Technical Article

How to Select the Best ADC for Radar Phased Array Applications—Part 2

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Abstract

Many papers discuss the system trade-offs and relative merits of digital vs. RF beamforming, and the hybrid blend thereof.[1] Building on prior work, this article 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. The optimal selection of sample rate, ADC ENOB, and RF vs. digital channel combining is weighed against DC power consumption. The popular Schreier and Walden ADC figures of merit (FOMs) are proposed as extensible to a multichannel system to express a single system FOM portraying optimal dynamic range normalized for DC power expense. The article has two parts. "How to Select the Best ADC for Radar Phased Array Applications—Part 1" explains the method of modeling the system, and Part 2 analyzes the results and draws conclusions from system FOM.

System Modeling Results

The system model results presented in the following plots consist of:

Table 1. Model Results

Merit Attribute	Swept Variables
SFDR	ADC ENOB; Blend of RF sum to digital sum, always totaling 64
Sensitivity	
DC Power/Channel	

The following examples use 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, sometimes called hybrid beamforming with increasing RF sum from left to right. These plots are in the next 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.

Figure 1 and Figure 3 are the parametric results from the system model. The trouble is, viewing sensitivity, SFDR, and DC power individually doesn't indicate good or bad because performance is portrayed separately from power. For example, maximum SFDR at the lowest possible DC power burn is the goal. But what configuration of ADC ENOB and RF: digital combining is better vs. another? The next section is a more useful apples-to-apples comparison as the results show performance as dynamic range normalized for DC power burn.

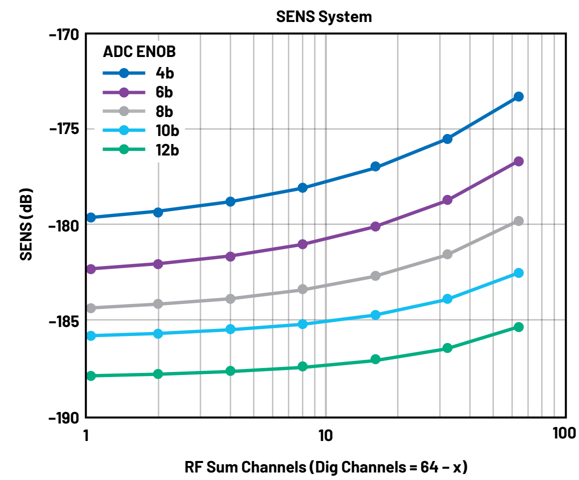

Figure 1. System sensitivity vs. number of RF sum channels and ADC ENOB.

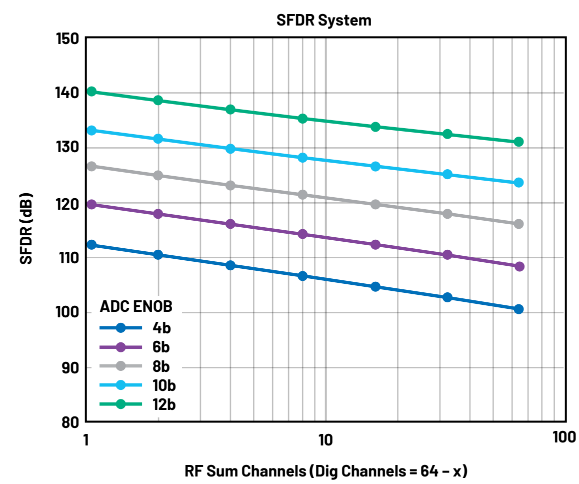

Figure 2. System SFDR vs. number of RF sum channels and ADC ENOB.

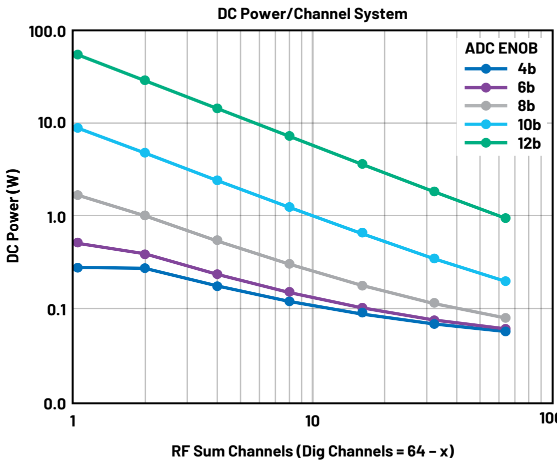

Figure 3. Overall system DC power per element vs. number of RF sum channels and ADC ENOB.

Figures 4, 5, and 6 show the relative percentage of power consumed by the RFFE, ADC, and digital summation/interface. At every-element digital (Figure 4) 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.

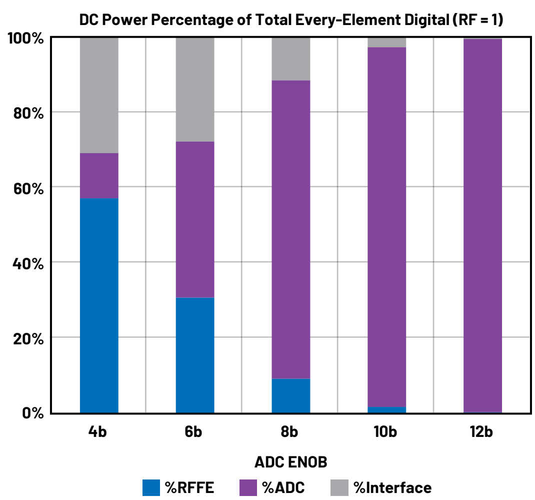

Figure 4. Percentage of DC power from RFFE, ADC, and digital summation, every-element digital.

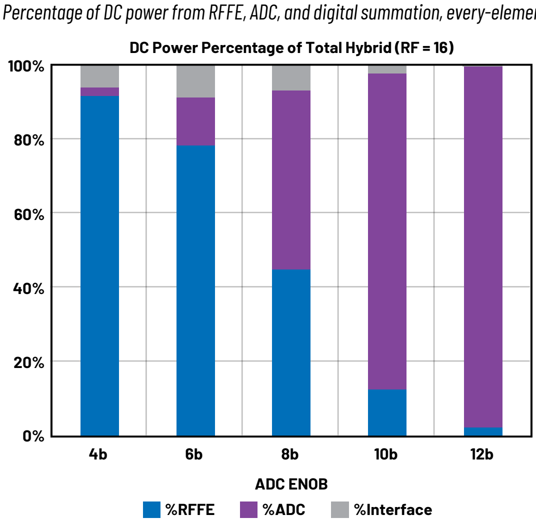

Figure 5. Percentage of DC power from RFFE, ADC, and digital summation, medium-sized RF subarray.

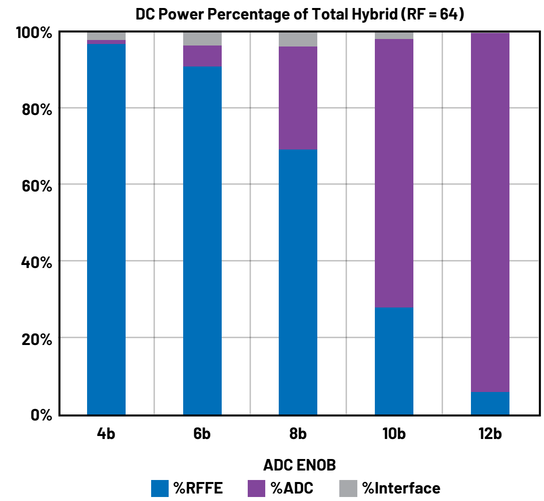

Figure 6. Percentage of DC power from RFFE, ADC, and digital summation, large RF subarray.

Next, the relative merit of SFDR and sensitivity is normalized for DC power/channel for different ADC ENOB and RF: digital channel sum schemes. The three independent plots of sensitivity, SFDR, and DC power vs. RF: digital channel summation from the prior sections is rearranged in the following figures to better visualize performance trends when normalized for DC power. Figure 7 and Figure 8 show SFDR and sensitivity vs. DC power for a few fixed RF: digital summation traces. The bit resolution is annotated and varies along the trace. Figure 9 and Figure 10 show the same underlying data but arranged a bit differently. The traces are a few ENOB cases, with the RF: digital summation varying along the trace from all-RF to all digital, left to right. Table 3 summarizes the conclusions from the plots.

Table 2. Aggregated Result Comparison

Attribute	Swept Variable	Markers on Each Trace
SFDR; sensitivity	DC power/channel Blend of RF to digital sum, always total = 64	ENOB increasing left to right 4b to 12b by 2b
SFDR; sensitivity	DC power/channel ADC ENOB	Blend of RF: digital sum, total = 64. 64:1 all-RF sum on left, going 32:2, 16:4, 8:8, 4:16, 2:32, ending 1:64 all-digital on right

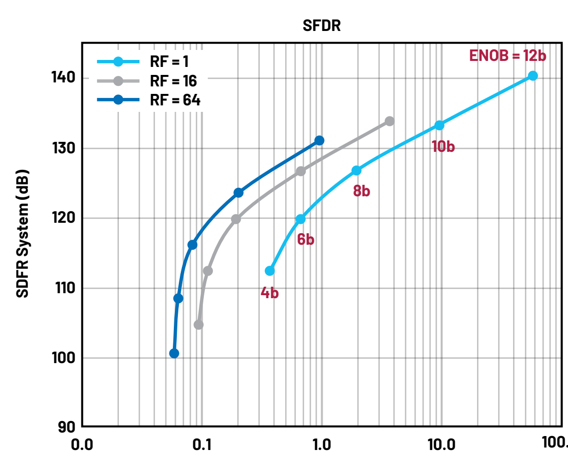

Figure 7. SFDR vs. DC power/channel, traces are RF: digital sum, each dot is ENOB.

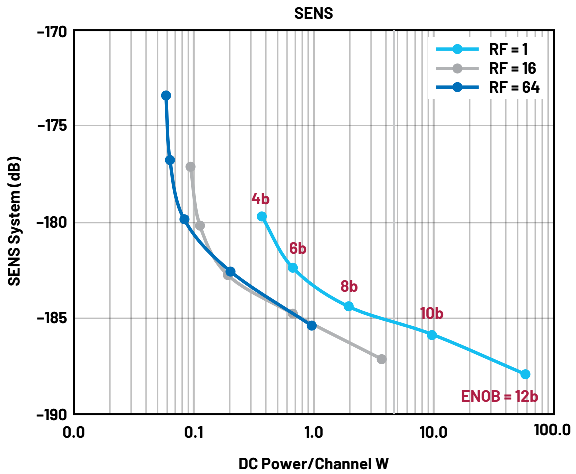

Figure 8. Sensitivity vs. DC power/channel, traces are RF: digital sum, each dot is ENOB.

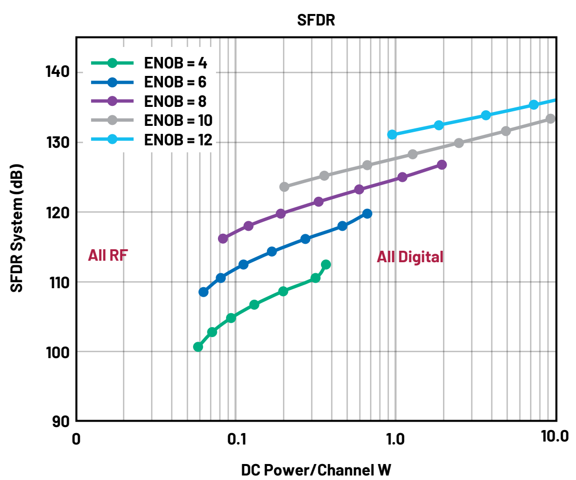

Figure 9. SFDR vs. DC power/channel, traces are constant ENOB, dots are RF: digital sum.

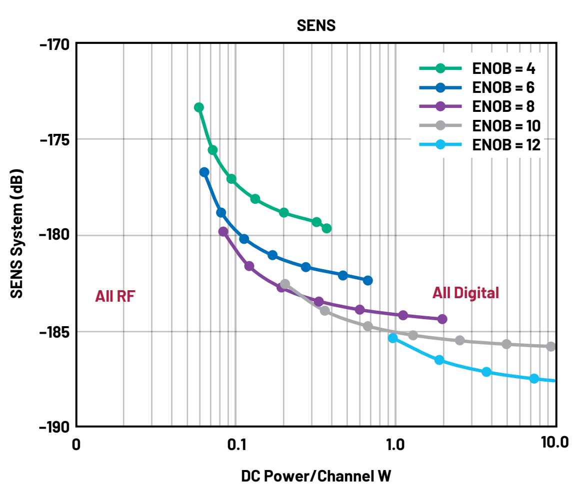

Figure 10. Sensitivity vs. DC power/channel, traces are constant ENOB, dots are RF: digital sum.

We can now draw performance vs. DC power conclusions from the plots:

Table 3. Conclusions from Plots

Topic	Observation	Why?	Conclusion
Best RF: digital Summation?	Increasing RF sum is beneficial in reducing system DC power, for the same SFDR and SENS	Fewer ADCs and lower linearity needed at RFFE (lower DC power)	Use max possible RF summation that meets beam-related objectives; rapid benefit RF = 2 to 16, slows RF>16 (that is, RF subarray size)
Best ADC ENOB?	SFDR and SENS vs. DC power improves rapidly going ENOB = 4 to 8, then slows	Knee in Figure 7 to Figure 10	ENOB = 6 to 8 offers the best performance vs. DC power value

In general, 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. The knees in the plots show that there exists a sweet spot of performance when SFDR, sensitivity, and DC power burn are evaluated together. Diminishing returns exist as ENOB improves beyond the knee, and things deteriorate fast as ENOB degrades from the knee. Is every-element digital better in any of these situations? From a dynamic range efficiency perspective where DC power is handicapped, no. The benefits of every-element digital are in software-defined beamforming flexibility and adaptability. Extra power is burned to achieve this.

Table 4 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 5 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 cannot be operated to full scale, in practice.

Evaluating System Results

It is proposed that the Walden and Schreier ADC FOMs can be used to establish 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 presented while:

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

Table 4. Breaking Out Some Common Sample Scenarios

Must-Have Objective	Trade-Off	RF: Dig Sum	ADC ENOB	SFDR dB 1 Hz	SENS dBm 1 Hz	DC Power/Channel W
All-digital beamforming	High DC power	1:64	8.2	127	–185	2
All-digital beamforming < 1 W/channel	Degraded SFDR and SENS	1:64	7.2	124	–184	1
All-digital beamforming ~ 0.25 W/channel	Much degraded SFDR and SENS	1:64	4	112	–180	0.28
Lowest power	Much degraded SFDR and SENS; Combo of RF and digital BF	64:1 64:1 64:1	4 6 8	101 109 116	–173 –177 –180	0.057 0.061* 0.080
Best Possible SFDR and sensitivity at 1 W/channel	Combo of RF and digital BF	64:1 16:4 2:32	12 10.5 8	131 128 125	–185 –185 –184	1 1 1

*Slightly higher, but better value

Table 5. Using Some Real Processing Bandwidths: Note the Limitation of ADC Input Power and How It Varies with IFBW

IF Bandwidth (That is, Processing BW)	RF: Dig Sum	ADC ENOB	SFDR dB	SENS dBm	RF Input Level for SFDR dBm	Pre-ADC Signal Gain dB	RF Input Level to ADC dBm	DC Power/Channel W
1 MHz	1:64	8.2	87	–125	–37	15	–22	2
10 MHz			81	–115	–34		–19	
100 MHz			74	–105	–30		–15	
1 GHz			67	–95	–27		–12	
1 MHz	4:16		84	–124	–40	20	–20	0.6
10 MHz			77	–114	–37		–17	
100 MHz			71	–104	–34		–14	
1 GHz			64	–94	–30		–10	

Table 6. ADC vs. System FOM

	ADC FOMs	ADC System FOM (Proposed)	Units	What's Good?
Walden	$FOM_W = \frac{Power}{2^{ENOB} \times f_{s,Nyq}}$ $ENOB = \frac{SNDR - 1.76}{6}$	→ Same $ENOB_{system} = \frac{SNR_{system} - 1.76}{6}$	$\left(\frac{fJ}{conv - step}\right)$	Lower is better
Schreier	$FOM_S = SNDR + 10Log\left[\frac{f_{s,Nyq}/2}{Power}\right]$ dB	$FOM_S = SFDR + 10Log\left[\frac{f_{s,Nyq}/2}{Power}\right]$ dB	dB	Higher is better

We suggest the Schreier FOM can be modified by swapping in SFDR for SNDR to make a FOM that reflects two-tone linearity performance. Figure 11 and Figure 12 plot the system FOMs vs. RF: digital sum ratio.

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

$$NSD_{system,input} = -174\ \frac{\text{dBm}}{\text{Hz}} + NF \tag{1}$$

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

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

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

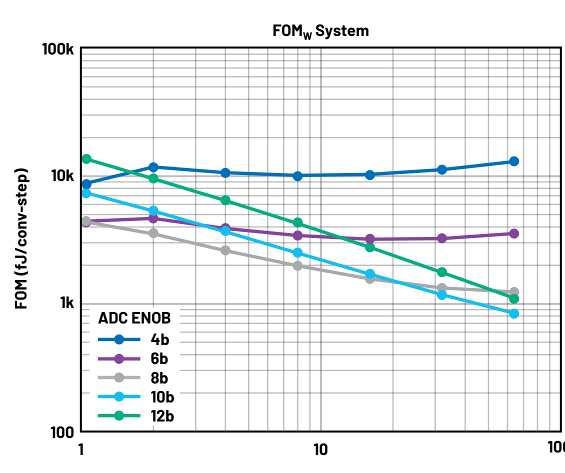

Figure 11. Walden system FOM (lower is better).

Table 7. Summary Observations

Topic	Observations
Sensitivity	The best sensitivity for DC power value occurs at high ADC ENOB (8 to 12) and high RF sum
	ENOB ~6 has merit at a low RF sum (all or mostly digital) but decreasing to ENOB = 4 to 5 is generally worse
SFDR	SFDR for DC power value is the same for ENOB 6 to 12 when using all-digital BF. As dynamic range increases, DC power increases, offsetting each other and holding the FOM constant
	The best SFDR performance for DC power value occurs at ENOB 8 to 12 and highest possible RF sum
	ENOB = 6 is ok at every-element digital, but when increasing RF sum to 2 or higher, ENOB 6 is an increasingly worse choice, while ENOB 8 to 12 is clearly better
	Over the RF sum range 2 to 8, ENOB 8 to 12 has equal merit
	At RF sum = 16 and above, ENOB 8 fades in preference, and ENOB 10 to 12 is the best choice
	Worse than the sensitivity case, ENOB = 4 to 5 is always bad for SFDR: worst value in any scenario

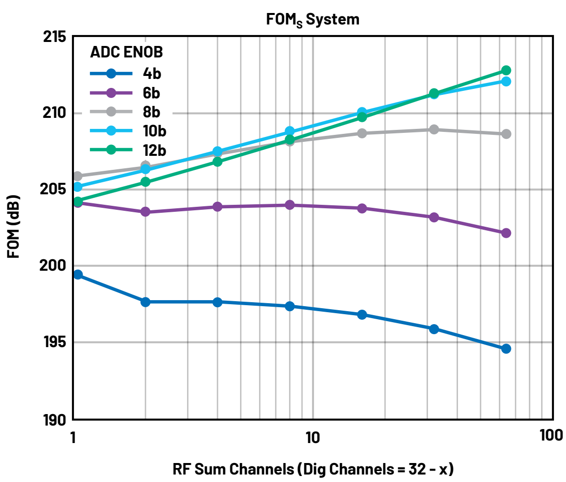

Figure 12. Schreier system FOM (Higher is better).

The phrase "best value" is meant in the sense of best return (that is, performance) for a given cost (that is, DC power burn). The FOMs assist in drawing best value conclusions because they normalize performance against DC power burn (see Table 7). Sensitivity observations are drawn from Walden (Figure 11, lower is better) and SFDR comments are drawn from Schreier (Figure 12, higher is better).

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 GSPS 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 the best compromise between dynamic range and DC power. Be careful how SNDR (ENOB) is defined and make sure to consider two-tone intermodulation performance with SNDR. 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.

You need to have a mission-critical reason to do high dynamic range, every-element digital beamforming. It 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. If beam attributes allow it, a small subarray of RF beamforming in front of each ADC is helpful in improving performance and lowering DC power. RF beamforming 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. 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.

References

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