maximize SFDR. RF gain is bad for SFDR so it should be minimized just enough to meet NF requirement. Lower-resolution ADCs have a much higher noise figure and require more RF gain in front (at low NF) to set acceptable system NF. In contrast, an ADC with ENOB = 12 has excellent NF and requires no front-end gain, a huge dynamic range benefit albeit at ADC DC power penalty. The ENOB = 8 case sees improving sensitivity and neutral SFDR impact as the gain is increased to ~15 dB. Above 15 dB, SFDR begins to degrade steadily. In contrast, the ENOB = 12 case has a superior ADC NF and as such wants no gain in front. Putting the same 15 dB gain block in front would have a net negative impact on ENOB = 12 performance.

RF front-end noise figure is set at 5 dB and held constant across all simulations. This is a middle of the road value that acknowledges the need for:

- Trade off with high linearity. A front-end block with NF = 5 dB and OIP3 = 30 dBm to 40 dBm is realistic. Assuming NF is much less than that while maintaining OIP3 isn't realistic.
- Front-end RF filtering, RF switching, RF limiter, or other loss elements.

The model sets RF front-end OIP3 as a function of ADC_IP3 and the number of summed RF ports. Every element digital summation (RF = 1) requires the highest OIP3 RF front end, 8 dB higher than the ADC IP3 to result in a reasonable ~0.8 dB degradation to system cascaded IP3. As RF sum channels increase, the single-channel OIP3 requirement eases. This in turn eases the DC power required in the RF front end.

The model sets RF front-end DC power as a function of RF front-end OIP3, which is a function of ADC IP3 and RF sum ports (described previously), shown in Table 1. The RF front-end function is different in the RF = 1 vs. RF > 1 cases.

- RF = 1 is the every-element digital case where the RF front end does no beamforming. It is primarily a variable gain stage with signal filtering.
- RF > 1 requires time or phase delay and attenuation control to accomplish RF beamforming. A time delay unit and a variable attenuator sit between two gain stages. The extra gain stage vs. the RF = 1 case doubles the DC power and is required to overcome the TDU and DATT loss. This is what causes the DC power to jump up from RF = 1 to RF = 2 in Figure 4.

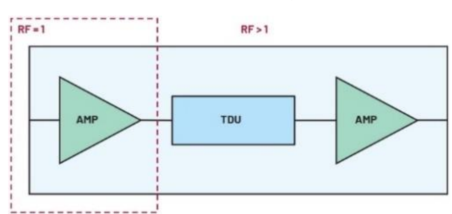

Figure 3 RF front end for RF = 1 and RF > 1 cases.

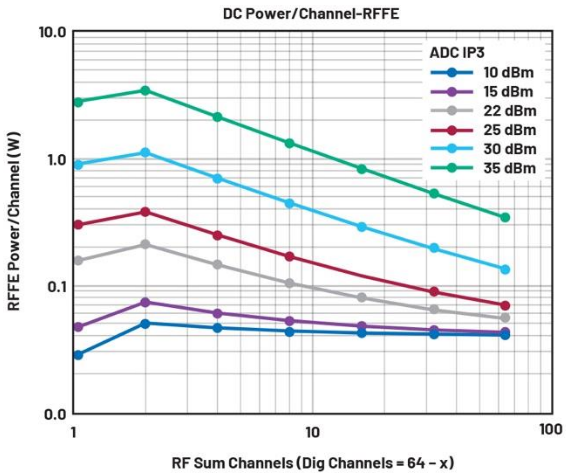

Figure 4 RF front-end DC power/channel.

System IP3 drives DC power, and the RF front end must have high enough IP3 so that the ADC is the linearity bottleneck, which drives up the RF front-end DC power.

Another notable relationship is the required front-end single-channel OIP3 decreases as the RF sum channels increase. Summing RF channels improves the signal-to-noise ratio (SNR) by coherent addition of the signal and noncoherent combination of Gaussian white noise, creating a stronger signal before the nonlinear ADC vs. the alternative of digitally summing channels after the ADC. The spur level resulting from multitone intermodulation is a function of ADC IP3 and the signal level into the ADC. For two tones at the same level:

$$P_{in,IM3}\ dBm = 3 \times P_{in} dBm - 2 \times IIP3\ dBm$$

In short, RF summing before the ADC improves SNR but degrades the two-tone spurs due to ADC nonlinearity compared to the same N channels summing digitally after the ADC. Digitally summing after the ADC, where the signal gain is computed in the digital realm after the ADC, has the SFDR advantage. The ADC is not asked to handle a larger signal; the SNR benefit is realized through summation of multiple digital data streams at the price of bit growth.

B. Modeling the ADC

The ADC model uses behavioral equations derived from population data from Boris Murmann's ADC survey [4]. Data points from similar-class ADCs are selected, reducing the population to 20 members sharing the following criteria: Analog Devices and industry peers; CMOS <32 nm; f_S> = 4 GSPS

A black box ADC model allowing swept attributes is created from a fit to population data points.

The analysis uses the same two FOMs as [4]. The Walden FOM favors low resolution ADCs as it moves 2× per bit. A lower FOM is better.

$$FOM_W = \frac{Power}{2^{ENOB} \times f_{s,Nyq}} \left(\frac{fJ}{conv - step}\right)$$

$$ENOB = \frac{SNDR - 1.76}{6}$$

The Schreier FOM favors high resolution ADCs as it moves 4× per bit. Higher is better.

$$FOM_S = SNDR + 10Log\left[\frac{f_{s,Nyq}/2}{Power}\right]\ dB$$

In both cases, for a fixed FOM value, DC power moves proportional to the sample rate and exponential with dynamic range (important rule of thumb).

To meet the high dynamic range and direct sampling requirements in radar, EW, and MILCOM, new ADCs will emerge in the boxes annotated Figure 5 and Figure 6.

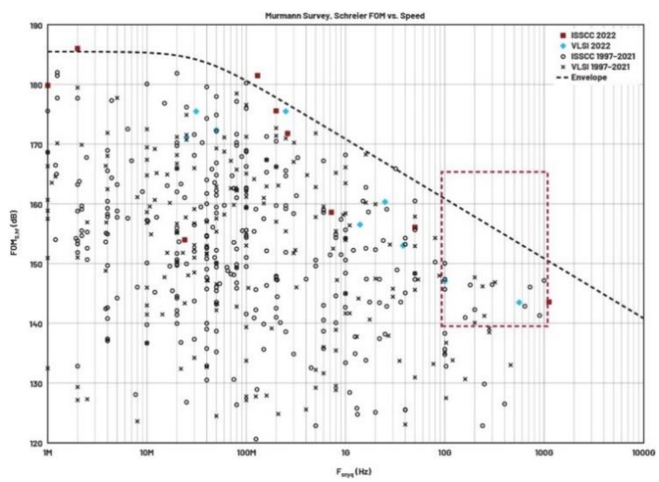

Figure 5 Schreier FOM from Murmann survey. [4]

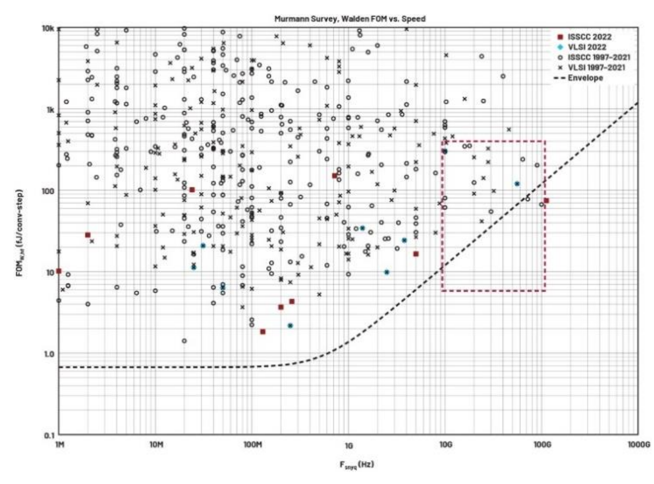

Figure 6 Walden FOM from Murmann survey. [4]

Points from [4] can be rearranged to plot the DC power vs. ENOB (dynamic range) relationship at the performance frontier.

$$FOM_W \times f_{s,Nyq} \times\ 2^{ENOB} = Power\ \text{(Walden)}$$

$$\left[\frac{f_{s,Nyq}/2}{10^{[FOMs - SNDR]/10}}\right]\ = Power\ \text{(Schreier)}$$

For a given sample rate on the frontier, Figure 7 and Figure 8 plot how power and ENOB trade off to arrive at the same FOM.

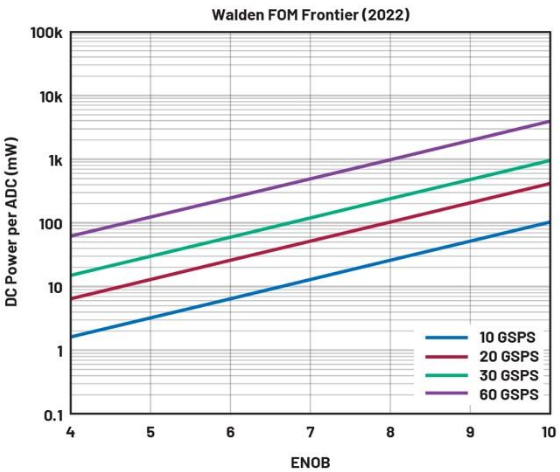

Figure 7 DC power vs. ENOB on the Walden frontier. [4]

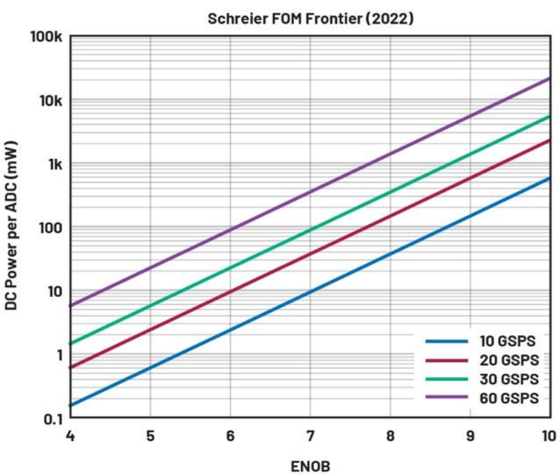

Figure 8 DC power vs. ENOB on the Schreier frontier. [4]

The best ADC for phased array Radar strikes an optimal balance between dynamic range, instantaneous bandwidth and DC power.

For example, with a DC power budget of 100 mW per ADC and sample clock at 60 GSPS, a 6 ENOB ADC is possible in literature. Lowering the sample rate to 10 GSPS allows an increase in dynamic range to ENOB = 8.7. Both scenarios are on the FOM state-of-the-art frontier, and so are equally good. The better choice depends on system priorities. In a radar application 60 GSPS at ENOB = 6 could be completely useless, and 10 GSPS at ENOB = 8.7 required. So, a compromise uses the 10 GSPS ADC to achieve the better ENOB at the max allowed DC power.

Using data from [4], the model derives best fit, low bound, and high bound equations for DC power as a function of ENOB in Figure 9,

$$\frac{Power_{DC}}{freq_{sample}} = ae^{k(ENOB)}\ pJ$$

and ENOB as a function of bits, in Figure 10.

$$ENOB_{ADC} = 0.6 \times bits_{ADC} + 1$$

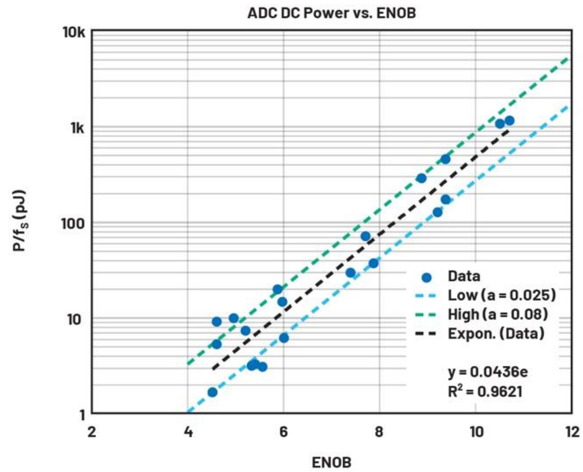

Figure 9 Fit curve for ADC DC Pwr vs. ENOB, using Murmann survey [4]

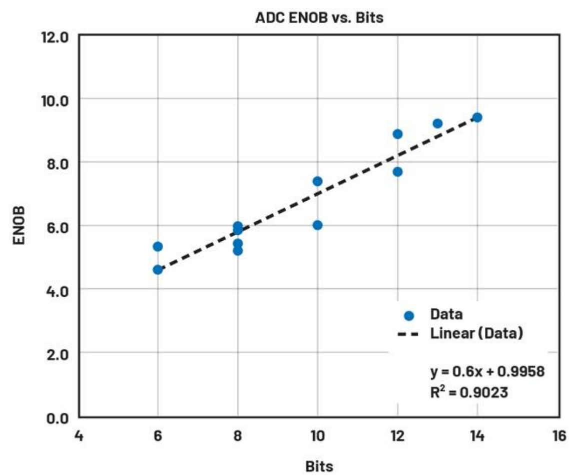

Figure 10 Fit for ADC ENOB vs. bits, using filtered Murmann survey [4]

The modeled ADC's DC power and RF attribute model as a function of ENOB is shown in Figure 11. The ADC model is an RF black box with attributes NF, IP3, and DC power that are functions of swept attributes. As the system model sweeps ADC ENOB, the ADC attributes tune.

The equation for ADC NF is a function of the effective number of bits (ENOB), or SNR.

$$NF_{ADC}\ dB = kTe_{ADC}\ \frac{dBm}{Hz} - (-174)\ \frac{dBm}{Hz}$$

$$kTe_{ADC}\frac{dBm}{Hz} = Full\ Scale_{ADC}\ dBm - SNR_{ADC}\ dB - 10Log\left(\frac{f_s}{2}\right)Hz$$

$$SNR_{ADC}\ dB = 6 \times ENOB_{ADC} + 1.76\ dB$$

Noise spectral density, kTe (dBm/Hz), is equivalent to sensitivity (dBm) in a 1 Hz bandwidth. To generalize, assume a 1 Hz bandwidth throughout, which can be adjusted to a specific bandwidth by adding 10LogBW.

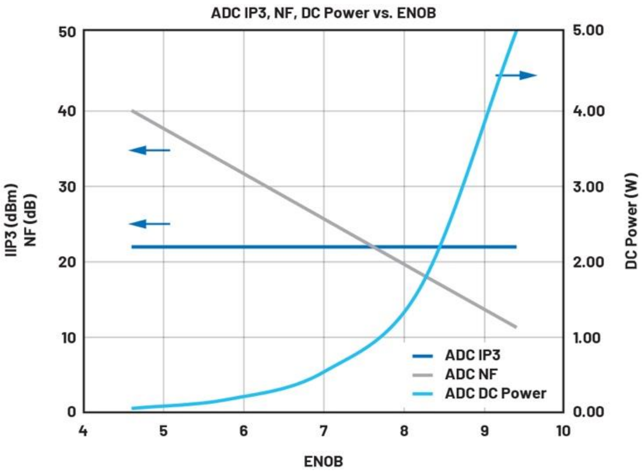

Figure 11 Generalized model for ADC NF and DC power vs. ENOB.

Figure 12 shows DC power/channel vs. ENOB and RF: digital beamforming.

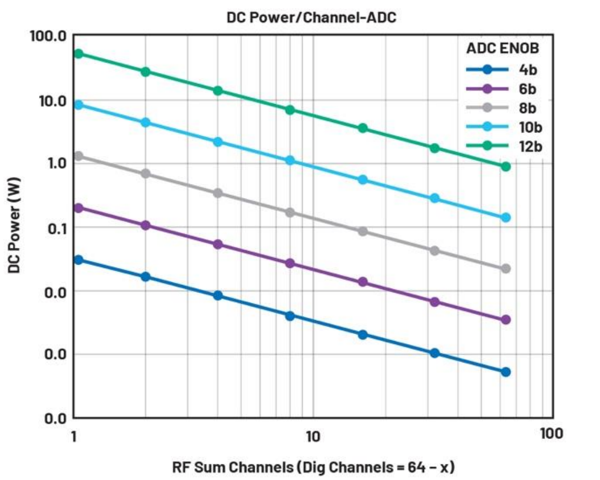

Figure 12 ADC DC power/element vs. # RF sum channels & ADC ENOB.

C. Modeling the Digital Payload Interface and Summation

The high speed data payload and sum computation DC power are estimated from the transport energy per bit. [8] The digital payload transport power associated with the ADC-to-digital sum node scales up as the number of digital sum channels and IBW increases. The DC power burn for the transport of the high speed digital payload is:

$$Power_{Digital\ Sum\ Interface}\ W$$

$$= [Energy\ _{Ser} + Energy\ _{Deser}\ J/bit] \times Payload\ bits\ \times Dig.Sum\ Chs$$

$$Payload\ bits = Encode\ Rate\ Gbps\ \times Overhead_{JESD204C}\ \times bits_{ADC}$$

$$Encode\ Rate\ Gbps = IBW\ GHz \times 2\ bits\ \times 1.2$$

$$Overhead_{JESD204C} = 66/64$$

A JESD link is assumed with IBW = 1 GHz and

$$Energy\ _{Serializer} = 3\ \frac{pJ}{bit}$$

$$Energy\ _{Deserializer} = 4\ \frac{pJ}{bit}$$

The computational power burn for the complex multiply is assumed equal to the interface power. This is a crude approximation dependent on other factors like beam-bandwidth, but reasonable. Figure 19 shows the overall interface plus digital sum DC power/channel vs. RF: digital sum ratio.

IV. Results

Figure 13 and Figure 14 show the relative percentage of power consumed by the RFFE, ADC, and digital summation/interface. At every-element digital and lower bit resolution, the digital interface and summation consume a large proportion of overall power. But for systems with higher RF channel summations, the digital interface is less significant. Another trend is that the RFFE is dominant at low ADC bit-resolution, and the ADC is dominant at high ADC bit-resolution. These plots show the big impact ADC ENOB and RF: digital channel summation ratio has on what dominates DC power consumption.

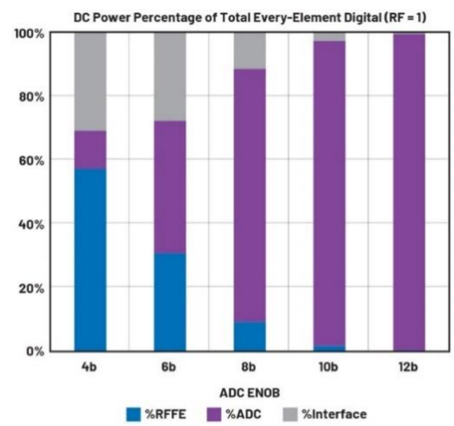

Figure 13 DC power % contribution, elemental digital

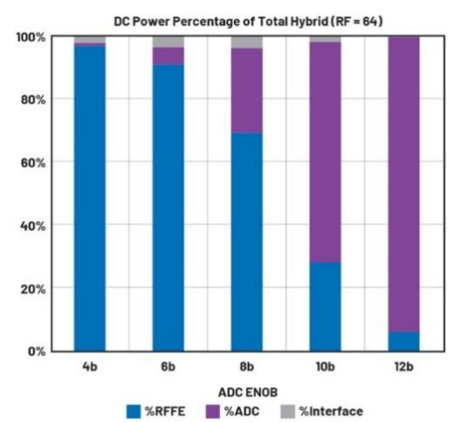

Figure 14 DC power % contribution, large RF subarray.

Next in Figure 15 and Figure 16, SFDR and sensitivity are plotted vs. DC power/channel for varied ADC ENOB and RF: digital summation. The points along the trace step the RF:digital summation ratio. Plotting the data this way adds DC power as a performance dimension to SFDR and Sensitivity, which allows some trend observations:

- For the same SFDR and sensitivity, hybrid beamforming systems employing a blend of RF and digital beamforming require a higher bit ADC vs. all-digital but are more power efficient overall due to fewer ADCs and lower required RFFE linearity.
- SFDR and SENS vs. DC power improves rapidly going ENOB = 4 to 8, then slows.
- For a given ENOB, SFDR & sensitivity improves as digital:RF summation increases but at the expense of increasing DC power.

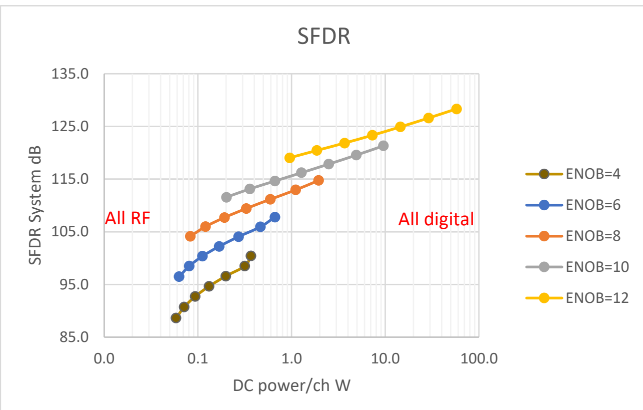

Figure 15 SFDR vs. DC power/channel, traces are constant ENOB, dots are RF: digital sum.

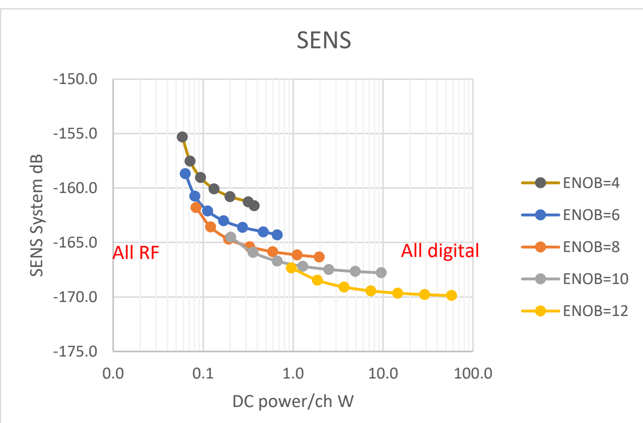

Figure 16 Sensitivity vs. DC power/channel, traces are constant ENOB, dots are RF: digital sum.

Is every-element digital better in any of these situations? From a dynamic range efficiency perspective where DC power is handicapped, no. The benefit of every-element digital is higher simultaneous beam count. Extra power is burned to achieve this.

Table 2 provides a comparison of example scenarios each with a different design priority. There is no one-config-fits-all scenario. Different system objectives drive different performance priorities, which force performance trades across other attributes.

Table 3 shows a popular ADC ENOB = 8 example assuming practical IF bandwidths. Pay attention to the signal level at the ADC, as the linearity of most ADCs degrade as full scale is approached. The optimal RF operating level at the ADC increases as processing bandwidth increases. The ADC isn't usually operated to full scale, in practice.

Must-Have Objective	Trade-Off	RF: Dig Sum	ADC ENOB	SFDR dB 1 Hz	SENS dBm 1 Hz	DC W/ch
All-digital BF	High DC power	1:64	8.2	115	–167	2.2
All-digital BF < 1 W/channel	Degraded SFDR and SENS	1:64	6.9	111	–165	1
Lowest power	Less beams; Degraded SFDR and SENS	64:1	4	89	–155	0.059
		64:1	6	96	-159	0.063
		64:1	8	104	-162	0.083
Best Possible SFDR and sensitivity at 1 W/channel	Less beams	64:1	12	119	-167	1
	|	16:4	10.5	116	–167	1
	More beams	2:32	7.9	113	–166	1

Table 2 Breaking Out Some Common Sample Scenarios

IF BW MHz	RF: Dig Sum	ADC ENOB	SFDR dB	SENS dBm	RF Input Level for SFDR dBm	Pre-ADC Signal Gain dB	ADC in dBm	DC Power/Channel W
1	1:64	8.2	75	-107	–31	15	–16	2.2
10			69	–97	–28		–13	
100			62	-87	-24		–9	
1k			55	-77	–21		–6	
1	4:16		72	–106	–34		–19	0.7
10			65	–96	–31		–16	
100			59	–86	–28		–13	
1k			52	-76	–24		–9	

Table 3 Using Some Real Processing Bandwidths

	ADC	System
Walden FOM_W $\left(\frac{fJ}{conv-step}\right)$	$= \frac{Power}{2^{ENOB} \times f_{s,Nyq}}$	same
$ENOB$	$= \frac{SNDR - 1.76}{6}$	$= \frac{SNR_{system} - 1.76}{6}$
Schreier FOM_S (dB)	$= SNDR + 10Log\left[\frac{f_{s,Nyq}/2}{Power}\right]$	$= SFDR + 10Log\left[\frac{f_{s,Nyq}/2}{Power}\right] dB$

Table 4 Extending Walden & Schreier FOM to system

Lastly in Table 4, the Walden and Schreier ADC FOMs are modified into system FOMs to compare performance vs. power trades for RF-to-ADC cascades. The goal is to sweep parameters and spot best value performance normalized for DC power at the system level.

Here, the FOMs are shown while:

- Varying RF:digital summation, from all-dig to all-RF
- Varying ADC ENOB, linearity, and DC power

$$SNR_{system} = NSD_{system,input} - Full\ Scale_{system,input} + 10\log\left(\frac{f_{s,Nyq}}{2}\right)$$

$$NSD_{system,input} = -174\frac{dBm}{Hz} + NF$$

$$SFDR\ dB = \frac{2}{3}(IIP3\ dBm - Sensitivity\ dBm)$$

$$Sensitivity\ dBm = -174\frac{dBm}{Hz} + NF + 10Log(IFBW)$$

T=290K and Full Scale$_{system.input}$ is the input-referenced full scale RF input.

The Schreier FOM is modified by swapping in SFDR for SNDR to make a FOM that reflects two-tone linearity performance. Figure 17 and Figure 18 plot the system FOMs vs. RF: digital sum ratio.

The phrase "best value" is meant in the sense of best return (SFDR and Sensitivity) for a given cost (DC power burn). The FOMs assist in drawing best value conclusions because they normalize performance against DC power burn. Sensitivity observations are drawn from Walden (Figure 17, lower is better) and SFDR comments are drawn from Schreier (Figure 18, higher is better).

The following trends are observed from the preceding FOM figures:

- The "best value" sensitivity for DC power is at high ADC ENOB (8 to 12) and high RF summation.
- ENOB ~6 has merit in all or mostly digital (hybrid) systems but decreasing to ENOB < 5 results in poor SFDR and sensitivity.
- ENOB=8 offers the best combination of sensitivity and SFDR in small-subarray (<16 element RF sum) systems.
- For all-digital BF, ENOB in the range 6 to 12 results in similar "value" because DC power burn perfectly offsets performance gains.
- The best SFDR-to-DC power value ratio occurs at ENOB 10 to 12 and employs larger subarrays (>16 element)

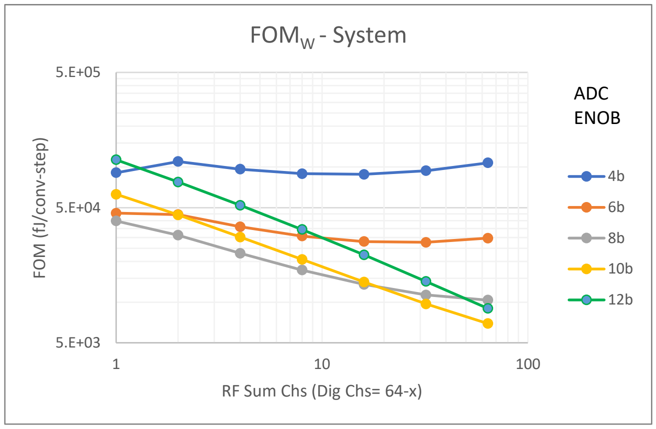

Figure 17 Walden system FOM (lower is better).

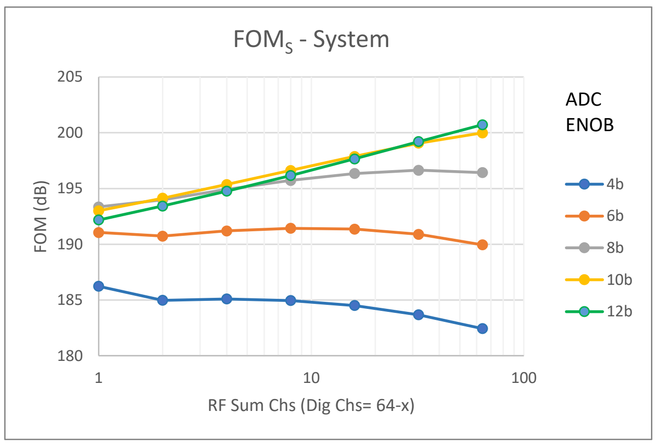

Figure 18 Schreier system FOM (Higher is better).

V. Conclusions

Performance-critical applications like radar phased arrays need to deploy the optimal balance of sample rate, dynamic range, and DC power. Overprioritizing any one of these will result in a suboptimal (or simply bad) solution. The era of 20 to >100 GSPS ADC sampling is here, but higher sampling is achieved at a cost to the other two critical performance attributes in the FOM triad—DC power and dynamic range (ENOB). High sample rates are not a design miracle, but a chosen prioritization of sample rate at the expense of higher DC power and lower ENOB. In many cases the optimal ADC for a phased array system will prioritize dynamic range and DC power, with just a high enough sample rate for frequency planning efficiency and oversampling gain.

High dynamic range, high sample rate data converters with ENOB ~8 are popular choices for phased array radar because they offer a good compromise between dynamic range and DC power. Phased array radar ADCs also need high linearity (that is, IP3 > 22 dBm). When evaluating SNDR, know whether it includes interleave spurs, and make sure spectral regions aren't cherry-picked.

Some systems have mission-critical requirements like beam count driving every-element digital beamforming. Nevertheless, all-digital comes at a steep DC power penalty. The arrays with the best balance of performance and DC power use a hybrid scheme, which is a combination of RF beamformed subarrays feeding distributed DAC/ADC nodes that are digitally beamformed. [2] If beam attribute requirements allow it, a small subarray of RF beamforming in front of each ADC is highly recommended for improving SFDR and sensitivity at lower DC power and providing blocker mitigation using beam null steering, to name a couple of benefits. Today, a lot of extra power is burned to achieve the software-defined adaptability of fully digital beamforming.

Over the next 5 to 10 years, every-element digital phased array will ramp in technology readiness and viability at increasingly better performance. To get there, new state-of-the-art ADCs will put a higher emphasis on lowering DC power while maintaining sample rate and ENOB. ADC sample rate capability will continue to push higher and grab headlines but might benefit wideband applications like EW more than phased array. The phased array market will figure out a sample rate sweet spot (10 GSPS to 20 GSPS?) and then the market winners will provide the best ENOB at lowest power.

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