

MPC57xx SAR ADC Implementation and Use

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1 Introduction

Analog-to-Digital Converters (ADCs) are used in a rapidly increasing number of automotive applications. From simply monitoring DC voltages to supporting radar detection of obstacles in ADAS solutions, ADCs find wide acceptance in automotive Micro Controller Units (MCUs). The highly integrated MPC57xx MCUs on the market today incorporate high performance ADCs supporting up to 84 channels with various combinations of Sigma Delta (SD) ADC, enhanced queued eQADC, and Successive Approximation (SAR) ADC architectures in the same device. In these advanced MCUs, conversions from multiple types of analog inputs are supported in real time with a minimum of control required by the CPUs inside the MCU.

Depending on the system application requirements, the MPC57xx devices use three different ADC architectures:

- eQADC (an RSD solution)
- Successive Approximation Register (SAR)
- Sigma Delta modulator (SD)

The SAR is available in two speed variants - a 1 MSPS (Mega Samples Per Second) SAR and 400 KSPS (Kilo Samples Per Second) SAR.

This application note discusses SAR ADC implementation and use in the MPC57xx family of devices. The document includes the following topics:

- MPC57xx Device Family ADC implementation

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- MPC57xx SAR ADC features
- Designing for best ADC performance
- Calibrating the SAR to minimize gain error and offset error
- Initializing the SAR ADC

2 MPC57xx ADC Integration and Feature Sets

Freescale supports a powerful family of MCUs focused on the automotive market space. Depending on the application, an MCU will contain various numbers of SAR ADCs, eQADCs and/or SD ADC's. The following table lists the number of ADCs, type of ADC, and number of inputs for each device in the MPC57xx family.

Table 1. ADC support in the MPC57xx family

Device	1 MSPS SAR ADC	400 KSPS SAR ADC	eQADC (RSD)	SD ADC	Total number of inputs	Target applications
MPC574xG	2	-	-	-	106	Safety / body motor control application, lower end requirements
MPC577xK	4	-	-	8 ¹	25 (SAR) 8 (SD)	ADAS application, Radar interface high end requirement
MPC574xP	4	-	-	-	25	Safety / body Motor Control application, mid-range requirements
MPC5746M	-	8	-	8 ²	60	Powertrain application, mid-range requirements
MPC5777M	-	12	-	12 ²	84	Powertrain application, high end requirements
MPC5776C	-	-	2	4 ²	48	Powertrain application, high-end requirements, compatible with MPC5676R
MPC5746R	4	-	-	3 ²	52 (SAR) 12 (SD)	Powertrain application, mid-range requirements

1. 320 MHz SD ADC for Analog Front End (AFE) radar interface, up to 5 MHz input bandwidth
2. 16 MHz SD ADC for engine knock processing, up to 300 kHz input bandwidth.

Each of the SAR ADCs supports similar functions such as multiplexed inputs, normal conversions, injected conversions, DMA of conversion data to System RAM, and interrupt generation. The following table summarizes features, and differences exist between the SAR ADC implementations supported for each SAR type .

Table 2. SAR ADC comparison table

Parameter	1 MSPS SAR ADC	400 KSPS SAR ADC	200 KSPS SAR ADC (input monitoring)
Resolution	10 or 12 bits	12 bits	12 bits
Conversion Time	1 microsecond conversion time	2.5 microsecond conversion time	5.0 microsecond conversion time
Clock	80 MHz	14.6 MHz	14.6 MHz

Table continues on the next page...

Table 2. SAR ADC comparison table (continued)

Parameter	1 MSPS SAR ADC	400 KSPS SAR ADC	200 KSPS SAR ADC (input monitoring)
Integration Strategy	Low ADC instance count (2 to 4 ADCs per device), high input channel count per ADC	Higher ADC instance count (8 to 12 ADCs per device), low input channel count (4 to 8 inputs) per ADC	Single ADC instance per device, monitors all inputs (60 inputs or 84 inputs, device dependent)
Inputs	Up to maximum 96 channels (32 A/D inputs, 32 on-chip inputs, and 32 external inputs)	typically 4 to 8 inputs	Supports up to 128 channels. Supports monitoring of all other SAR ADC inputs and Sigma-Delta ADC inputs in the device
Operating Modes	3 modes: Normal / Injected / CTU	2 modes: Normal / Injected	2 modes: Normal / Injected
Scanning Modes	One shot, chain, and continuous modes of scanning	One shot, chain, and continuous modes of scanning	One shot, chain, and continuous modes of scanning
Presampling	supported	supported	supported
Abort	Abort capability for either a single channel or chain in Normal or Injected modes	Abort capability for either a single channel or chain in Normal or Injected modes	Abort capability for either a single channel or chain in Normal or Injected modes
Analog Watchdog	supported	supported	supported
DMA	supported	supported	supported
Interrupts	Interrupt for the following conditions:	Interrupt for the following conditions:	Interrupt for the following conditions:
	End of conversion of single channel for both normal, injected conversions	End of conversion of single channel for both normal, injected conversions	End of conversion of single channel for both normal, injected conversions
	End of conversion chain for both normal, injected conversions	End of conversion chain for both normal, injected conversions	End of conversion chain for both normal, injected conversions
	End of CTU conversion	No CTU interrupt	No CTU interrupt
	Watchdog thresholds crossover	Watchdog thresholds crossover	Watchdog thresholds crossover
Calibration	Software Initiated Calibration	Automatic, hidden from user	Automatic, hidden from user
Self Test	Integrated Self Testing feature, software driven	Uses SAR ADC B supervisor for monitoring test channel	supported: Test channel impedance comparison to external input impedance
Triggers	Trigger from Cross Triggering Unit (CTU)	Trigger sources from external pins and GTM channels	Trigger sources from external pins and GTM channels
CTU / BCTU	Supported	None	None

3 SAR ADC integration examples

The MPC57xx family of devices integrates 1 MSPS SAR ADCs, 400 KSPS SAR ADCs, and 200 KSPS SAR ADCs depending on application requirements. 1 MSPS SAR ADC integration typically includes the following:

- Self Test logic in each SAR ADC
- Calibration logic initiated by software

SAR ADC integration examples

- Triggers from Cross Triggering Logic
- Triggers from eTPU and external sources
- Monitoring of internal voltages

Figure 1 illustrates 1 MSPS SAR ADC integration in the MPC5746R device.

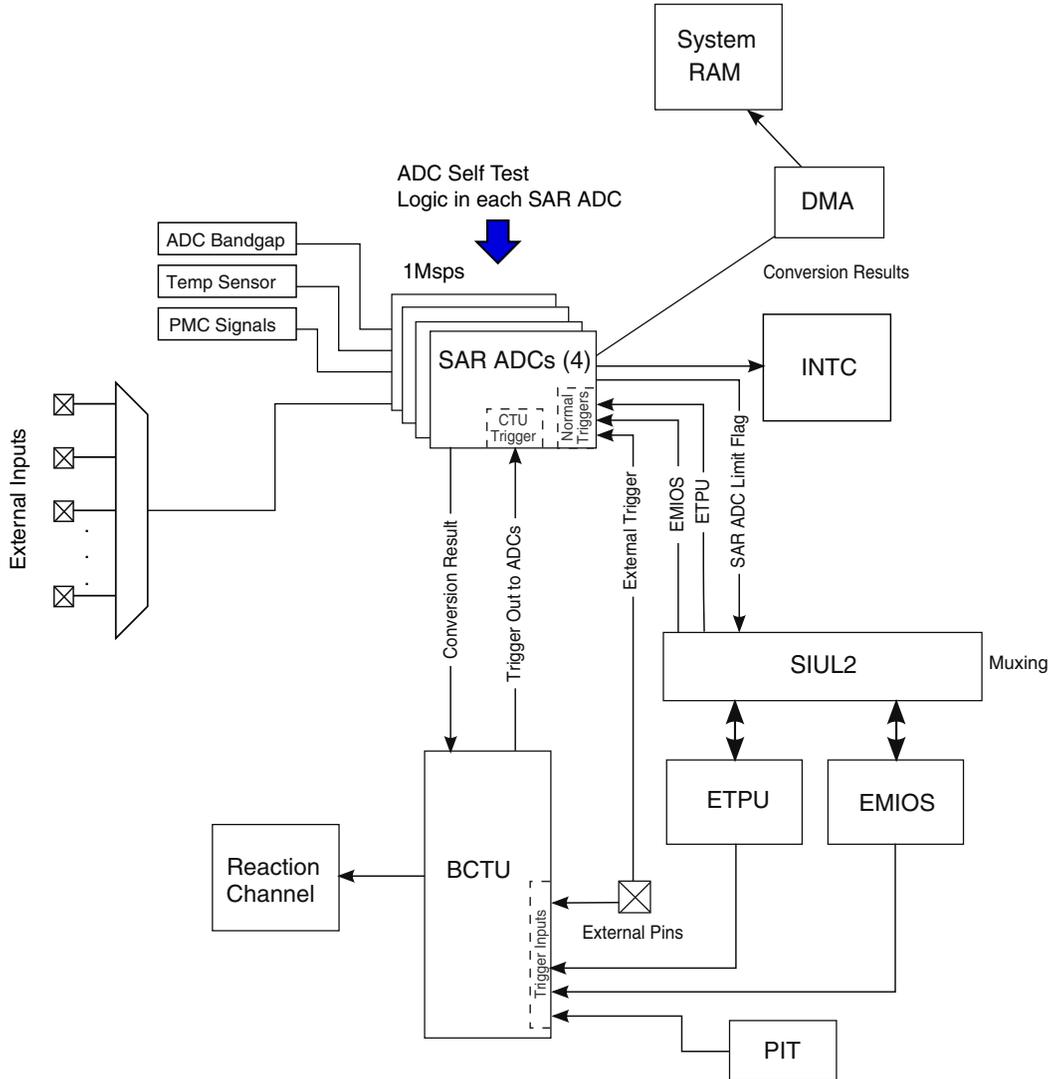


Figure 1. 1 MSPS SAR ADC integration

400 KSPS and 200 KSPS SAR ADC integration typically includes the following:

- Self Test of 400 KSPS SAR ADCs supported by the 200 KSPS SAR ADC_B
- No Calibration needed
- No CTU logic support
- Triggers from external sources such as Generic Timer Module (GTM)

Figure 2 illustrates 400 KSPS and 200 KSPS SAR ADC implementation in the MPC5777M device.

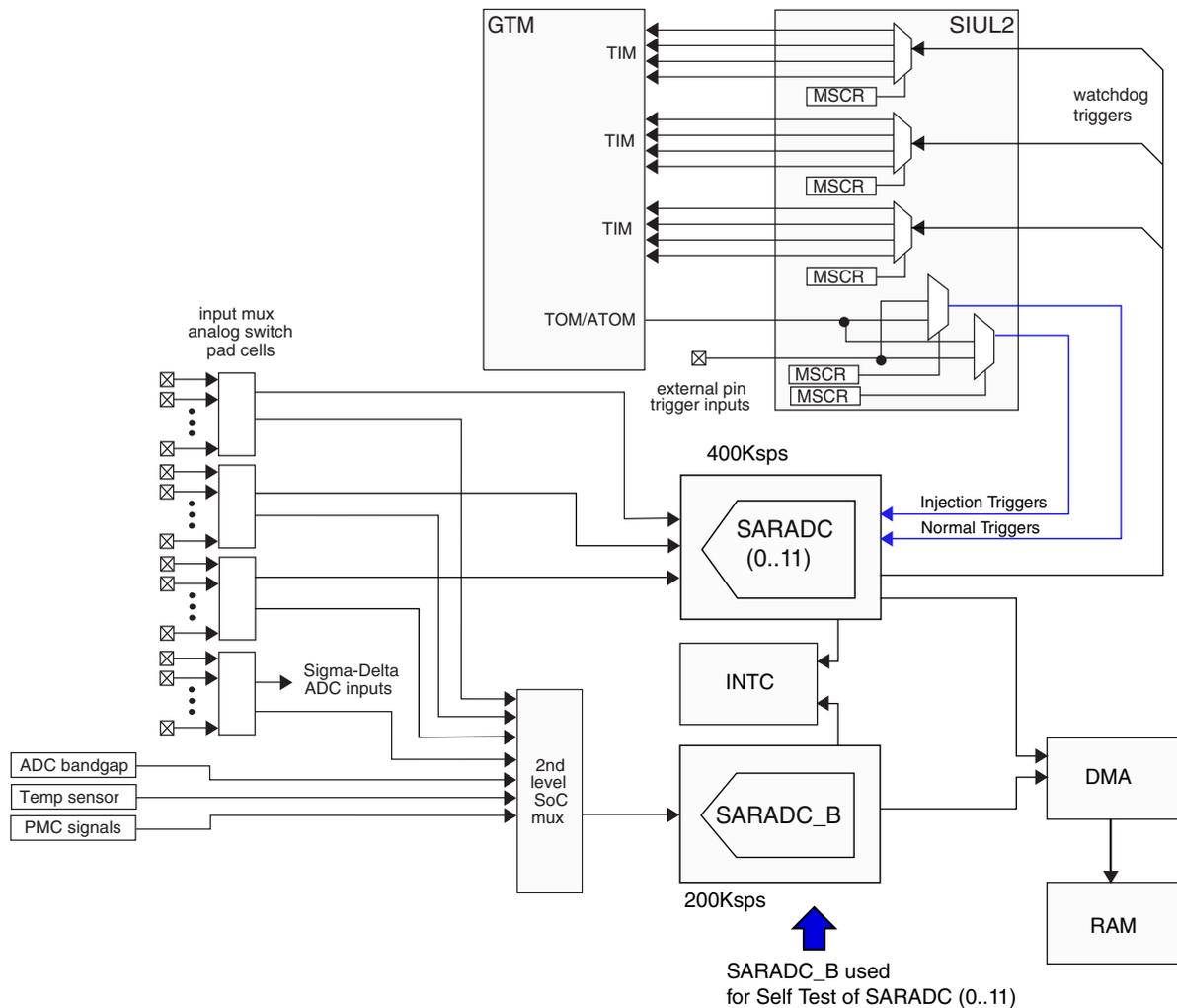


Figure 2. 400 KSPS and 200 KSPS SAR ADC integration (MPC5777M example)

4 Designing for best possible performance

This section provides guidelines to achieve the best dynamic performance from a Successive Approximation Register (SAR) ADC. There are several parameters defining performance for an ADC [4]. This document concentrates only on dynamic parameters and how to achieve maximum dynamic performance. Signal-to-Noise Ratio (SNR), Total Harmonic Distortion (THD), and Signal-to-Noise and Distortion (SINAD) are the most common dynamic specs for ADCs.

These recommendations are supported by theory and silicon test data which was collected at Freescale on a Bench Validation board for the MPC57XX device family. Even though silicon results are shared for a 12-bit SAR ADC only, guidelines are applicable for any other SAR ADC evaluation. It is strongly recommended to validate the dynamic performance in addition to adhering to guidelines in this note.

The [Figure 3](#) below shows a typical ADC interface in a System on a Chip (SoC). It consists of:

1. Input signal: Signal conditioning circuit to feed input analog signal to the ADC
2. ADC Clock: Clock synthesis circuit to provide required clock frequency to the ADC
3. ADC Supply & Reference: Power supply circuits to provide analog and reference supplies to the ADC

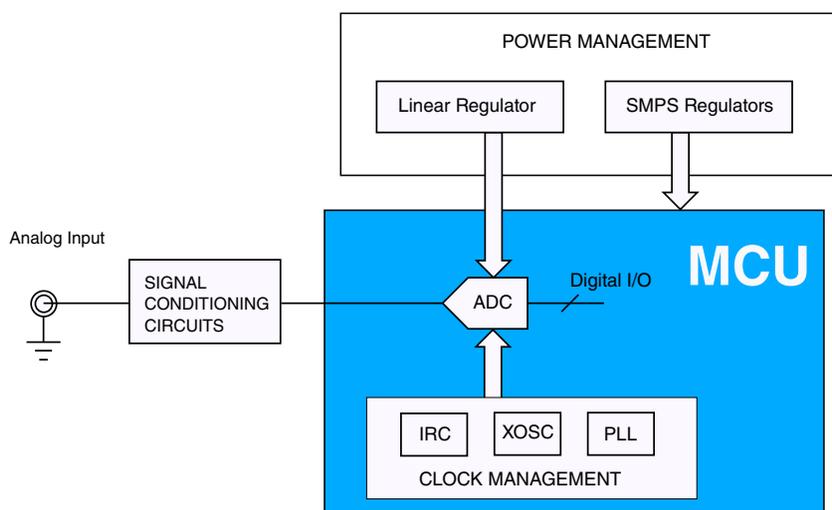


Figure 3. Typical ADC in an SoC

Equation 1 on page 6 gives the relation between ADC output, input and reference voltage for an ideal SAR ADC.

$$ADC \text{ OUTPUT CODE} = V_{IN} \left[\frac{2^N}{V_{REF}} \right]$$

Equation 1

V_{IN} = Analog input voltage

V_{REF} = ADC reference voltage

N = resolution of the ADC (number of bits)

From Equation 1 on page 6 it is clear that any noise at the input and reference will have direct impact on the output voltage. Noise at the ADC clock input will also impact the ADC performance. To measure true performance of an ADC, performance of all these circuits should be better as compared to ADC. Table 3 shows the effect of external noise on the overall performance of the ADC. Here external noise refers to input signal source noise, clock jitter related noise, ADC reference voltage noise or combination of all. From Table 3 it is clear that to get true performance of ADC, quality of external system should be at least 10 dB better than Device Under Test (DUT). In this application note, basic circuit details, their importance and results are shared for an ADC input, clock and supply interfacing blocks.

Table 3. Effect of external circuit noise on ADC performance

VREF (V)	ADC SNR (dB)	ADC Noise (rms μ V)	External Circuit Noise (dB)	External Circuit Noise (rms μ V)	System SNR (dB)	System Noise (rms μ V)	Error in measured SNR (dB)
5	70	559	90	56	70.0	562	0.0
5	70	559	85	99	69.9	568	-0.1
5	70	559	80	177	69.6	586	-0.4
5	70	559	76	280	69.0	625	-1.0
5	70	559	70	559	67.0	791	-3.0

4.1 Input circuit

The SAR ADC consists of a sample-and-hold circuitry to acquire the input voltage V_{IN} , a comparator, a successive approximation register sub-circuit, and an internal reference capacitive Digital to Analog Converter (DAC). This DAC supplies the comparator with an analog voltage equivalent of the digital code output of the SAR, for comparison with V_{IN} . Any SAR ADC will have two phases: sampling phase and conversion phase. During the sampling phase the input has to settle to the less than or equal to quantization level, i.e. 0.5 LSB. In the sampling phase, the sample and hold switch is closed, thereby charging the internal SAR ADC capacitors. During the conversion phase, the sample and hold switch is open and the SAR approximates its registers to the held V_{IN} .

The Input signal conditioning circuit typically consists of buffer followed by a first order RC-low pass filter. [Figure 4](#) shows a simple mixer circuit using an ideal Op Amp.

In the input circuit, the RC filter serves two purposes, it limits the amount out-of-band noise arriving at the ADC input and helps to attenuate any voltage kicks from the ADC sampling. Low pass filter RC bandwidth is a function of input frequency, resolution, sampling time of ADC. For a given RC bandwidth, selection of the R and C values depends on the Op Amp driving capability and ADC Input channel capacitance. The lower limit on the R value comes from the Op Amp. There is an upper limit on C also due to the Op Amp capability. The Op Amp cannot drive big capacitance values in the order of tens of nF. [Figure 6](#) shows an FFT plot using $R = 1 \text{ Ohm}$ and $C = 47 \text{ nF}$. [Figure 6](#) clearly shows that the Op Amp is not able to drive big capacitances such as 47 nF and due to this quality of the input signal is distorted -- notice the harmonic components in the FFT at the output of the ADC. The lower limit on the capacitance is a function of SoC input sampling capacitance. There is a limit on the boundary values of R and C, but within the range any value of R and C is allowed. Freescale recommends checking the ADC performance on silicon to get optimal R and C values. [Figure 5](#) shows a typical FFT plot with $R = 36 \text{ Ohm}$ and $C = 3 \text{ nF}$.

For capacitor, selection of type of dielectric material is important. Capacitor voltage coefficient determines the THD of the system. Select the capacitor with low voltage coefficient. Silver Mica, polypropylene, polystyrene, and COG/NPO types have lower voltage coefficient as compared to other types. Generally COG/NPO types are readily available in wide range and with different foot print sizes.

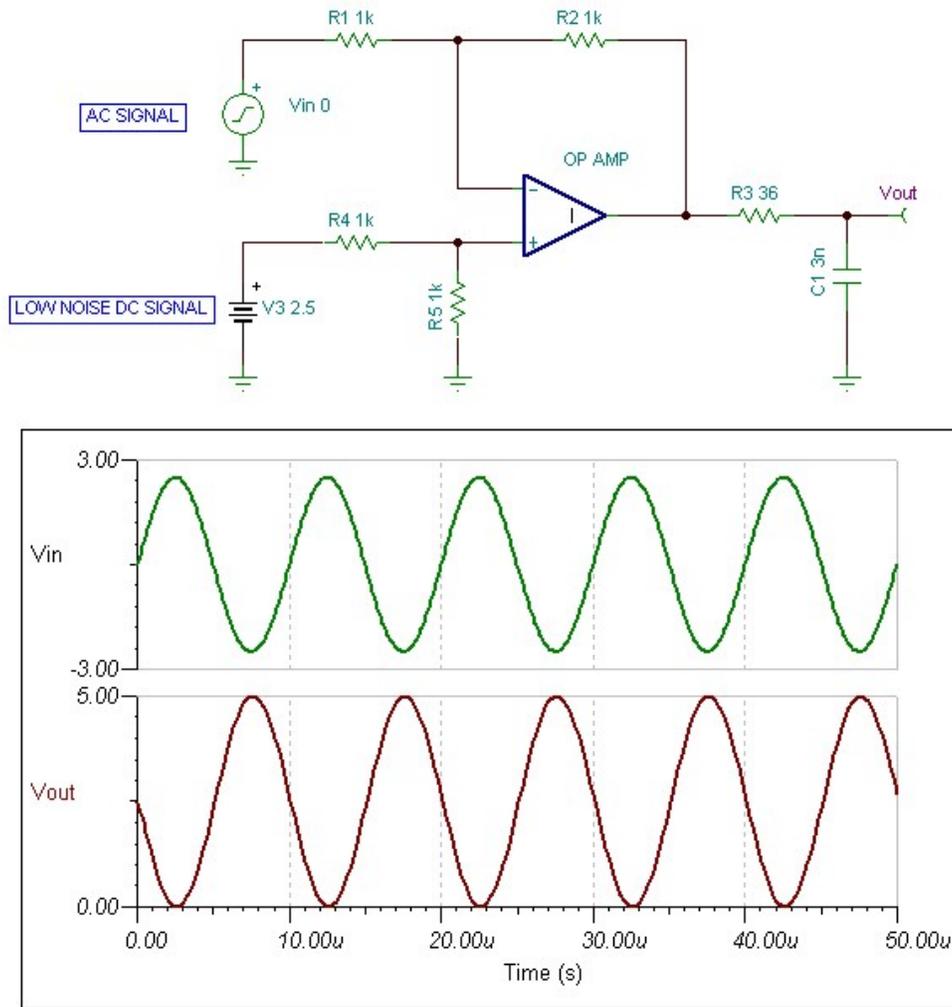


Figure 4. Typical Op Amp driver circuit input and output waveforms

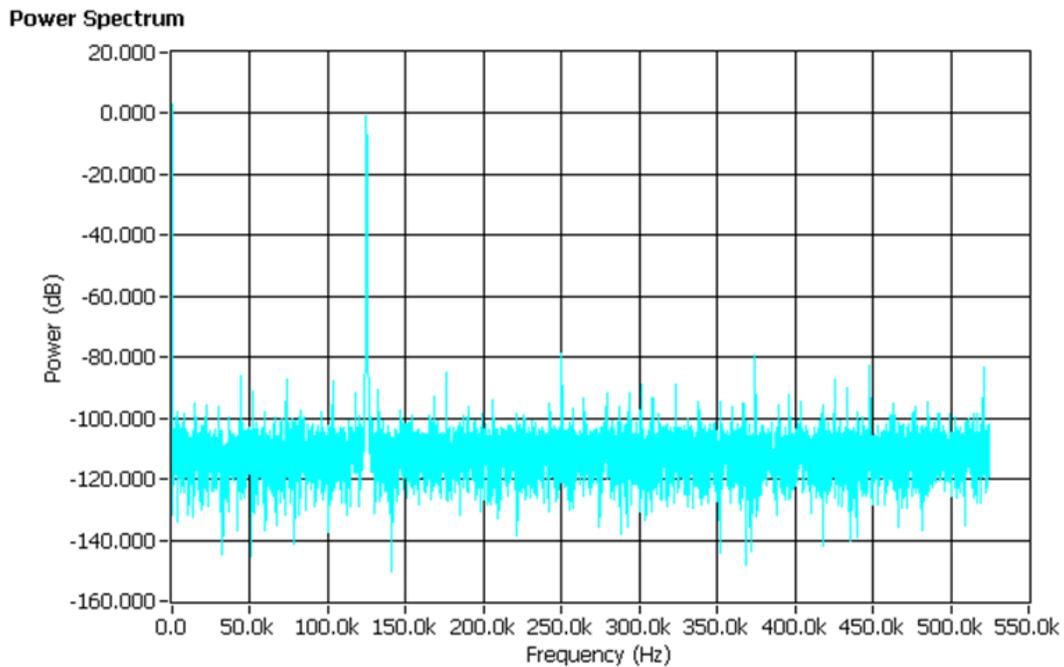


Figure 5. ADC FFT with $F_{in} = 125$ kHz, $R = 36$ Ohm and $C = 3$ nF

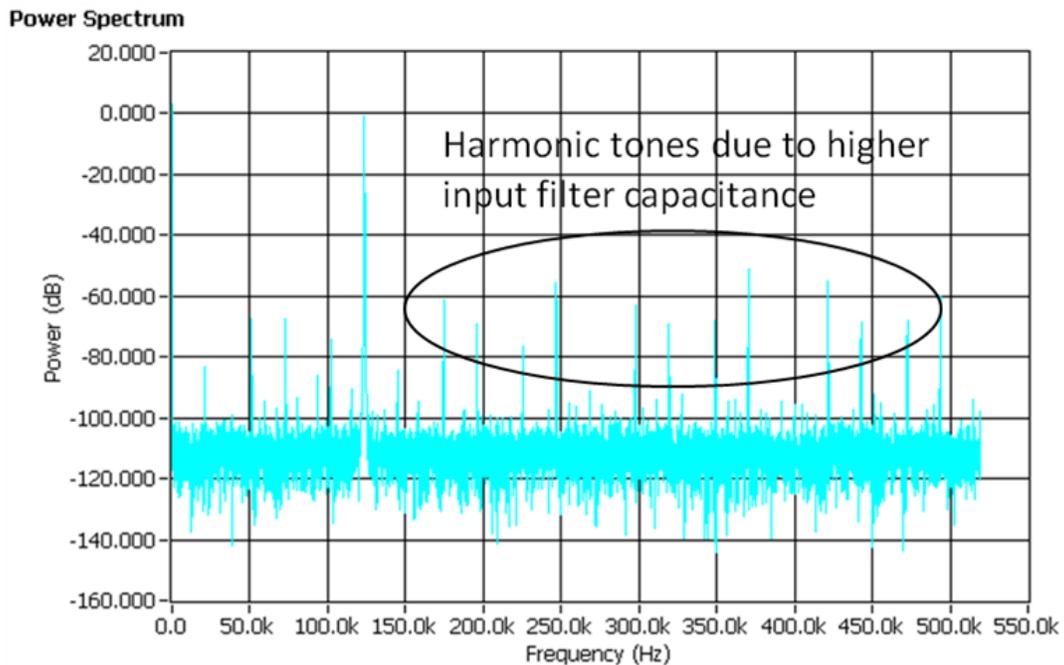


Figure 6. ADC FFT with $F_{in} = 125$ kHz, $R = 1$ Ohm and $C = 47$ nF

4.2 Clock circuit

Freescale MCUs provides several options to feed clocks to the ADC module through on-chip options. The internal RC oscillator and Crystal oscillator circuits are commonly available circuits in most of the MCUs. The following is the brief description of common clock modules available in a typical MCU.

Designing for best possible performance

Internal RC Oscillator (IRC OSC): Provides fast startup, low power, but generally suffer from high jitter, poor accuracy over temperature and supply voltage.

CRYSTAL OSCILLATOR (XTAL OSC): Typically provides very high initial accuracy and a moderately low temperature coefficient, low jitter and will have higher startup time and consumes more power.

PLL: Generally it will be used to bring different frequency clocks to various modules of SOC using a fixed reference source. Input reference clock to the PLL can be either IRC or XTAL OSC. Proceeding further below nomenclature will be used.

IRC+PLL: Input reference clock to the PLL is Internal RC oscillator. PLL is programmed to provide required clock frequency to ADC

XTAL+PLL: Input reference clock to the PLL is crystal oscillator. PLL is programmed to provide required clock frequency to ADC

Selection of clock circuit combinations is important because it will impact the dynamic performance of the ADC. The term "jitter" describes timing errors within a system.

It can be shown that jitter on the sampling clock degrades the overall SNR per the simple equation:

$$SNR = 20 \log_{10} \left[\frac{1}{2\pi f_{IN} t_{RMS}} \right]$$

Equation 2

$$SNR = 6.02N + 1.72$$

Equation 3

where:

f_{IN} = analog input frequency

t_{RMS} = RMS clock jitter

N = resolution of the ADC (number of bits)

From [Equation 2 on page 10](#) it is clear that the degradation in SNR is dependent on the input frequency and clock RMS jitter. It should be noted that this equation assumes IDEAL ADC of infinite resolution, where the only error source is clock jitter. Ideal SNR limitation of the ADC for a given resolution is given by [Equation 3 on page 10](#). From [Table 3](#) it is clear that clock source quality should be at least 10 dB better than DUT. Consequently, to get proper performance for a 12-bit SAR ADC at $f_{IN} = 125$ kHz, clock jitter should be less than 100 ps (corresponds to 82 dB at $f_{IN} = 125$ kHz).

RMS clock jitter can be calculated by integrated phase noise to the required BW. Generally the upper frequency range for the integration should be twice the sampling frequency [3]. In our example case we use the 1 MSPS SAR ADC, therefore, integration bandwidth is from zero to 2 MHz. [Figure 7](#) and [Figure 8](#) shows phase noise plot of IRC+PLL and XTAL+PLL collected using Agilent E5052B Signal Source Analyzer with integration from close to DC to 2 MHz. Measured RMS jitter is 50 ns and 25 ps approximately for IRC+PLL and XTAL+PLL respectively.

[Figure 9](#) and [Figure 10](#) show the effect of clock sources on the ADC dynamic performance for a 12-bit 1 MSPS ADC with $F_{in}=125$ kHz for IRC+PLL and XTAL+PLL respectively. From the figures it is clear the noise floor has gone up and also some smearing is observed around the fundamental for IRC+PLL as clock source for ADC. IRC should never be used as a clock source if dynamic performance is important. Below are some of the reasons for this:

- IRC has very high Jitter (in nS range)
- Jitter will not be constant, multiple measurements will result in varying Jitter
- IRC Jitter will vary with Voltage & Temperature

Due to above issues Run-to-Run variation can be observed in the SNR measurements.

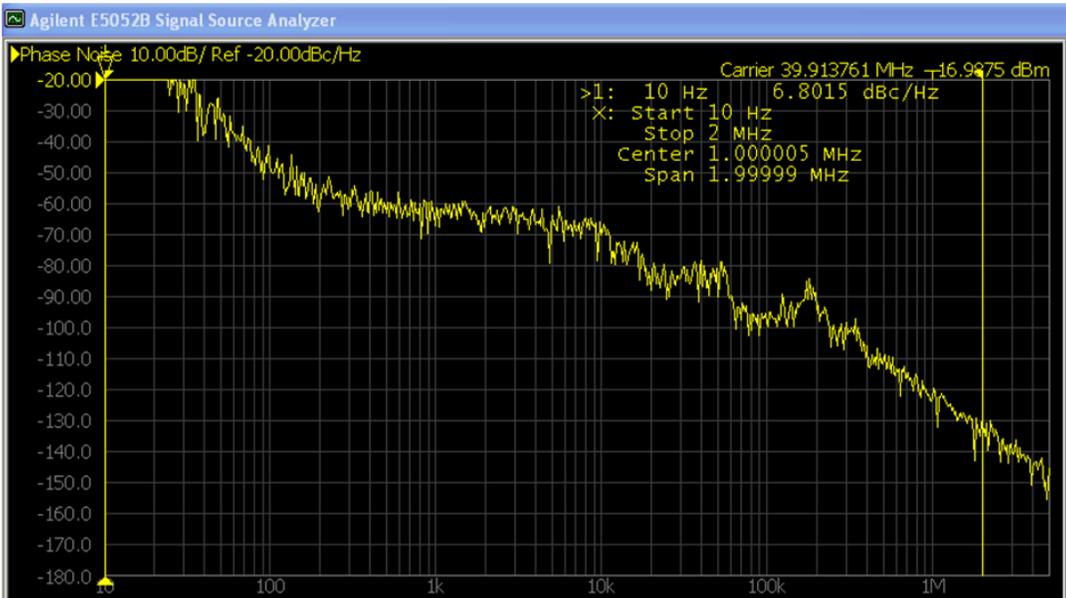


Figure 7. Phase noise plot of IRC+PLL

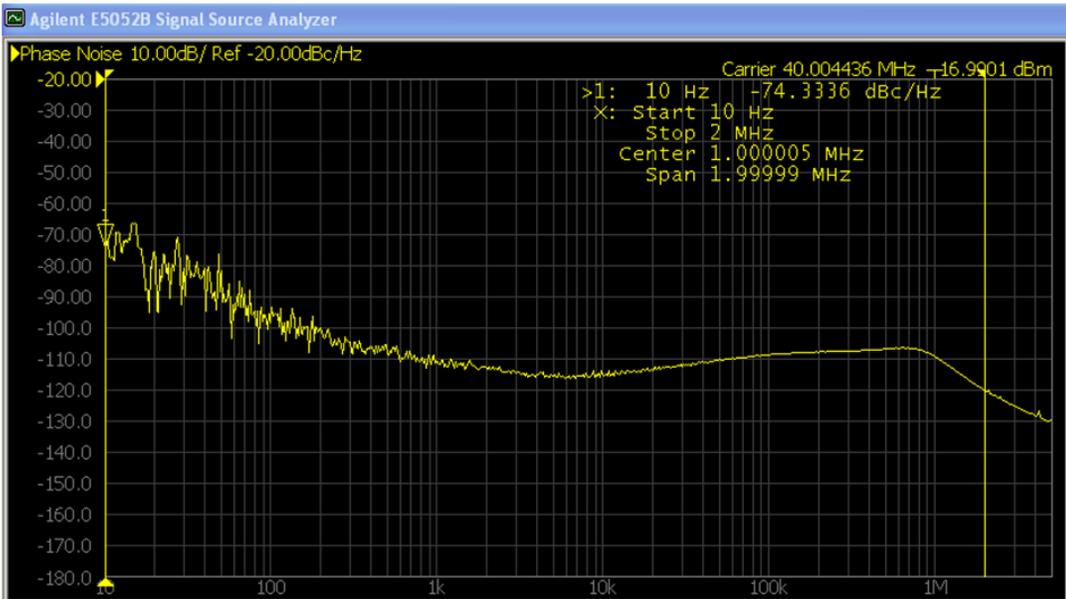


Figure 8. Phase noise plot of XTAL+PLL

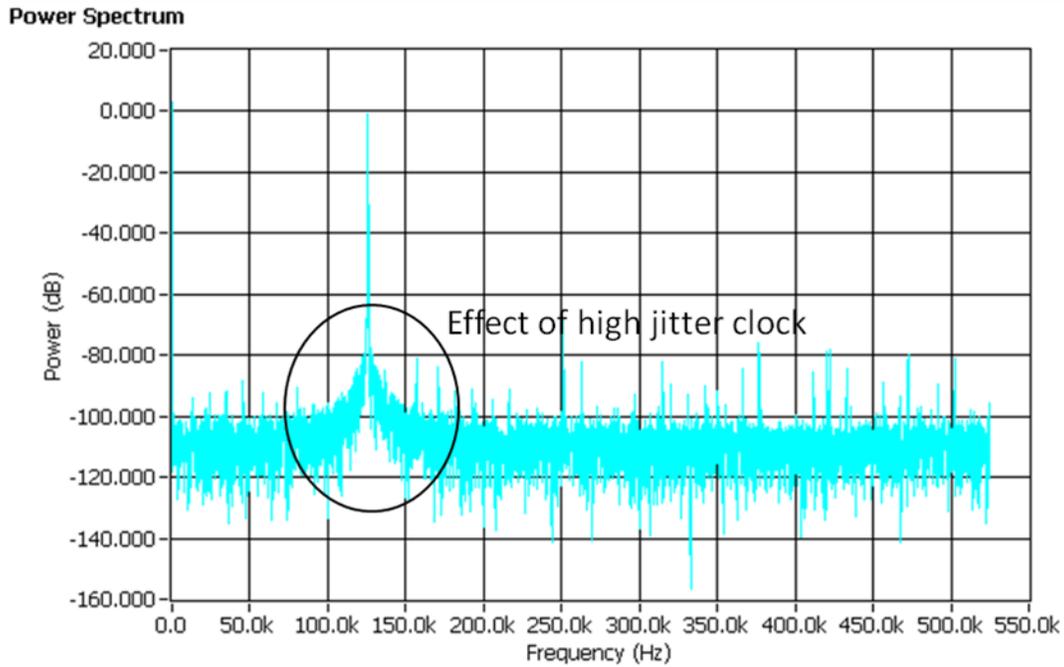


Figure 9. IRC + PLL as clock source

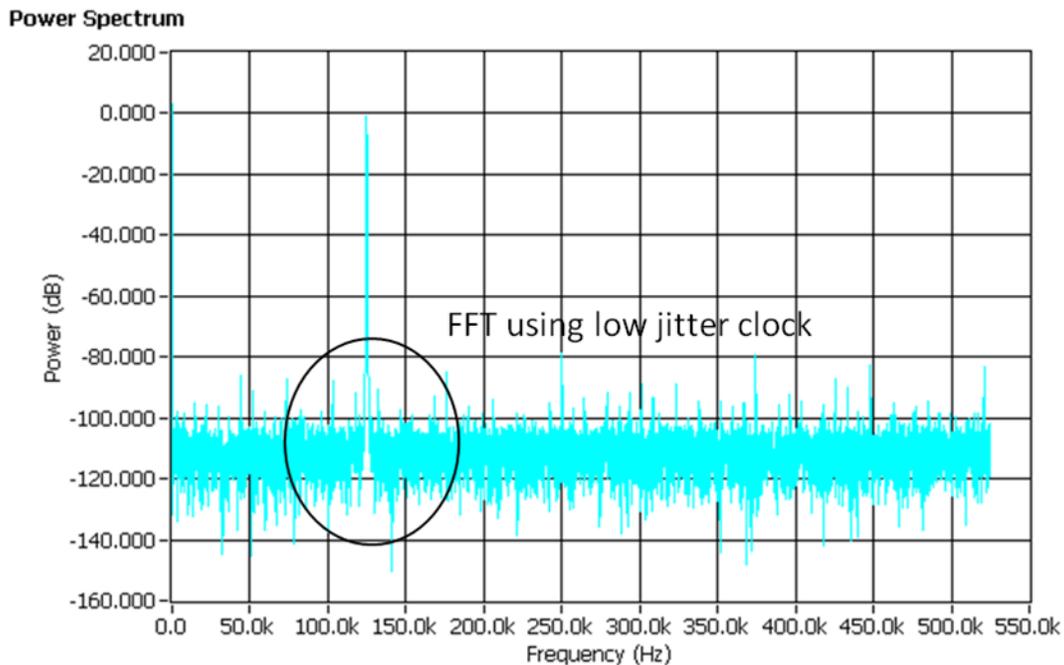


Figure 10. XTAL + PLL as clock source

Figure 11 shows variation of SNR with input frequency with different clock sources. For below 1 kHz, SNR is almost same with IRC+PLL and XTAL+PLL as a source. As frequency increases effect of jitter is clearly observed for IRC+PLL. Therefore, for frequency >1 kHz, XTAL+PLL circuit should be used as clock source for the ADC.

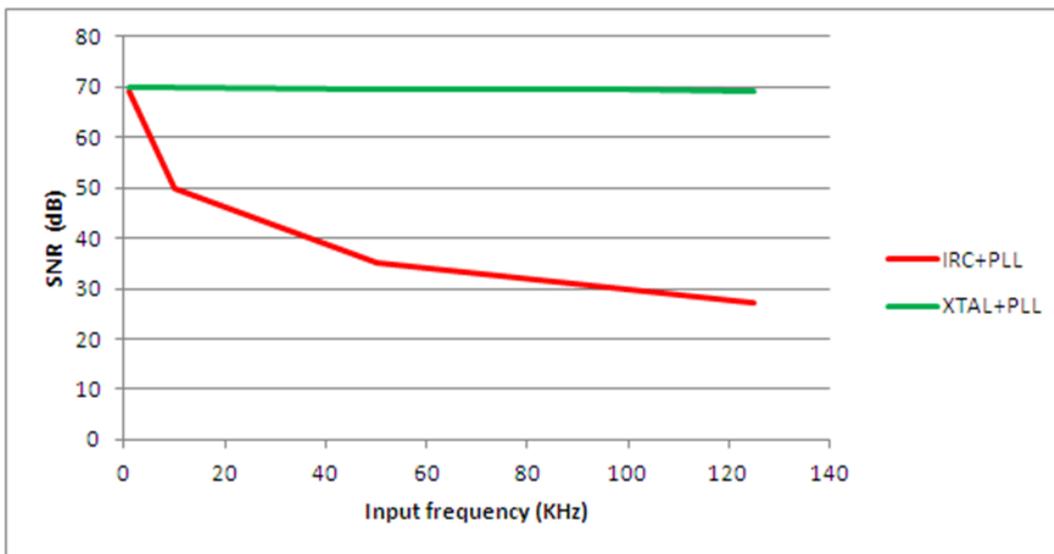


Figure 11. Effect of clock source on ADC performance

4.3 Power supply circuit

Noise, stability and drive capability are some of the important characteristics need to be considered for a SAR ADC voltage reference circuit. From [Equation 1 on page 6](#) it is clear that noise at the reference will impact the ADC performance. [Figure 12](#) shows the variation of system noise with DC input voltage for a SAR ADC. Here data is collected with a low noise and noisy voltage reference circuit at the same conditions. From [Figure 12](#), it is clear that effect of the reference noise is not constant and is dependent on the ADC input [\[2\]](#).

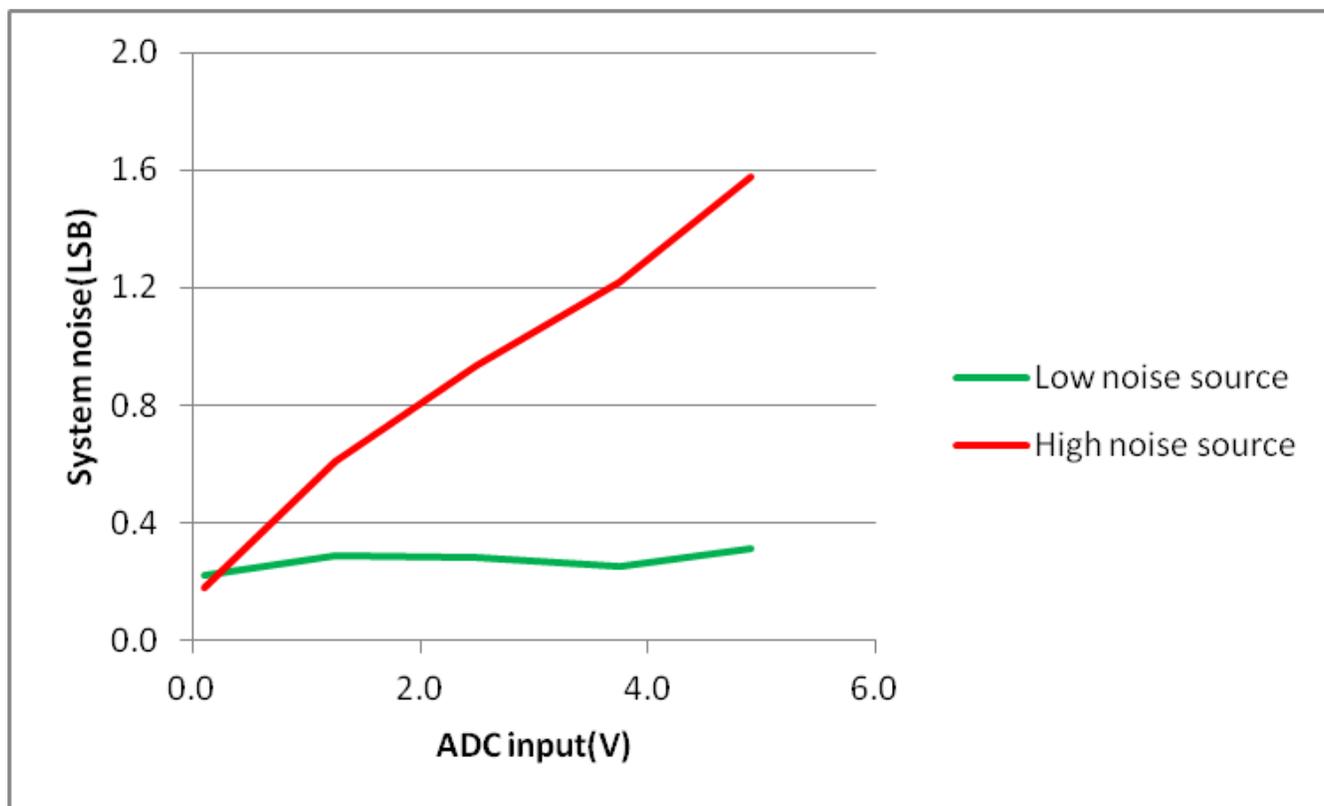


Figure 12. Effect of reference noise on the ADC performance

Given the importance of a low noise reference source, it is important to pick a good quality IC to drive the ADC reference. Selection of the reference source depends on application. In case of standalone ADCs, voltage references can be used. However an ADC reference source in a SoC typically has some, if not all, of the below requirements:

- Wide working reference voltage range (for example, some SAR ADCs support both a 3.3 V supply option and a 5.0 V option.) If the application requires, a dynamically adjustable reference could be used.
- In SoCs, generally multiple ADC will be used. Most of the times all will share common reference. Therefore, it is good to go for higher driving capability source to supply any surge current requirements.
- In SoCs, generally supply will be shared across the several IPs, so recommended decoupling capacitors will be in the order of μF . The reference source should be capable of driving capacitance in the order of μF .
- The reference source should have good immunity across temperature, supply.

For the above requirements an adjustable Low Drop Out (LDO) regulator supply is a better choice as compared to voltage references. From [Table 3](#), it is clear that for MPC57XX family, any regulator whose RMS noise is less than $100 \mu\text{V}$ (corresponding to 85 dB at $V_{\text{REF}} = 5 \text{ V}$) is sufficient to achieve datasheet performance specifications. [Figure 13](#) and [Figure 14](#) show FFT plots collected using low noise and noisy source reference circuits.

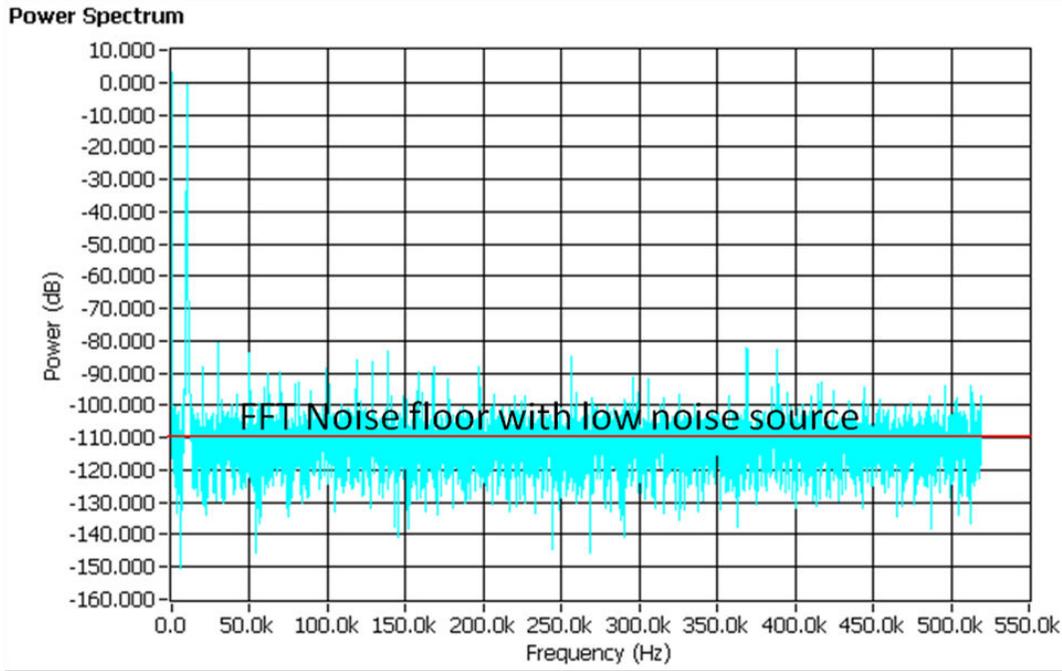


Figure 13. Low noise VREF. 12-bit 1 MSPS SAR ADC FFT; $F_{in}=10$ kHz, SNR= 70 dB, THD= 77 dB

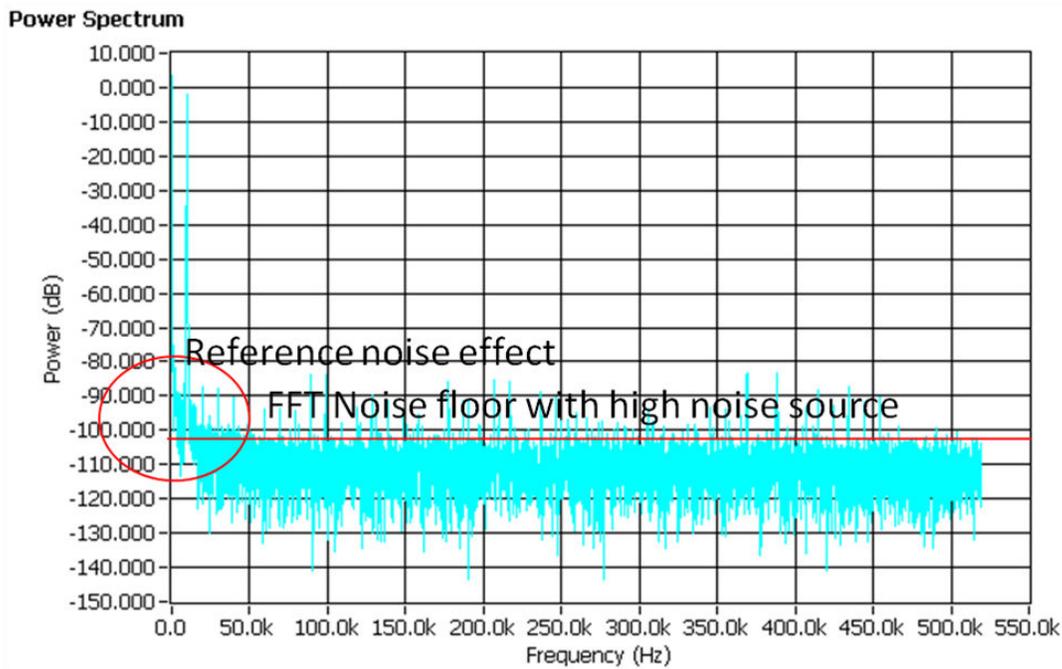


Figure 14. High noise VREF. 12-bit 1 MSPS SAR ADC FFT; $F_{in}=10$ kHz, SNR= 63 dB, THD= 77 dB

4.4 PCB design recommendations

Designing for best possible performance

The physical design of Printed Circuit Boards (PCBs) has a significant effect on SAR ADC performance. The MPC57xx family are mixed signal MCUs and require best practice analog and digital design techniques.

For optimal SAR ADC performance, four major items must be properly managed:

1. Power supply design
2. Decoupling capacitors
3. Grounding
4. PCB routing

4.4.1 Power supply design

SAR ADC circuits require two power supplies:

- VDD_HV_ADV - 3.3 V digital supply for the ADC
- VDD_HV_ADR - 3.3 V or 5.0 V analog reference supply for the ADC

Power supplies shall be designed to have a minimum of voltage ripple. Specific attention must be paid to the ADC reference supply voltage. Total integrated RMS Noise should be less than 100 μ V for MPC57xx Family SAR ADCs. VDD_HV_ADRn uses a linear power supply and provides the best possible ADC performance. Switched Mode Power Supplies should be avoided for supplying the VDD_HV_ADRn voltages. See [Power supply circuit](#) of this application note for more details.

4.4.2 Decoupling capacitors

Decoupling capacitors are an important tool for the PCB designer. Decoupling capacitors shall be placed as close as possible to the device power supply balls. Low Equivalent Series capacitors shall be used.

Recommended decoupling capacitor values are shown the following table:

Table 4. Power supply and recommended decoupling capacitors

Power Supply Name	Recommended Decoupling Capacitors
VDD_HV_ADR	10 μ F, 0.1 μ F, 1nF
VDD_HV_ADV	10 μ F, 0.1 μ F, 1nF

4.4.3 Grounding

Freescale recommends PCB designs use a common ground plane with no discontinuities. There is no need to provide separate analog and digital ground planes. Use the shortest possible path from the system ground plane to the device VSS balls.

It is often suggested that an analog circuit should have a separate ground plane. This solution still requires a connection between the two grounds. This solution forces any interference currents to concentrate near the point of connection. This interference field, in turn, couples interference into the A/D converter. This approach is thus not recommended.

The easiest way to limit interference coupling is to make sure that the fields of the analog and digital signal processing do not share the same physical space.

The analog signal fields and digital signal fields must be separated by the system ground plane.

4.4.4 PCB routing

For proper PCB routing, the designer must use transmission line and field energy concepts to ensure noise and cross coupling effects are properly managed within the design. Analog signals shall have their own physical space, one dielectric away from ground. Digital signals and supplies shall have their own physical space, separated by exactly one dielectric away from ground. The designer must ensure the digital signals and analog signals are not routed in the same space.

The following points must be achieved in the design:

- Power distribution: All power supply planes shall be placed one dielectric away from system ground. This can be achieved by keeping power supply feeds on the layer adjacent to a system ground plane layer
- Charge Well placement: For 55 nm compatible designs, decoupling capacitors providing charge wells shall be placed within ½ cm from each power supply ball / via.
- High noise immunity: Route the following elements in their own space immediately adjacent (e.g. one dielectric away from ground):
 - Analog power supplies
 - Analog signals
 - Digital power supplies
 - Digital signals

NOTE

- Avoid routing digital power supply traces and/or digital signals in the same space as analog supplies and/or signals.
- Ensure the return paths for all signals are kept within their respective spaces. Do not cross or share return paths for different types of signals.

5 SAR ADC calibration for gain error and offset error

Most SAR ADCs exhibit gain error and offset errors. These errors manifest as non-linearity at the zero scale endpoint (minimum voltage level) and the full scale endpoint (maximum voltage level). These non-linearities are defined as:

- **Zero-Scale Error (E_{ZS})** is the difference between actual first transition voltage and the ideal first transition voltage. Considering the first transition Ideal Code Width (ICW(0)) occurs at 1/2 LSB, and the first transition Calculated Code Width (CCW(0)) occurs at some input voltage level measured during device test, the Zero-Scale Error is given by: $E_{ZS} = CCW[0] - ICW(0)$
- **Full-Scale Error (E_{FS})** is the difference between the actual last transition voltage and the ideal last transition voltage. Assuming the last transition Ideal Code Width (ICW(last)) is 1 1/2 LSB, the Full-Scale Error is given by: $E_{FS} = CCW(last) - ICW(last)$

The following graphs show Zero-Scale Error, Full-Scale Error and their relationship to Offset Error and Gain Error.

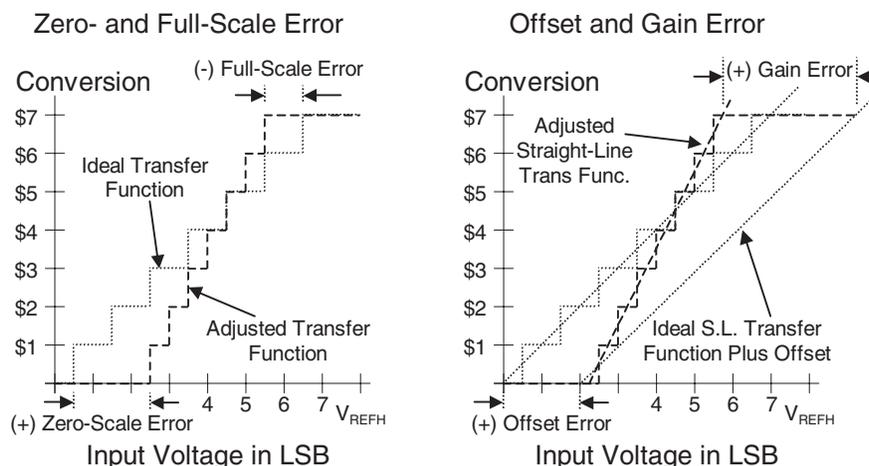


Figure 15. Endpoint error graphs

In relation to E_{ZS} and E_{FS} , Offset Error and Gain Error are defined as:

- **Offset Error (EO), Adjusted Offset, or Zero-Scale Offset** is the difference between the actual and ideal first transition voltages. This is the same definition as Zero-Scale Error.
- **Gain Error (EG) or Adjusted Gain Error** is the difference in the slope of the Actual and the Ideal Straight-Line Transfer Functions. The error is not measured as a slope but rather as the difference in the total available input range from the first to the last conversions between the Ideal and Adjusted Straight-Line Transfer Functions. It can also be expressed by: $E_G = E_{FS} - E_{ZS}$

The above definitions are adapted from AN2438/D ADC Definitions and Specifications. For a complete discussion of Zero-Scale Error, Full-Scale Error, Offset Error and Gain Error, refer to AN2438/D [1].

The 1 MSPS SAR ADC has a user software driven calibration feature to compensate for Offset and Error and Gain Error. The calibration is initiated by programming fields in the Calibration, Built-In Self Test (BIST) Control and status Register (CALBISTREG). The user software initiates the calibration procedure at device boot time and can further execute the procedure during run time if the application requires it (e.g. if the supply voltages change). The 1 MSPS SAR is designed to be performance stable over temperature, therefore, no re-calibration is required at hot or cold temperature extremes.

NOTE

- Calibration must be run after power-up reset and any reset (when registers are initialized). The routine must also be recalled if the operating conditions (specifically V_{REFH}) change. This should also be re-called, if the Self-Test indicates that a recalibration is needed.
- If Calibration fails as indicated by the status bit $CALBISTREG[TEST_FAIL] = 1$, the user should execute the Calibration one more time. If the calibration succeeds, then continue normal device operation. If the Calibration fails repeatedly, the device should be replaced.

Refer to the [SAR ADC initialization example](#) section of this application note for step-by-step calibration programming example.

6 SAR ADC initialization example

To initialize the SAR ADC, the following steps must be completed as a minimum:

1. Configure input pads and ADC normal conversion registers
2. Calibrate the ADC
3. Initialize SAR ADC modes and clock
4. Power on the ADC and start conversions

The tables below list the major steps and registers involved to support the initialization.

Table 5. Sample code high level overview

Step	Description	Sample Code Function Name	Details
1a	Configure input pads for analog	ADC1_PadConfig_ChانSelect()	Program the SIUL2.MSCR register. Refer to I/O signal definition spreadsheet for your specific SOC. Determine which pads to configure for analog inputs.
1b	Select the channels to scan	ADC1_PadConfig_ChانSelect()	Program the Normal Conversion Register (SARADC_n.NCMR0). Align the NCMR0 channel to the input pin(s) configured in Step 1.
2	Calibrate the ADC	ADC1_Calibration()	See separate table for details (SAR ADC calibration)
3	Initialize SARADC Mode, Clock, and start conversions	ADC1_Init()	See separate table for details (SAR ADC configuration)
5	Read the conversion data	ADC1_Read_Chان()	Read conversion data from the SARADC_n.CDR[adc_channel] register.

Table 6 shows the steps for configuring the SAR calibration feature.

Table 6. SAR ADC calibration sequence

Step	Description	Register Programming Sequence
1	Configure the ADC (reset MCR[PWDN] and MCR[ADCLKSEL])	ADC_1.MCR.B.PWDN = 1; ADC_1.MCR.B.ADCLKSEL = 1;
2	Configure the Calibration, BIST Control, and Status Register (CALBISTREG) for test conditions. The default values are set for maximum accuracy (recommended).	/* Modify here if default values from CALBISTREG need to be changed */
3	Set CALBISTREG[TEST_EN]. The routine will start immediately.	ADC_1.CALBISTREG.B.TEST_EN = 1; ADC_1.MCR.B.PWDN = 0;
4	Wait until CALBISTREG[C_T_BUSY] becomes 0.	while(ADC_1.CALBISTREG.B.C_T_BUSY){}
5	Check the value of MSR[CALIBRATD] to determine whether calibration was successful.	if(ADC_1.CALBISTREG.B.TEST_FAIL) { ADC1_Calibration_Failed = 1; /* Calibration not done but failed*/ } else { ADC1_Calibration_Failed = 0; /* Calibration done and passed*/ }

Table 7 lists the steps for initializing the SAR and starting conversions.

Table 7. SAR ADC initialization sequence

Step	Description	Details
1	Specify how to handle overwriting older conversion results	OWREN = 0 (do not overwrite) OWREN = 1 (enable overwrite)
2	Select channels if not already selected prior to initialization	NMCR, etc.
3	Specify mode, such as normal scan	MODE = x
4	Specify ADC clock	PWDN = 1 ADCLKSEL = x PWDN = 0
5	Trigger or enable trigger to module	Example: Normal conversion start: NSTART=1. Can also use injected conversion start (JSTART=1). If supported, Cross Triggering Unit (CTU) is used.

The following lists C code in main.c and adc.c supporting SAR ADC calibration and initialization.

```

/*****
/* FILE NAME: main_core_0.c                                COPYRIGHT (c) Freescale 2014 */
/*                                                    All Rights Reserved */
/* DESCRIPTION:  Initializes ADC1 to read to analog channels 9 & 10.          */
/* The four most significant bits read from channel 9 light up LEDs on Freescale evaluation board. Channel 9 is connected to a pot on the EVB so turning the pot outputs values 0-0xF.*/
/*                                                    */
/*****

#include "project.h"
#include "ADC.h"

extern void system160 MHz(void);
extern void __ghs_board_devices_init_AFTER_main(void);
void peri_clock_gating(void); /* Configure gating/enabling peri. clocks for modes*/
void LED_Config(void); /* Assign LED ports on Freescale EVBs as GPIO outputs */
void update_LEDs(void); /* Update LEDs with scaled chan 9 result */

extern uint16_t Result[3]; /* ADC channel conversion results */

/***** Main *****/

void main(){
    SWT_disable_0(); /* Disable watchdog for core 0 */
    memory_config_160 MHz(); /* Configure wait states, flash master access, etc.*/
    crossbar_config(); /* Configure crossbar */
    peri_clock_gating(); /* Configure gating/enabling peri. clocks for modes*/
    system160 MHz();

    LED_Config(); /* Assign LED ports on Freescale LED as GPIO outputs*/

    ADC1_PadConfig_ChainSelect(); /* Configure ADC pads & select scan channels */
    ADC1_Calibration(); /* Calibrate the ADC */
    ADC1_Init(); /* Init ADC1 to read channels 9, 10 (ports PB4, PB5) */

    while(1){
        if (ADC_1.ISR.B.ECH) { /* If selected normal scan channels finished converting */
            ADC1_Read_Chain(); /* Read conversion results */
            update_LEDs(); /* Update LEDs with scaled chan 9 result */
            ADC_1.ISR.R = 0x00000001; /* Clear End of Chain (ECH) status bit */
        }
    }
}

```

```

/***** End of Main *****/

void peri_clock_gating (void) {
    MC_ME.RUN_PC[0].R = 0x00000000; /* gate off clock for all RUN modes */
    MC_ME.RUN_PC[1].R = 0x000000FE; /* config. peri clock for all RUN modes */
    /* Note: RUN_PC0 is default cfg for PCTLs */
    MC_ME.PCTL[25].B.RUN_CFG = 0x1; /* ADC1: select peri. cfg. RUN_PC[1] */
    MC_ME.PCTL[94].B.RUN_CFG = 0x1; /* SIUL: select peri. cfg. RUN_PC[1] */
}

void LED_Config(void) { /* Assign LED ports as GPIO outputs */
    SIUL2.GPDO[98].R = 1; /* LED1 Initial value: 1 = LED off on FSL EVB */
    SIUL2.GPDO[99].R = 1; /* LED2 Initial value: 1 = LED off on FSL EVB */
    SIUL2.GPDO[100].R = 1; /* LED3 Initial value: 1 = LED off on FSL EVB */
    SIUL2.GPDO[101].R = 1; /* LED4 Initial value: 1 = LED off on FSL EVB: scaled ch 9 LSB */

    SIUL2.MSCR[ 98].B.OBE = 1; /* Port PG2 - LED 1 on Freescale EVB */
    SIUL2.MSCR[ 99].B.OBE = 1; /* Port PG3 - LED 2 on Freescale EVB */
    SIUL2.MSCR[100].B.OBE = 1; /* Port PG4 - LED 3 on Freescale EVB */
    SIUL2.MSCR[101].B.OBE = 1; /* Port PG5 - LED 4 on Freescale EVB */
}

void update_LEDs(void) { /* Update LEDs with scaled chan 9 result */
    /* If Result bit is 0, then LED is turned ON */
    /* If Result bit is 1, then LED is turned OFF */
    SIUL2.GPDO[98].R = (Result[0] & 0x0800)>>11; /* LED1: scaled ch 9 LSB */
    SIUL2.GPDO[99].R = (Result[0] & 0x0400)>>10; /* LED2 */
    SIUL2.GPDO[100].R = (Result[0] & 0x0200)>>9; /* LED3 */
    SIUL2.GPDO[101].R = (Result[0] & 0x0100)>>8; /* LED4: scaled ch 9 MSB */
}

/*****
/* FILE NAME: ADC.c COPYRIGHT (c) Freescale 2014 */
/* All Rights Reserved */
/* DESCRIPTION: ADC module functions. */
*****/
#include "ADC.h"

#define ADC_VREF 5000 /* *** ADC ref voltage for both ADC modules. 3300 mv or 5000 mv */
uint16_t Result[3]; /* ADC channel conversion results */
uint16_t ResultInMv[3]; /* ADC channel conversion results in mv */

void ADC1_PadConfig_ChansSelect(void) { /* Config ADC pads & select scan chans */
    /* Note: MSCR.SSS configuration is not needed for inputs if there is */
    /* no SSS value is in signal spreadsheet */
    /* Note: ADC1 channel 9 on port PB4 is connected to pot on FSL EVB */
    SIUL2.MSCR[20].B.APC = 1; /* PB4 = func ADC1_P[0] = ADC 1 chan 9 */
    SIUL2.MSCR[21].B.APC = 1; /* PB5 = func ADC1_P[1] = ADC 1 chan 10 */
    SIUL2.MSCR[22].B.APC = 1; /* PB6 = func ADC1_P[1] = ADC 1 chan 11 */
    ADC_1.NCMR0.B.CH9 = 1; /* Enable chan 9 for normal conversion on ADC1 */
    ADC_1.NCMR0.B.CH10 = 1; /* Enable chan 10 for normal conversion on ADC1 */
    ADC_1.NCMR0.B.CH11 = 1; /* Enable chan 11 for normal conversion on ADC1 */
}

void ADC1_Calibration(void) {

uint32_t ADC1_Calibration_Failed = 1; /* Calibration has not passed yet */

    ADC_1.MCR.B.PWDN = 1; /* Power down for starting calibration process */
    ADC_1.MCR.B.ADCLKSEL = 1; /* ADC clock = bus clock (80 MHz FS80) */
    /* Note: Since ADC is at max 80 MHz frequency, use default values */
    /* for Calibration, BIST control and ADCx_CALBISTREG */
    ADC_1.MCR.B.PWDN = 0; /* Power back up after setting ADCLKSEL */
    ADC_1.CALBISTREG.B.TEST_EN = 1; /* Enable calibration test */
    while(ADC_1.CALBISTREG.B.C_T_BUSY){ /* Wait for calibration to finish */
    if(ADC_1.CALBISTREG.B.TEST_FAIL) { /* Check for Calibration Fail */
        ADC1_Calibration_Failed = 1; /* Calibration not done but failed*/
    }
}

```

Conclusion

```

    }
    else {
        ADC1_Calibration_Failed = 0;          /* Calibration done and passed*/
    }
}

void ADC1_Init(void) {
    ADC_1.MCR.B.PWDN      = 1;  /* Power down for starting module initialization */
    ADC_1.MCR.B.OWREN     = 1;  /* Enable overwriting older conversion results */
    ADC_1.MCR.B.MODE      = 1;  /* Scan mode (1) used instead of one shot mode */
    ADC_1.MCR.B.ADCLKSEL  = 1;  /* ADC clock = bus clock (80 MHz FS80) */
    ADC_1.MCR.B.PWDN     = 0;  /* ADC_1 now on ready to receive conversion triggers */
    ADC_1.MCR.B.NSTART   = 1;  /* Initiate trigger for normal scan */
}

void ADC1_Read_Chan (void) {
    Result[0]= ADC_1.CDR[9].B.CDATA; /* Read Chan 9 conversion result data */
    Result[1]= ADC_1.CDR[10].B.CDATA; /* Read Chan 10 conversion result data */
    Result[2]= ADC_1.CDR[11].B.CDATA; /* Read Chan 11 conversion result data */

    ResultInMv[0] = (uint16_t) (ADC_VREF*Result[0]/0xFFF); /* Converted result in mv */
    ResultInMv[1] = (uint16_t) (ADC_VREF*Result[1]/0xFFF); /* Converted result in mv */
    ResultInMv[2] = (uint16_t) (ADC_VREF*Result[2]/0xFFF); /* Converted result in mv */
}

```

7 Conclusion

The 1 MSPS and 400 KSPS SAR ADC implementation in the MPC57xx family of MCUs provide industry leading analog to digital conversion solutions. The MCUs support a wide range of analog sensing applications including knock sensing, voltage monitoring, and Advanced Driver Assistance Systems (ADAS).

The strength of MCUs designed for the automotive market is their mixed signal feature set, incorporating both high performance analog circuits with high-speed digital multi-CPU-cores. Freescale invests significant engineering research and development in adhering to best practices of mixed signal design techniques and validating the MCUs across semiconductor process variation, temperature extremes, and voltage extremes. This focus on meeting design performance across Process / Voltage / Temperature (PVT) in a mixed signal MCU for automotive applications requiring single digit part per million failure rates is the ‘holy grail’ of the industry. Intelligent architectures and design diligence coupled with exhaustive testing bring this holy grail of reliable MCUs to reality.

For an ADC, input signal, clock and reference supply are most critical sources of noise. They are equally important and have a direct impact on the ADC dynamic performance. For input frequencies up to 200 kHz and high resolution ADC testing, Audio Precision AP27XX is one of the promising sources available in the market. But AP27XX can provide only bipolar signal. Op Amp can be used as signal conditioning circuit between source and DUT. Input RC filter bandwidth depends on several factors such as input frequency, resolution of the ADC, throughput, sampling time and input sampling capacitance. The designer must ensure proper selection of R and C values such that the driving Op Amp is stable. If RC filter bandwidth is selected lower than the requirement, which will cause less than required settling while sampling the input signal, it will distort the input signal resulting in as harmonic tones in the ADC FFT.

Several clock source options are available in the MCU. Selecting a proper clock source for an ADC is important to get true dynamic performance of the ADC. For dynamic performance, the best combination (lowest jitter) clock source is the XOSC and PLL.

Noise, stability and drive capability are some of the important characteristics to be considered while selecting a reference power supply source for the SAR ADC. SAR ADC presents a dynamic load, so both input and reference circuit should have good driving capability. To achieve the best dynamic performance, the external system (input signal, power supply, and clock circuits together) should be at least 10 dB better than DUT.

8 References

1. IEEE Std 1241-2010, IEEE Standard for Terminology and Test Methods for Analog-to-Digital Converters.
2. Data Conversion Handbook, By Walt Kester, Analog Devices, Inc.
3. Oljaca, M., Klein, W., "Converter voltage reference performance improvement secrets", Instrumentation & Measurement Magazine, IEEE, Volume: 12 Issue: 5 October 2009, Page(s): 21-27
4. "AN2438/D ADC Definitions and Specifications." J. Feddeler and Bill Lucas, available at <http://www.freescale.com/>, 2003.

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