Application Report

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S-Parameters for ADC32RF45: Modeling and Application

Sourabh Gupta, Nagarajan Viswanathan — *High Speed ADCs*

ABSTRACT

In this application report, S-parameters model for analog inputs of the ADC32RF45 is explained. As an application of the model, a matching network example is taken and step-by-step procedures to design the network is described. Simulation and lab results are analyzed and a strong correlation between simulation and lab is demonstrated validating accuracy and usefulness of the model.

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1 Introduction

S-parameters are frequency-domain quantities which are commonly used to model behavior of RF circuit components. Since the ADC32RF45 is an RF-sampling ADC, the availability of S-parameters of ADC32RF45 will enable the RF system designer to have models of complete RF-signal chains. It will help simulate the system upfront and optimize various components to meet desired specifications. This application report discusses how an S-parameter model for the ADC32RF45 is made and how it can be used by the system designer.

2 High-Speed ADCs in Receiver Chain

Figure 1 shows a receiver signal chain in a wireless infrastructure system employing RF sampling ADCs.

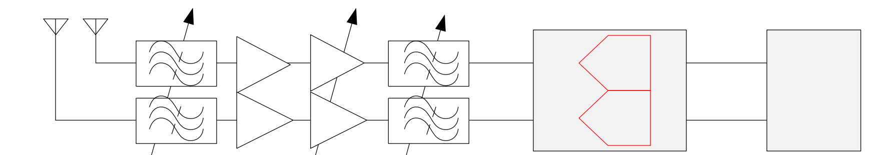


Figure 1. RF-Sampling ADC in RX Signal Chain

In RF sampling systems, the signal received by an antenna is filtered, amplified and filtered and sampled directly by a high-bandwidth ADC with its sampling rate in Giga-samples-per-second (GSPS) ,omitting any down-conversion stage in analog link. The frequency of the RF signal depends upon the standard being used, see Table 1.

Table 1. Frequency Band Examples

Standard	RF Signal Band
UMTS TDD1 TX/RX	1900 to 1920 MHz
UMTS TDD2 TX/RX	2010 to 2025 MHz
UMTS FDD TX	1920 to 1980 MHz
UMTS FDD RX	2110 to 2170 MHz
GSM (DCS) 1800-MHz TX	1710 to 1785 MHz
GSM (DCS) 1800-MHz RX	1805 to 1880 MHz
GSM (PCS) 1900-MHz TX	1850 to 1910 MHz
GSM (PCS) 1900-MHz RX	1930 to 1990 MHz

TI's ADC32RF45 is designed for RF sampling systems offering best-in-class performance with high linearity and low noise-density. In the RX signal chain, the out-of-band filter preceding the ADC plays a critical role. It rejects the signals aliasing from other Nyquist zones as well as any out-of-band interferer which may appear in-band in an interleaving-ADC's output.

To achieve desired in-band flatness and out-of-band rejection, it is imperative that the out-of-band filter be carefully designed taking the ADC's input impedance into account. Since the ADC's internal sampling network has finite bandwidth, knowledge of the ADC's transfer function under a given source impedance is equally important to meet overall in-band flatness and out-of-band rejection specifications. Figure 2 illustrates this scenario with a simplified RF signal chain diagram.

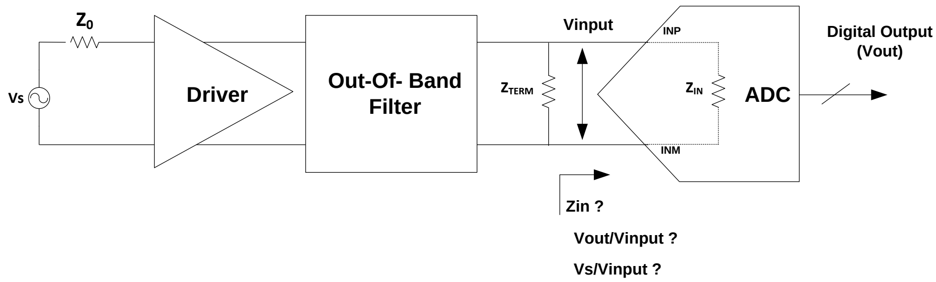


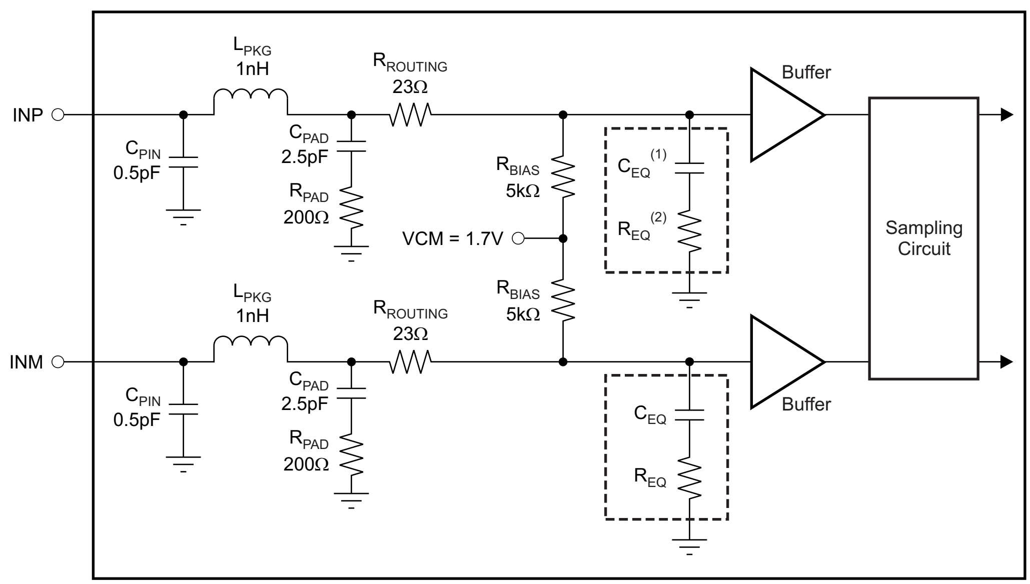
Figure 2. ADC Input Impedance and Transfer Function

3 Out-of-Band Filter Design With ADC Load

As explained in the preceding section, knowledge of the ADC's input impedance (Z_{IN}) and transfer function is important to extract the correct amount of out-of-band rejection and in-band flatness from an out-of-band filter and ADC assembly. This section explains how this information is provided.

3.1 Using Equivalent Network

Usually an equivalent network representing a sampling network inside an ADC is provided by extracting a netlist of various components in the sampling path. An example input equivalent network is shown in Figure 3, taken from the ADS41B49 datasheet (SBAS486).



(1) C_{EQ} refers to the equivalent input capacitance of the buffer = 4 pF.

(2) R_{EQ} refers to the R_{EQ} buffer = 10 Ω.

(3) This equivalent circuit is an approximation and valid for frequencies less than 700 MHz.

Figure 3. Equivalent Network for Analog Inputs in ADS41B49

The equivalent network can be used to find out the ADC's input impedance Z_{IN}. It can also be used to find the ADC's transfer function. However, the network remains accurate only for the sub-GHz range of frequencies by S11 at differential input port in Smith chart of Figure 4. Since the bandwidth of an RF sampling ADC is in the GHz range, an equivalent network approach can be used to represent the sampling network inside the ADC.

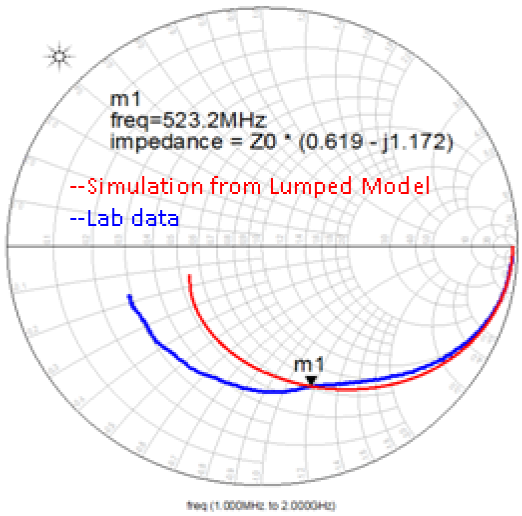


Figure 4. S11 Comparison Between Equivalent Network and Lab Data in ADS41B49

3.2 *Using 2-Port S-Parameters Model*

For a *bi-directional*, 2-port device, the input impedance and transfer function can be represented by S-parameters as shown in Figure 5. The S-parameters can be measured in the lab in the GHz range of frequencies using a *Vector Network Analyzer* (VNA).

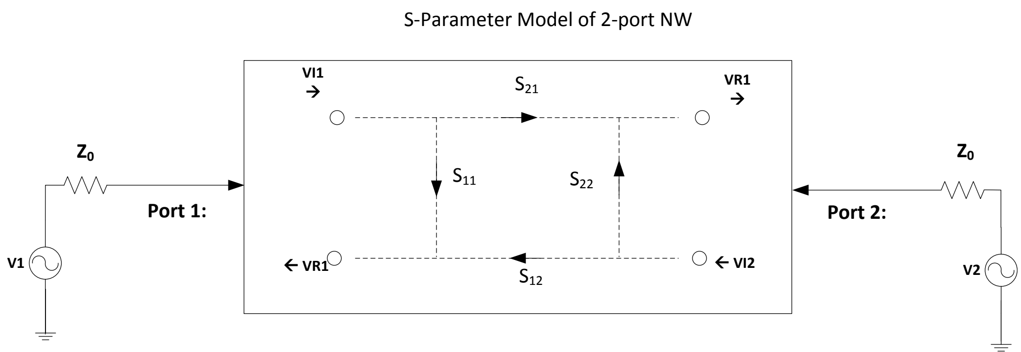


Figure 5. S-Parameter Model for a 2-Port Device

However, the ADC is not a bi-directional two-port device with one port being an analog input (differential) port and the other one being a digital output port, as shown in Figure 6. So the ADC does not fit into the definition of a conventional S-parameter and VNA cannot be directly used to characterize the ADC's S-parameter in a lab.

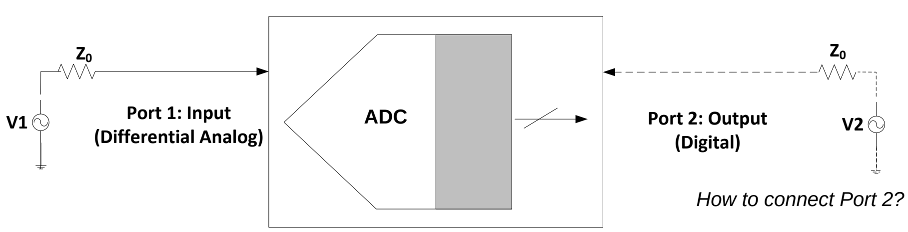


Figure 6. ADC as a 2-Port Network for S-Parameter Modeling

Taking a closer look at the definition of an S-parameters, observe that only S11 and S21 are of relevance for uni-directional 2-port devices such as ADC, since port 1 cannot be deactivated and the signal cannot be fed from port 2. A list of the 2-port S-parameter functions follows:

S11 = Reflected Voltage at port 1 / Incident Voltage at Port1 with port 2 deactivated

S21 = Reflected Voltage at port 2 / Incident Voltage at Port1 with port 2 deactivated

S12 = Reflected Voltage at port 1 / Incident Voltage at Port2 with port 1 deactivated

S22 = Reflected Voltage at port 2 / Incident Voltage at Port2 with port 1 deactivated

The conclusion of this observation is that if S12 and S22 can be **arbitrarily chosen as 0** so that port 2 never feeds any signal into the network, and measure S11 and S21 in lab, then the resulting model fits well into the S-parameter definition for bi-directional devices while representing a uni-directional device. Figure 7 shows the resulting S-parameter model for ADC, comparing it against a conventional equivalent network model. At high frequencies, accurate extraction of different components (package, ESD protection diode, termination or routing, and so forth) inside the chip becomes increasingly difficult, limiting the ability of the equivalent network to represent device characteristics. In such conditions, the S-parameter model becomes a superior alternative by working as input pin-to-output pin model made from measurement data collected in the lab through sophisticated RF-measurement techniques.

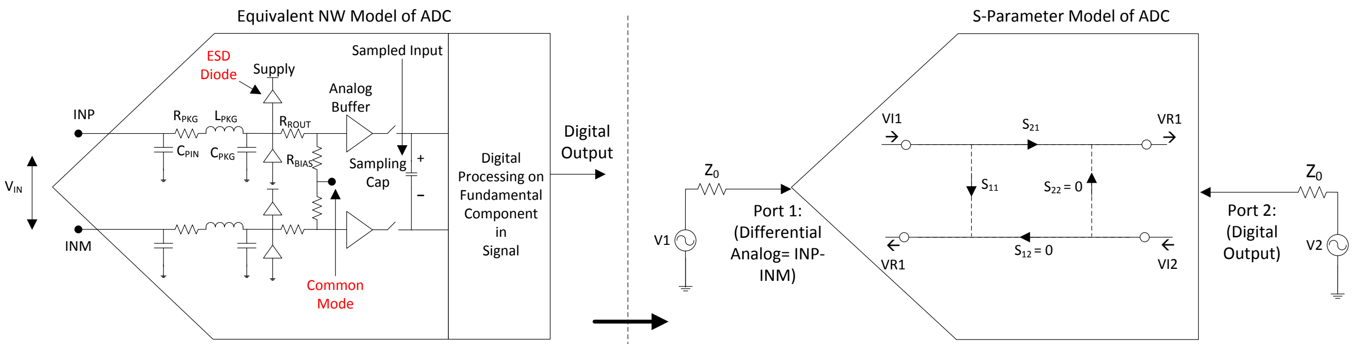


Figure 7. Equivalent NW Model and S-Parameter Model for ADC With S12 and S22 Chosen as 0

In this model, S11 carries information about the ADC's input impedance (Z_{IN}), whereas S21 carries information about the ADC's transfer function when the system (source) impedance is Z_0. VI and VR represent incident and reflected voltage waves at a given port.

Note that the S-parameter model does not represent small signal performance metrics such as noise (SNR) and non-linearity (SFDR) of the device. However, it represents the large signal transfer function from the ADC input to digital output including digital signal processing, if any, used inside the ADC.

Also note that, all S-parameters mentioned in this report are 'differential mode' quantities. To ease the understanding of the model, the 'DD' sufix is not added. For example, SDD11 is mentioned as S11 in this report.

4 S-Parameters for ADC32RF45

Figure 8 and Figure 9 show S11 and S21-parameters, respectively, for the ADC32R45 for DC to 5-GHz range.

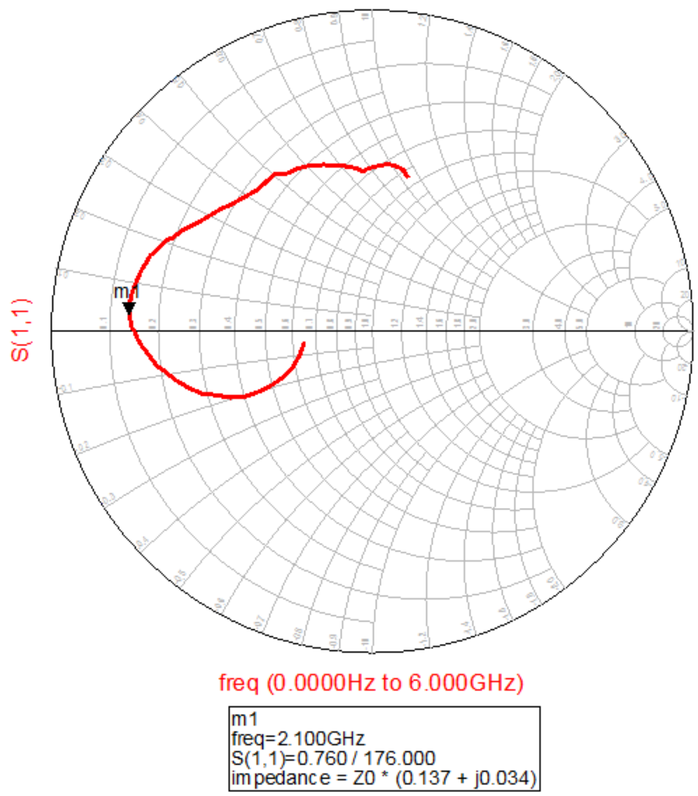


Figure 8. Differential S11 on Smith Chart (Z_0 = 100 Ω)

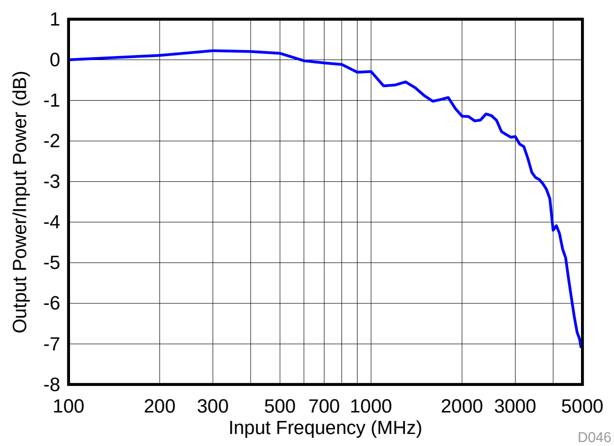


Figure 9. S21 Magnitude (Z_0 = 100 Ω)

5 Using S-Parameter Model in System Design

The ADC's S-parameter model can be used in a general purpose simulator as shown in Figure 10. An ideal 1:1 transformer can be used to convert a differential mode input signal into a single-ended input signal to feed the analog port of an S-parameter model.

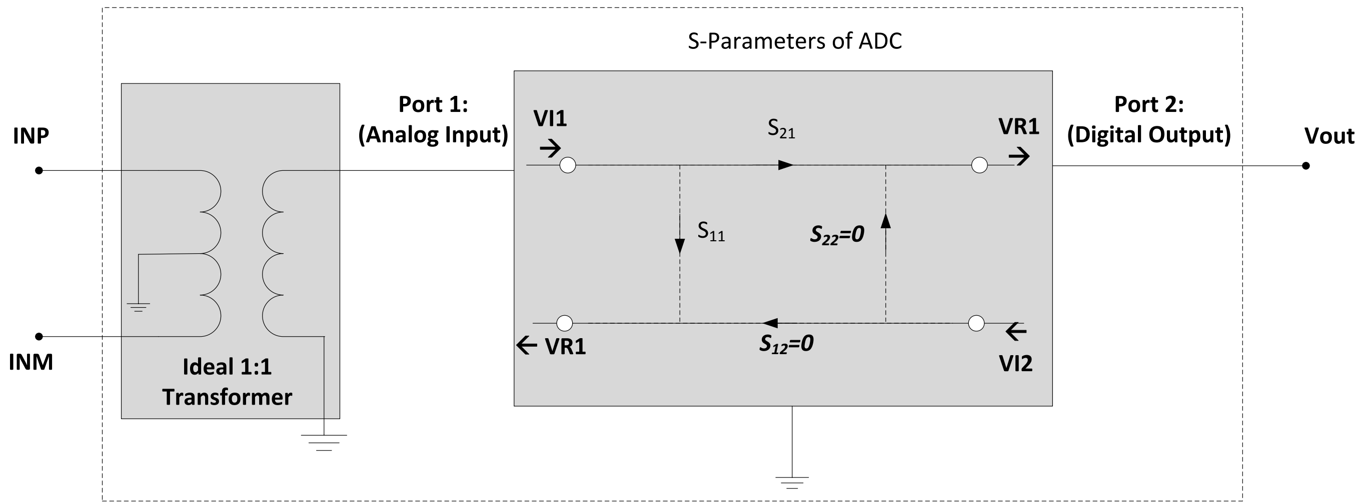


Figure 10. Ideal 1:1 Transformer in Front of S-Parameter ADC Model

The digital port can be left open as shown in Figure 10. Voltage at the digital port is the digital output of the ADC.

5.1 *Matching Network Design Example*

Objective: Purpose of a matching network is to cancel the reactive component of the load and translate the real part such that full available power is delivered into the real part of the load impedance. The ADC's input impedance is complex in nature with frequency-dependent real and imaginary parts. However, in a small band of frequencies, it may not vary significantly and can be translated to match the source impedance using standard LC matching networks.

An example matching network is designed which translates the ADC's input impedance into 100 Ω within a signal band of 1.7 GHz to 2.0 GHz. As shown in Figure 11, the driving source has 100-Ω differential impedance which is different than the ADC's impedance in signal band. Hence, a matching circuit is required to deliver maximum power from source to the ADC.

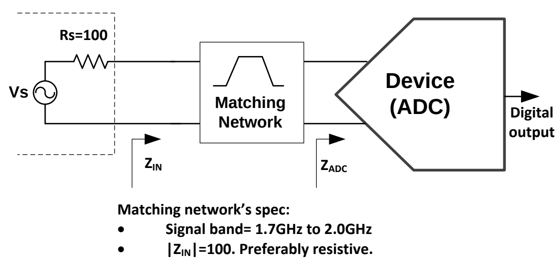


Figure 11. Matching Network Example

5.1.1 Design Procedure

In a frequency band of 1.7 GHz to 2.0 GHz, the S11 parameter of the device changes from 0.67∠163° to 0.7∠154° which is equivalent to a differential impedance of 25 Ω∠35° to 29 Ω∠50°, respectively, as shown in Figure 12. Using the S11 information of the device in a Smith chart, an LC matching network can be designed.

Figure 12 shows S11 of the device on a Smith chart for 1.7 GHz to 2.0 GHz. To find the optimum matching network for complete band:

1. Choose a near mid-band point of 1.82 GHz with S11 = 0.68 ∠160°. Normalized impedance at this point is z = 0.193 + j 0.169.

2. Next, move it counter-clockwise to point B on the constant resistance circle by adding a series reactance of x = –0.4 – 0.193 = –0.593.
3. Then move from point B to point C (S11 = 0,0°) counter-clockwise on the constant conductance circle by adding a shunt susceptance of b = 0 – 0.2 = –0.2.

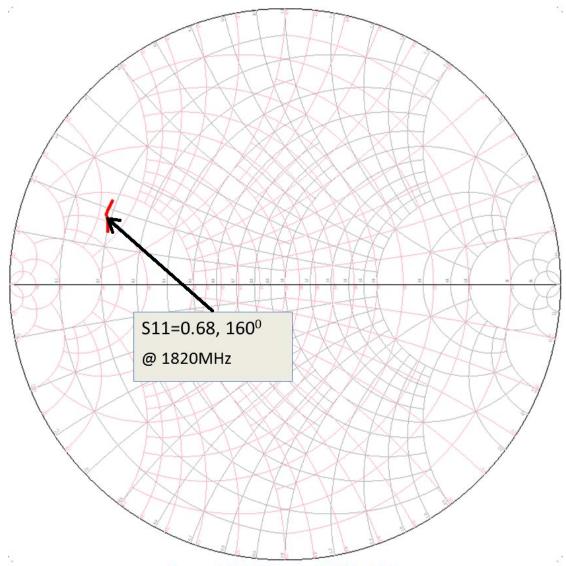


Figure 12. S11 of Device on Smith Chart

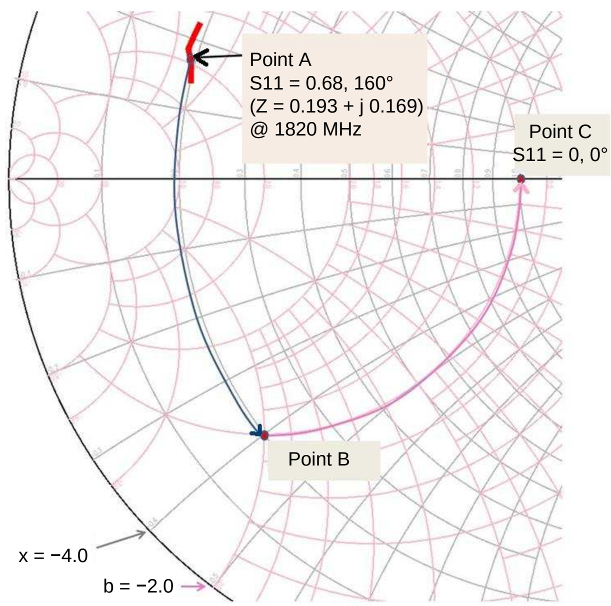


Figure 13. Finding Matching Network Using Smith Chart at 1.82 GHz

4. Finally, since the required series reactance has a negative sign, it can be realized with capacitance. Similarly, required shunt susceptance can be realized by inductance. The resulting matching network is a single-ended structure. It can be converted to equivalent differential structure as shown in Figure 14.

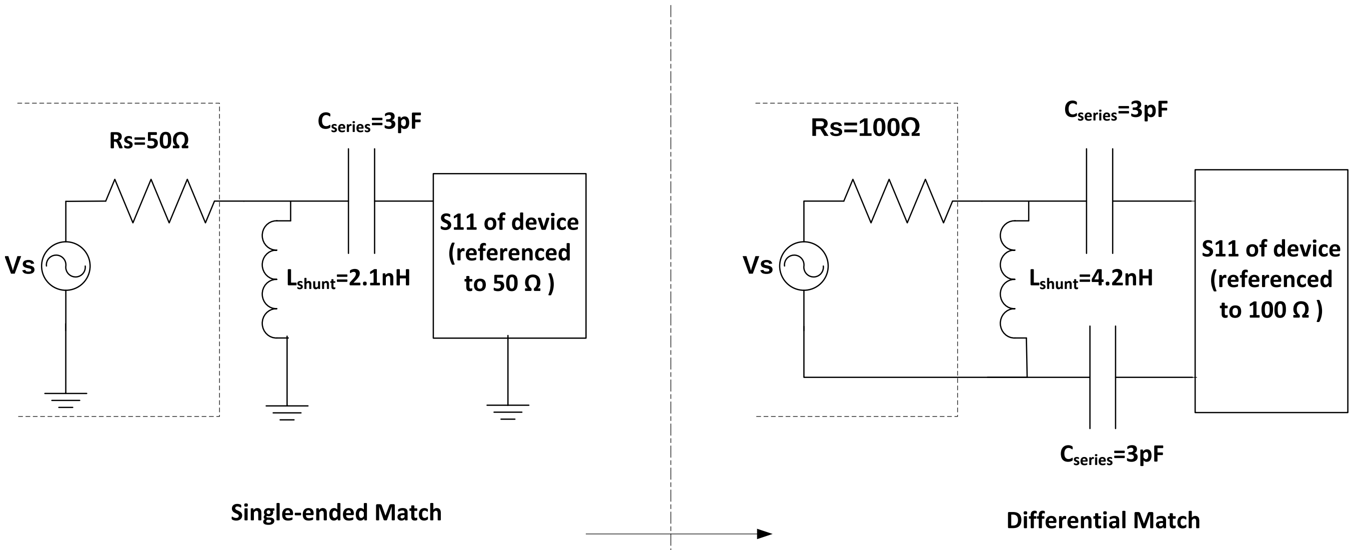


Figure 14. Single-Ended and Equivalent Differential Matching Network

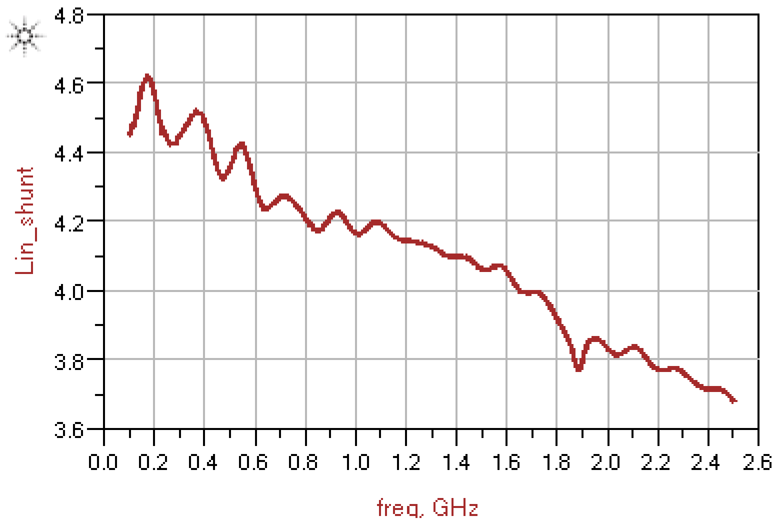
Since design values of each component may not be available in the lab, they must be replaced with the nearest available values as shown in Table 2.

Table 2. Matching Components for Series C and Shunt L Network

	Required Series x	Required Shunt b
Normalized	–0.569	–2
De-Normalized (to 50 Ω)	28.45	0.04
	Equivalent Series cap, pF	**Equivalent Shunt ind, nH**
Single-Ended Match	3.0	2.1
Differential Match	3.0	4.2
Nearest Values Used in Lab Expt	2.7	3.9

While choosing a surface-mount-device (SMD) component to realize the L and C value of a matching network, note the following:

1. The SMD components (both capacitor and inductor) come with inherent parasitic, and a frequency profile. Always see the self-resonating specification provided in the manufacturer datasheet.
2. Sometimes the component values, especially the inductor, change significantly over frequency (see Figure 15). Since required components are not too many, it may be helpful to characterize the SMD components separately on a coupon board by collecting S-parameter data. Then choose a part which provides the required value in frequency band of interest.



The frequency profile was obtained through an S-parameter characterization of the component in the lab.

Figure 15. Frequency Profile: 0402 Size, 4.7-nH Inductor Over 2-GHz Range

5.1.2 Results

The matching network of Figure 14 is redrawn in Figure 15 for simulation in the Advanced Design System (ADS) tool using the S-parameter model of the device. To make a correlation, the component values chosen in simulation were the same values used in lab. The simulation deck is shown in Figure 16.

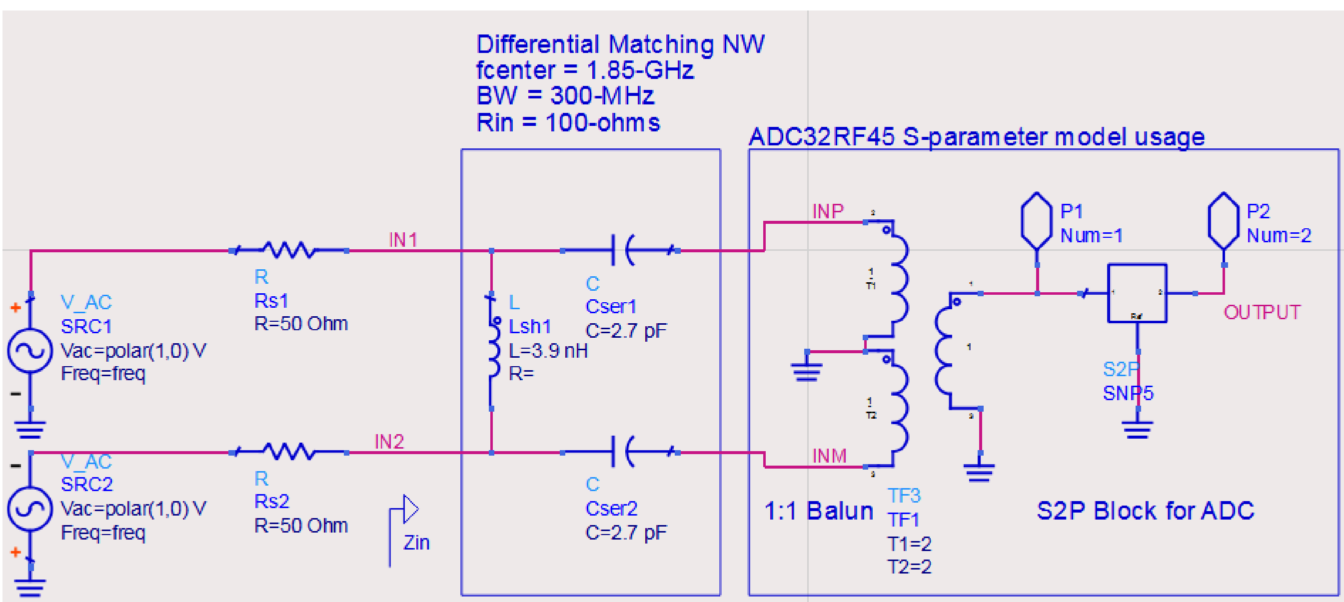


Figure 16. Simulation Deck for Matching Network Analysis

5.1.2.1 Simulation Result for S11

When the matching network is used, the magnitude of impedance in the desired signal band improves to nearly 100 Ω. In the Smith chart, 100-Ω constant magnitude of impedance is represented by a vertical line crossing zero. Table 3 lists the improvement in S11 by adding a matching network, while Figure 17 shows the S11 movement on a Smith chart before and after the matching network was added.

Table 3. Effect of Match on Z_{IN}

Freq, GHz	Condition	S11diff[1]		Z_{IN}(diff), Ω	
		Mag	Angle(degree)	Mag	Angle(degree)
1.7	without matching ckt	0.67	163	24	35
1.76	without matching ckt	0.68	162	25	39
1.82	without matching ckt	0.68	160	26	41
1.88	without matching ckt	0.7	159	26	45
1.94	without matching ckt	0.7	156	28	48
2	without matching ckt	0.7	154	29	50
1.7	with matching ckt	0.44	84	108	47
1.76	with matching ckt	0.33	76	116	35
1.82	with matching ckt	0.21	67	117	22
1.88	with matching ckt	0.1	48	114	8
1.94	with matching ckt	0.04	-121	96	-4
2	with matching ckt	0.14	-137	82	-11

(1) S11diff is referenced to 100-Ω impedance.

Figure 17 highlights S11 movement from 1.7 GHz to 2.0 GHz on the Smith chart when a matching network is added.

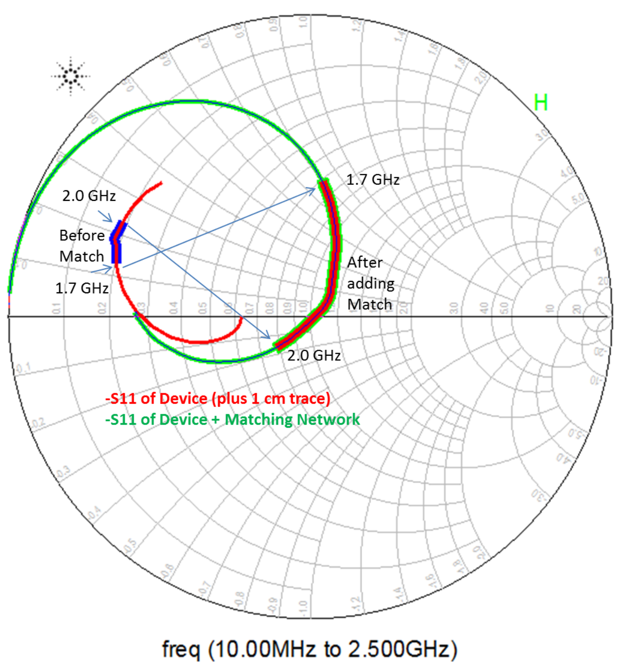


Figure 17. S-Parameters Before and After Adding Matching Network

Figure 18 shows how resistive and reactive parts of input impedance change when a matching network was added.

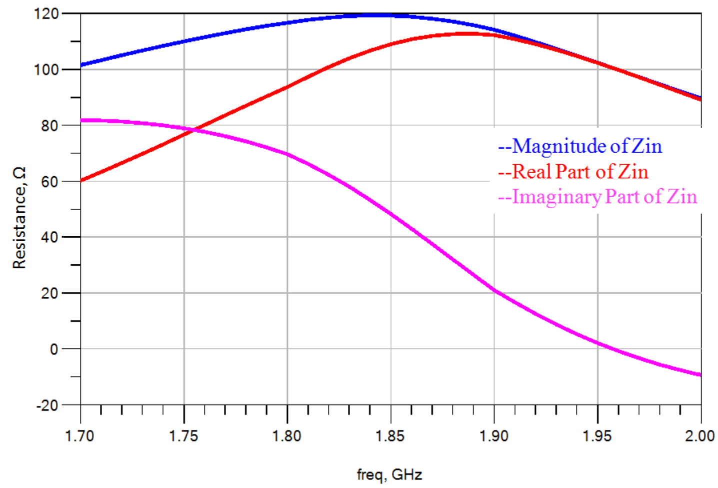


Figure 18. Effect of Match on Magnitude, Resistive and Reactive Parts of Impedance

5.1.2.2 Simulation and Lab correlation for S11

Figure 19 shows S11 comparison between simulation and lab results. Though results correlate reasonably well, the small discrepancy comes from the fact the components used in the lab have a certain frequency profile while the ones used in simulation are constant over any range of frequency. Using equivalent S-parameters of components in the simulation deck of Figure 19 will result in stronger correlation between lab and simulation results.

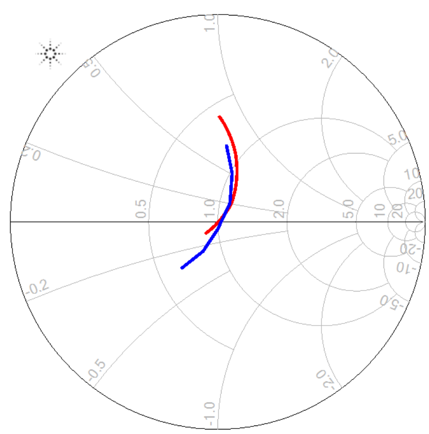


Figure 19. Comparison Between Lab and Simulation for S11

Figure 20 shows simulation and lab correlation between magnitude of input impedance after a matching network is added.

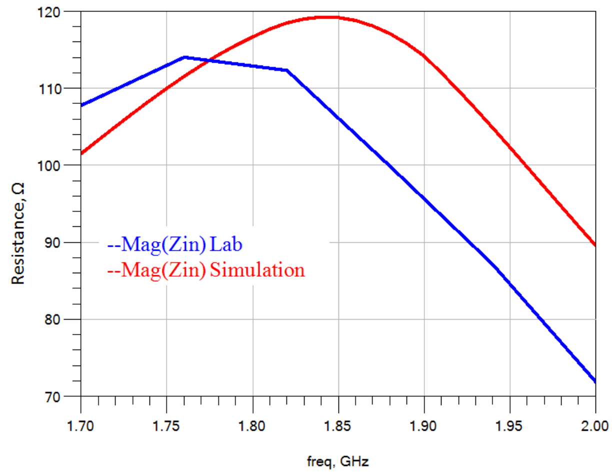


Figure 20. Comparison Between Lab and Simulation for Input Impedance

5.1.2.3 Simulation Result for S21

Reiterating that the S-parameter model of the ADC contains S21 information as well, this information can be used in simulation to see the effect of a matching network on the ADC's output power. Since the matching network improves the ADC's looking-in impedance to near 100 Ω, it results in improvement in power delivered by source to the ADC as well.

The simulation result in Figure 21 shows the addition of a matching circuit increases power delivered to the ADC by more than 3 dB in signal band.

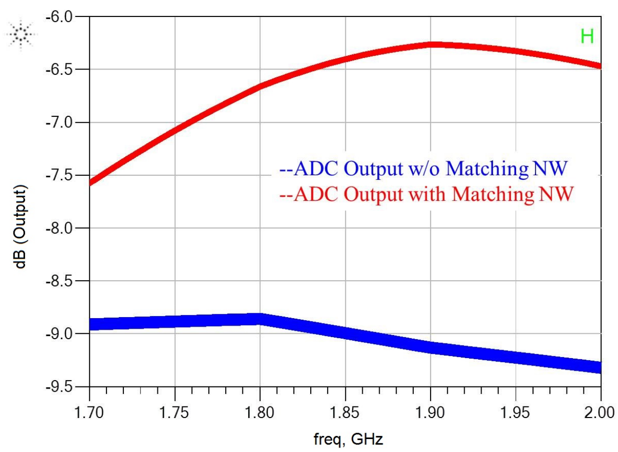


Figure 21. Effect of Matching Network on Power Delivered to ADC

5.1.2.4 Simulation and Lab Correlation for S21

The ADC output power data was collected to see the correlation with simulation results. The lab data shows that the matching network provided nearly 4-dB improvement in ADC output in a signal band of 1.7 GHz to 2.0 GHz, as shown in Figure 22. The improvement was nearly 3 dB in simulation showing a strong correlation with lab data. As explained in the case of S11, the frequency profile of components used in the lab was the reason behind the small discrepancy between lab and simulation results.

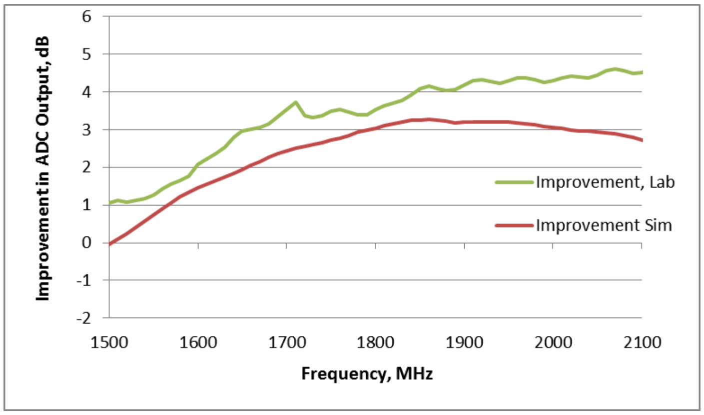


Figure 22. Comparison Between Lab and Simulation for Improvement in ADC's Output Power

6 Conclusion

In conclusion, the S-parameter model of an ADC provides useful information about ADC's looking-in impedance which must be considered while designing a matching circuit or band-pass filter preceding ADC. The S-parameter model also provides information about the ADC's transfer function which includes the frequency response of the buffer inside ADC. The ADC's S21 must be considered when looking at overall frequency response in a signal chain involving ADC. In this report, a matching circuit was designed and evaluated as an example to describe how the ADC's S-parameters can be used in system design. Simulation results were validated by lab data indicating that model can reliably be used up to 2nd Nyquist range of frequencies.

7 References

1. *ADC32RF45 Dual-Channel, 14-Bit, 3.0-GSPS, Analog-to-Digital Converter* (SBAS747)
2. *ADC32RF45 EVM User Guide* (SLAU620)

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