

Discrete ADC Input Expansion Using Precision Multiplexers



ABSTRACT

Data acquisition systems are critical electrical sub-systems that are prevalent in many different applications. However, the complex nature of designing these systems can be reduced with the addition of analog multiplexers. This application report will focus on the use of analog multiplexers and discrete analog to digital converters (ADCs) – primarily in the $\Sigma\Delta$ and SAR ADC architectures. First, it explores the data acquisition system and how a mux can benefit, then the channel effects of the multiplexer on the signal. Finally, it explores other multiplexer parameters that impact the data acquisition system.

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1 Data Acquisition System and Multiplexer Overview

1.1 ADCs in Data Acquisition Systems

Analog to Digital Converters (ADCs) are common ICs that convert analog signals to digital signals for data processing. The ADC allows the analog stimulus of the world to be quantized into discrete data strings that can be read and processed by various digital systems. This, however, presents a problem. The amount of variance that exists between different ADC applications leads to a wide array of ADC options in performance and architecture. This application note explores the SAR ADC and the Sigma-Delta ADC architectures as to keep this application note focused on precision applications with a sampling speed that is less than or equal to 10 Mega-Samples Per Second (MSPS).

ADCs are complex devices, but the ultimate goal for any data acquisition system is to easily recreate the signal that the ADC reads from the data output. This requires very little change to the shape of the signal. [Figure 1-1](#) shows a simplified signal path block diagram.

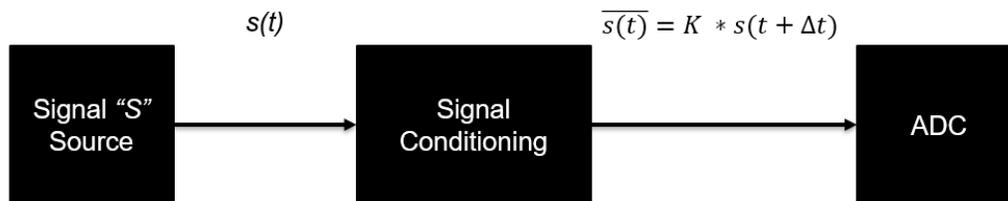


Figure 1-1. Simplified Data Acquisition System Signal Chain

The ideal data acquisition system is going to take the signal $s(t)$ and have it routed through a signal conditioning block which will, ideally, result in the output equation shown in [Equation 1.1](#).

$$\text{Eq. 1.1) } \overline{s(t)} = K * s(t + \Delta t)$$

Where K is a constant gain term and is a constant term representing the propagation delay through the signal conditioning block. Ideally the gain and propagation delay are going to be constant so that they do not affect the signal's data that is being transmitted.

However, a closer look at the ADCs used is critical to understand how the signal conditioning affects the signal being routed through. Sigma-Delta and SAR ADCs are typically used for high resolution applications. Sigma-Delta ADCs use Sigma-Delta Modulators in combination with filtering and decimation to achieve high resolution ADCs – however, these devices are used on lower frequency signals as the maximum sampling speed is often under 1 MHz. The input of the Sigma-Delta ADC when sampling is typically modeled as a singular capacitor to ground and data sheets will give an input impedance versus frequency plot to judge what the input impedance looks like for different input frequencies. SAR ADCs on the other hand use successive approximations to approach the correct input value. This architecture has a lot of flexibility of usage. As sampling speed ratings of the IC go down, the resolution increases giving a wide range of sampling speed and resolution combinations. However, the Sigma-Delta Architecture is able to reach higher resolutions. The SAR ADC can be modeled as a capacitor to ground in parallel with a resistor and capacitor in series. The first capacitor to ground is representative of the capacitance that is there when the device is in hold mode, and the RC is representative of when the ADC is sampling.

1.2 Multiplexers in Data Acquisition Systems

Data acquisition systems are complex systems and complexity begins to compound with more analog inputs being monitored. The system designer has a few tools that they can implement to solve this problem. They could add more ADC ICs or replace current ADCs with higher channel count variations, but this can add to board size and BOM cost very quickly. With the use of analog multiplexers, however, multiple inputs can be supported by a single ADC input. This now opens a new option for system designers where multiplexers can be used to reduce overall ADC channel need.

Figure 1-2 shows how this application can be generalized.

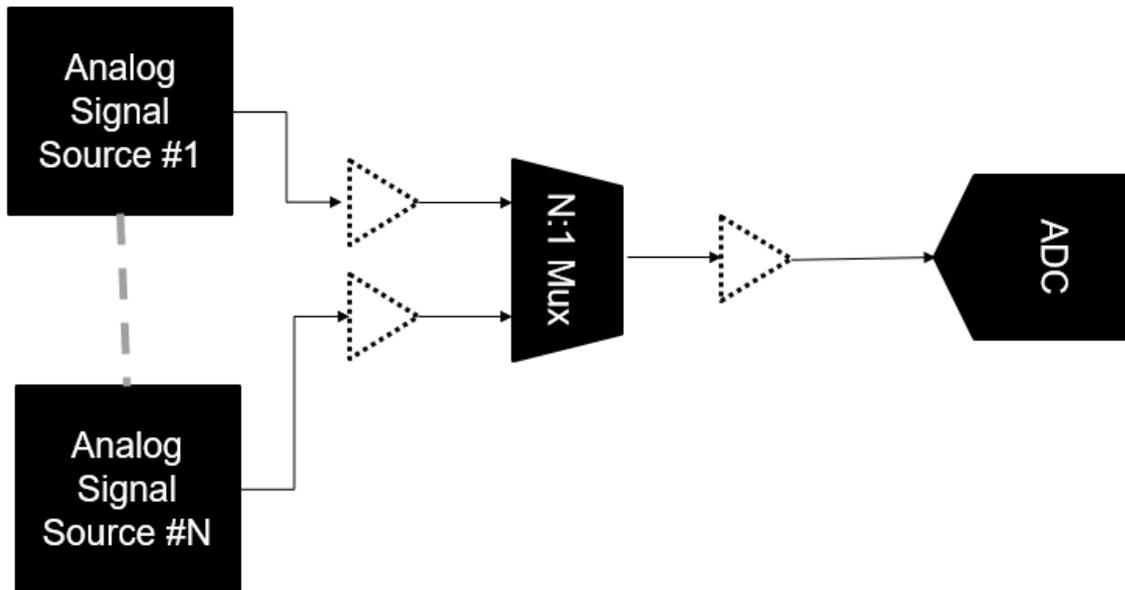


Figure 1-2. Data Acquisition System with Multiplexer and Possible Buffers Shown

The amplifiers or buffers in the signal chain, if present, can be before the mux input or after the mux output. When the amplifiers or buffers are implemented they act as the signal driver for the ADC when reading from high impedance sources such as sensors. The above figure shows where amplifiers or buffers may be placed in the signal chain.

The analog multiplexers in this system offer three main benefits:

1. Reduced solution size.
2. Reduced BOM cost.
3. Increased design flexibility.

The solution size can be reduced because instead of having to add a new ADC block for every additional analog signal one mux can replace the need for adding additional ADC ICs. The BOM cost is related directly to the solution size – there will be less total ICs on the system, and multiplexers are rarely more expensive than the ADCs being used. So, cost can be reduced compared to not using a multiplexer. The BOM cost is also reduced indirectly as each ADC channel may require its own buffer, amplifier, or passive filtering. By reducing the total number of ADC input channels, less of the aforementioned components would be required. Finally, the multiplexer allows for design flexibility, which can allow for simple redesigns of older systems to accommodate additional analog signal inputs. To fully realize the benefits without a cost to system performance, the multiplexers impact on the signal chain must be explored.

2 Multiplexer Channel Effects on Data Acquisition Systems

Ideally the active channel of the analog multiplexer will act as a perfect conductor that passes the signals through the device without any distortion or attenuation. This, however, is not the case as an analog multiplexer channel has resistance and parasitic capacitors to ground. [Figure 2-1](#) shows a simplified RC model of the analog multiplexer.

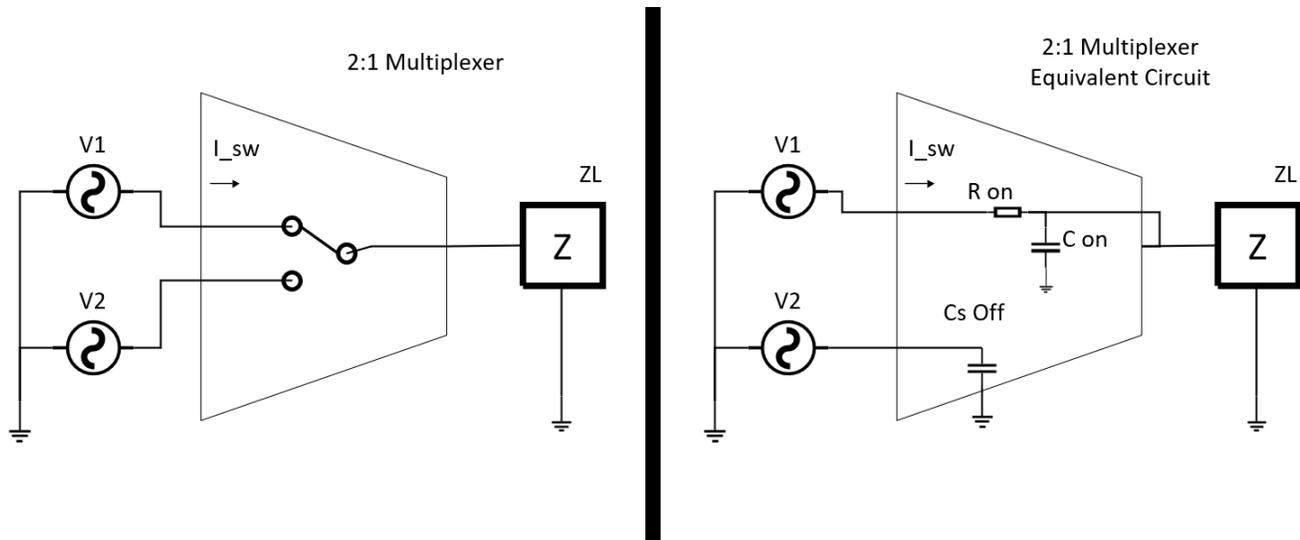


Figure 2-1. 2:1 Multiplexer – Analog I/O Pathway and Simplified Equivalent Circuit

The channel now has added resistance and capacitance that will affect the signal chain resulting in a change to [Equation 1.1](#). The on resistance and capacitance will affect gain, K , and propagation delay, Δt and these values can no longer be treated as constant.

The gain, K , is affected by the impedance of the multiplexer and the output impedance as seen by the multiplexer. First, the on resistance of the multiplexer will reduce signal voltage according to [Equation 2.1](#).

$$\text{Eq. 2.1) } V_{loss} = I_{sw} * R_{on}$$

Where I_{sw} is dependent on the load and input voltage. The second factor that affects K is impedance of the load as this will dictate how much current is requested from the source. At DC steady state this follows [Equation 2.2](#) shown below.

$$\text{Eq. 2.2) } V_{out} = \frac{R_L}{R_{on} + R_L}$$

But, since an ADC's input impedance is capacitive and the mux has a capacitive output, the output impedance (as seen by the mux's input) will be frequency dependent as well. Finally, on resistance will vary with the input voltage w.r.t, ground, and the operating temperature. This now introduces gain as a function dependent on input voltage, frequency, and temperature. To help reduce issues from gain variations, use multiplexers that have a flatter resistance response over voltage and temperature as constant gains can be easily corrected during digital processing. A simple example can be explored using the RC model of a multiplexer's active channel and an SAR ADC's equivalent input model, shown in [Figure 2-2](#).

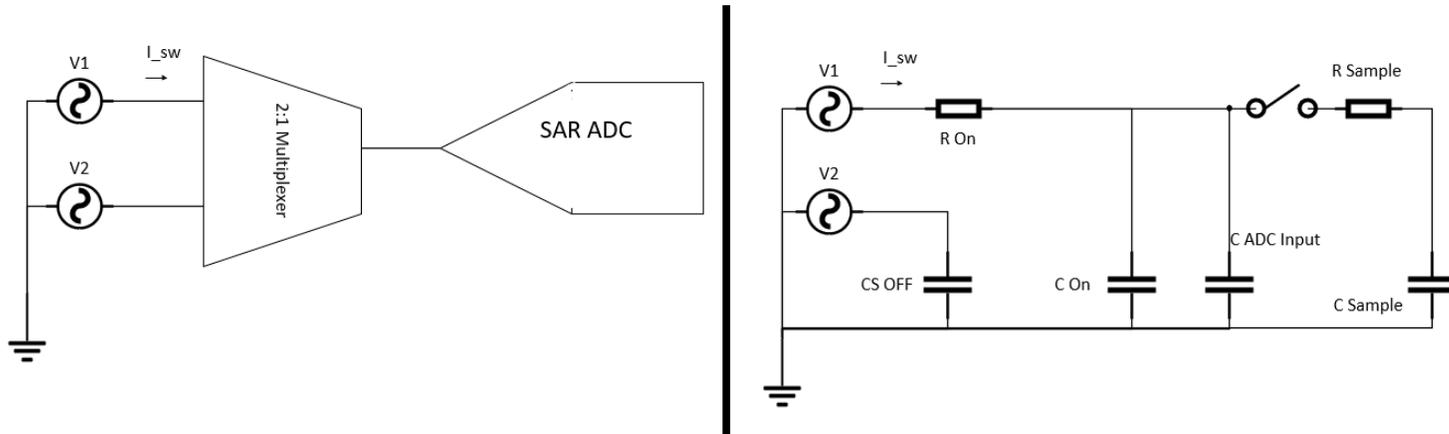


Figure 2-2. 2:1 Multiplexer Connected to SAR ADC - Simplified Equivalent Circuit

During sampling mode, the switch is closed and the output of the mux is connected to the sample and hold circuit represented by R_{Sample} and C_{Sample} . When the SAR ADC is in hold mode, the switch is opened and the voltage across C_{Sample} is read by the ADC. For this example, the ADC will be assumed to be in sampling mode. See below for the application parameters.

$$V_{in} = 0V \text{ to } 5V; F_{in} = 100KHz; C_{ADC_{IN}} = 3pF; C_{Sample} = 30pF; R_{Sample} = 500\Omega; T = 25^{\circ}C$$

On resistance and capacitance are going to depend on the multiplexer. To show how these parameters affect the system, an example with the general-purpose mux (TMUX1308) will be shown first, then the precision mux (TMUX1108). The on resistance for the TMUX1308 is shown in Figure 2-3.

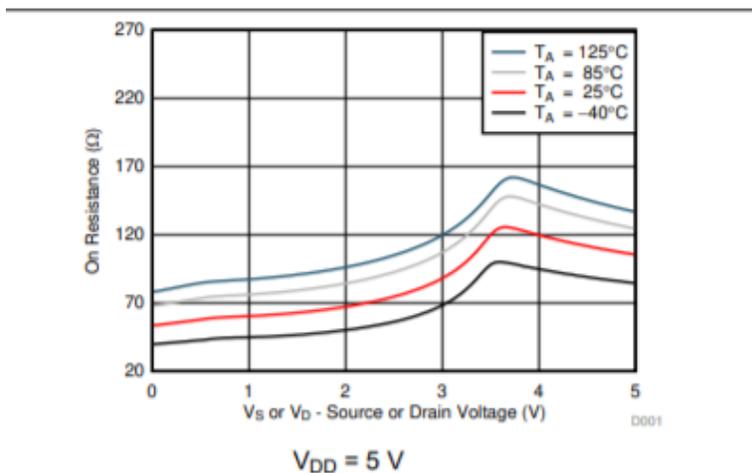


Figure 2-3. TMUX1308 On Resistance Vs. Input Voltage (VDD = 5V)

This puts the minimum typical resistance at $\approx 50\ \Omega$ and a maximum typical resistance at $\approx 125\ \Omega$ for the TMUX1308 at $25^{\circ}C$. The on capacitances are typically 11 pF for the TMUX1308. Using s domain calculations – the impedances of each capacitor is found with Equations 2.3, Equation 2.4, and Equation 2.5 shown below where $s = j\omega + \sigma$:

$$\mathbf{Eq. 2.3)} Z_{C1} = \frac{1}{sC_{on}}$$

$$\mathbf{Eq. 2.4)} Z_{C2} = \frac{1}{sC_{ADCin}}$$

$$\mathbf{Eq. 2.5)} Z_{C3} = \frac{1}{sC_{Sample}}$$

The output impedance of the multiplexer can now be calculated as shown in [Equation 2.6](#):

$$\mathbf{Eq. 2.6)} Z_{out} = \frac{1}{\frac{1}{Z_{C1}} + \frac{1}{Z_{C2}} + \frac{1}{Z_{C3} + R_{in}}}$$

The magnitude of the output impedance along with the on resistance of the multiplexer creates a voltage divider that is equal to the gain of the circuit – shown in [Equation 2.7](#) below:

$$\mathbf{Eq. 2.7)} K \rightarrow |K(v_{in}, f, T)| = \frac{|Z_{out}(f)|}{|Z_{out}(f)| + R_{on}(v_{in}, T)}$$

For the system specifications, the output impedance is shown below with the TMUX1308 being used.

$$|Z_{Out-TMUX1308}(f = 100KHz)| = 36.173K\Omega$$

$$R_{OnLow(typ)} = 50\Omega; R_{OnHi(typ)} = 125\Omega$$

$$K_{TMUX1308_{typicalMin}} = 0.9965562841; K_{TMUX1308_{typicalMax}} = 0.9986196615$$

$$\Delta K_{TMUX1308} = 0.0020633774$$

In this specific example, the gain of the signal through the signal chain varies across input voltage with attenuation of between roughly 0.15% to 0.35% across the rated signal range. This shows that a multiplexer will attenuate the signal, but not by much. However, there are applications where this amount of attenuation and difference in gain can be too much, and the application will require a more precise mux. The TMUX1108 is a precision mux that can help improve the systems performance.

Figure 2-4 shows the on resistance for the TMUX1108.

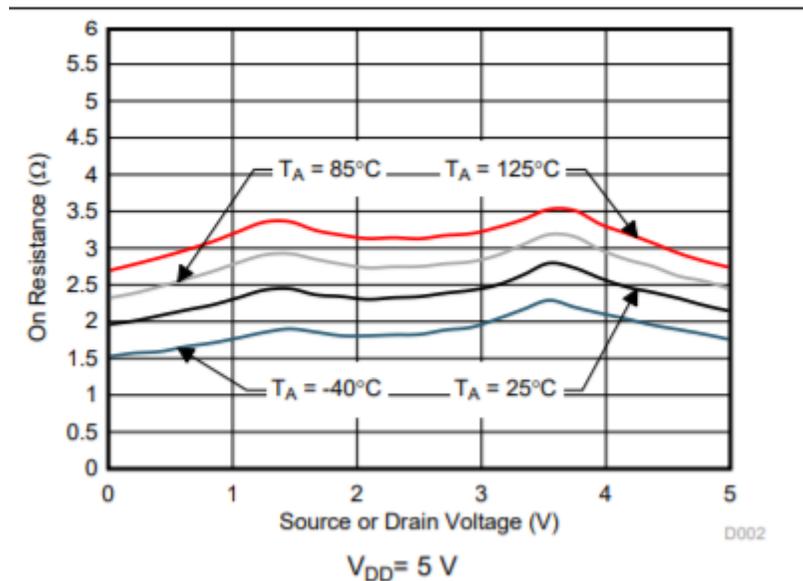


Figure 2-4. TMUX1108 On Resistance Vs. Input Voltage (VDD = 5V)

This varies between $\approx 2\ \Omega$ and $2.8\ \Omega$ At room temperature. The on capacitance is rated at 65 pF (typical).

If the same application as the last example is used for the TMUX1108 – where the TMUX1108 replaces the TMUX1308, then the following results are produced when using Equations 2.3 – 2.7:

$$|Z_{Out-TMUX1108}(f = 100KHz)| = 16.241K\Omega$$

$$R_{OnLow(typ)} = 2\Omega; R_{OnHi(typ)} = 2.8\Omega$$

$$K_{TMUX1108_{typicalMin}} = 0.9998276265; K_{TMUX1108_{typicalMax}} = 0.99987687$$

$$\Delta K_{TMUX1108} = 0.0000492435$$

The gain in the signal chain will vary between roughly 0.0124% to 0.0173% across voltage when using the TMUX1108 in this specific application at room temperature. There is a much smaller difference between the system's minimum and maximum gain at room temperature and a smaller overall attenuation for the TMUX1108 versus the TMUX1308 in this application.

The precision TMUX1108 variation in gain is approximately 42 times smaller than the TMUX1308. A smaller change in gain for the system across input voltage allows for more precision applications as the smaller variation in gain allows for higher resolution applications. The accuracy of both devices degrades as temperature increases, but the TMUX1308's more resistive and less flat response will degrade precision on higher resolution devices, while the TMUX1108 will not affect the signal chain nearly as badly. As even at maximum temperature, the on-resistance curve is still very flat with a worst-case flatness of 1.6 Ω – leading the TMUX1108 to be a great part when precision is needed in these types of applications.

Channel gain is not the only concern, however, as propagation delay is a result of the resistance and capacitance of the multiplexer. Since these specifications can change with the input signal – propagation delay is no longer constant. The propagation delay through the mux is proportional to the time constant of the output impedance as seen by the input of the multiplexer. If the multiplexer was left open circuited, the propagation delay through the mux would simply be $\approx R_{On} \times C_{On}$. The propagation delay will change as the mux's output is loaded, but the device with the lowest RC time constant is going to have the shortest propagation delay for the same loading conditions. However, the on-resistance changes with the input voltage. So, propagation delay will vary in the system as well – this variation can cause distortion to the input signal. If the variation in the propagation delay versus the incoming signal frequency is large, then distortion of the signal can occur. Using devices with the smallest change of RC time constants can help reduce this issue. The TMUX1308 can have a typical variation of 550 ps to 1.375 ns with the longest delays expected at around 3.5 V. In contrast, the TMUX1108 can have a typical variation of open circuit propagation delay time of 130 ps to 182 ps with the longest delays also at around ≈ 3.5 V. Distortion is not as much a problem, because the amplitude on slow moving signals does not change very much in the span of pico seconds.

The signal read by the ADC can be affected by the mux's channel. However, knowing the output of the mux, the input voltage swing, the operating temperature, and input signal frequency can help guide the designer to choose a mux that will have the least impact on the signal being passed through. This is simplified by choosing multiplexers with a flat multiplexer response to make gain correction easier on the output data stream.

3 Other Multiplexer Parameters Effects of Data Acquisition Systems

The multiplexer in the data acquisition system has more effects on the system than just attenuating and distorting the signal passing through the active channel. The signal received by the ADC does not match the equation shown in Equation 1.1. As there are three other error terms that the multiplexer adds to the system as shown in Equation 3.1.

$$Eq. 3.1) \overline{s(t, v_{in}, f, T)} = K(v_{in}, f, T) * s(t + \Delta t(v_{in}, f, T)) + E_{timing}(t, v_{in}, f, T) + E_{AC}(t, v_{in}, f, T) + E_{DC}(t, v_{in}, f, T).$$

These error terms can be grouped as timing errors, AC errors, and DC errors. With proper care these errors can be neglected or accounted for with proper system design.

Timing errors, E_{timing} , are errors due to reading the output during a channels transition or shortly thereafter. Two specifications can be focused on here – transition time and charge injection. Transition time is the time it takes to deselect one channel and enable the other. While one channel is shutting off, the channel resistance increases with an invalid signal on the output. If there is break-before-make switching, then there is a point when the output is disconnected. Finally, while the new switch connection is being made, the channels resistance goes from high to low. See Figure 3-1 and Figure 3-2 for diagrams on transition time and break before make time respectively.

Transition time (t_{TRAN}) — The time taken by the switch output to rise or fall within a given percentage of the final value after the address signal has risen or fallen past the logic threshold.

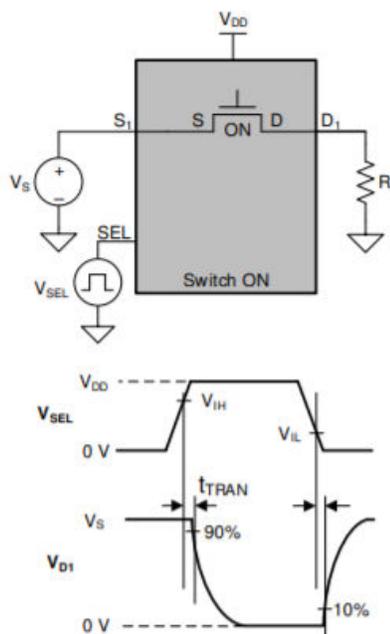


Figure 26. Transition Time

Figure 3-1. Multiplexer Parameter – Transition Time

Break-before-make time ($t_{OPEN(BBM)}$) — Ensures that in a multiplexer, two multiplexer paths are never electrically connected when the signal path is changed by the select input.

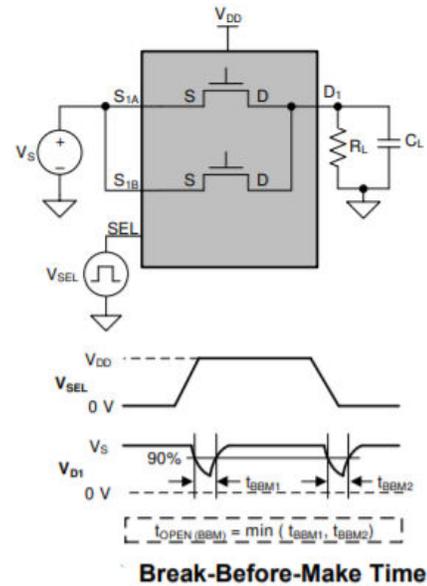


Figure 3-2. Multiplexer Parameter – Break-Before-Make Time

During these time periods, data cannot be collected accurately. A delay that matches the transition time should be instituted after a channel has been switched to receive valid data and prevent issues. This error can be neglected if the proper timing is considered.

However, this delay can also help prevent invalid data reads due to charge injection. Charge injection is the phenomenon in which the voltage at the control pin is coupled to the output causing a voltage transient during switching these transients, which can cause errors in the output voltage. Higher load capacitances can help reduce transients by charge injection – Equation 3.2 can be used to calculate transient spikes caused by charge injection:

$$Eq\ 3.2) \Delta V_{out} = \frac{Q_{inj}}{C_{load}}$$

The output loading conditions will determine the length of the charge injection event. See Figure 3-3 for a quick diagram about charge injection.

Charge injection (Q_c) — Charge injection is a measurement of unwanted signal coupling from the control (EN) input to the analog output. This is measured in coulomb (C) and measured by the total charge induced due to switching of the control input.

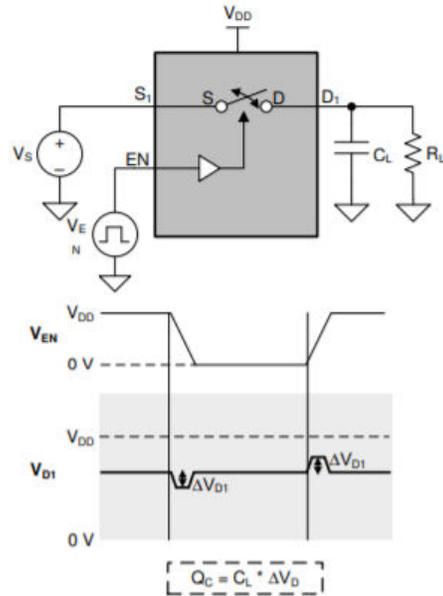


Figure 22. Charge Injection

Figure 3-3. Multiplexer Parameter - Charge Injection

The next type of errors are AC errors, E_{AC} , and they are comprised of signal feedthrough when the device is disabled (Off Isolation) and when the device is enabled (Channel-to-Channel Cross Talk). When a switch is disconnected it becomes Hi-Z, but there is a parasitic capacitor from input to output that will conduct high frequency content to the output. Figure 3-4 shows the multiplexer circuit with AC error components placed into the diagram.

2:1 Multiplexer Equivalent Circuit

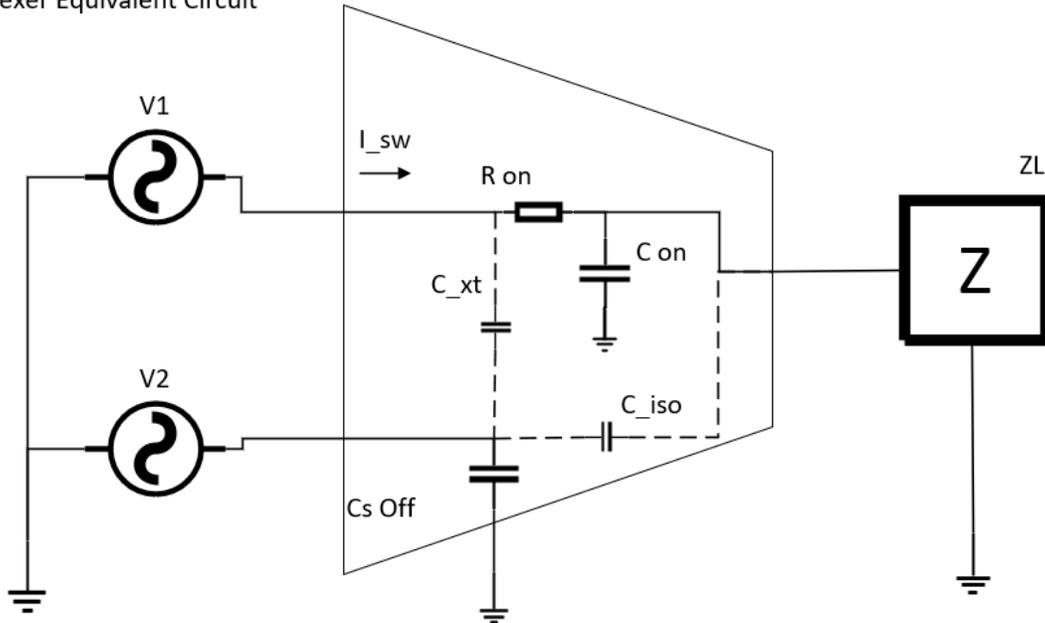


Figure 3-4. Multiplexer Equivalent Circuit with AC Error Components Modeled

Cross talk is caused by the parasitic capacitor C_{xt} while off isolation leakage is caused by C_{iso} on the off channel. These values are typically not specified in the data sheet but the results of their existence are through the off isolation and cross talk parameters.

This signal leakage can allow other signals to interfere with the signal being measured. For example, the TMUX1108 has an off isolation and cross talk of -65 dB at an input frequency of 1 MHz. That means if a 1 V signal at 1 MHz was applied to a disabled input pin the output would have an $\approx 562 \mu\text{V}$ at 1 MHz signal at the output. However, an increase of output capacitance will increase the off isolation and cross talk performance but at the risk of a reduced system bandwidth. AC errors can be predicted by knowing what kind of signals are going to be the input – at lower frequencies very little energy is going to couple through a mux, but as frequency increases the impedance between input and output decreases allowing feedthrough. Choose a part with low off isolation and cross talk over the frequencies of interest to have the least amount of interference.

Finally, the last type of error that needs to be focused on are DC errors, E_{DC} , which can be more commonly referred to as errors due to leakage currents. They can be broken up into two different categories off and on leakages. Off leakage is the leakage current that flows through a switch that is disconnected. On leakage, in contrast, is leakage in the device's on channel which causes the input current to not equal the output current. In data acquisition systems off and on leakage can cause issues by forcing current over the resistance of the multiplexer. This problem is minimized for the TMUX1108 by having exceedingly low leakage currents with a typical value of $\pm 3 \text{ pA}$ for the on leakage and $\pm 5 \text{ pA}$ on the source side for the off leakage. The on leakage can produce a voltage differential across the switch of $\pm 6 \text{ pV}$ and $\pm 8.4 \text{ pV}$ for the TMUX1108, which typically swings between 2 and 2.8 Ω . If larger on leakages are used with higher on-resistances, then the voltage differential across the switch will be larger (such as the TMUX1308, which has $\pm 1 \text{ nA}$ for the on leakage). Pair this with the on-resistance swing of 50 to 124 Ω (typical), which can see a voltage differential across the switch of $\pm 50 \text{ nV}$ to $\pm 125 \text{ nV}$. As temperature increases, leakage currents will also increase. But, the TMUX1108 maxes out at $\pm 5.5 \text{ nA}$ in the same temperature range, and the TMUX1308 maxes out at $\pm 800 \text{ nA}$ in the same temperature range. Choosing low leakage parts will reduce error of data acquisition systems.

Adding a multiplexer to a data acquisition system produces [Equation 3.1](#).

$$\text{Eq. 3.1 } \overline{s(t, v_{in}, f, T)} = K(v_{in}, f, T) * s(t + \Delta t(v_{in}, f, T)) + E_{timing}(t, v_{in}, f, T) + E_{AC}(t, v_{in}, f, T) + E_{DC}(t, v_{in}, f, T).$$

To keep the signal read by the ADC, the following considerations must be made:

- The system's gain will approach a constant value for multiplexers with a flat on resistance response. A constant gain can be corrected in the output data stream – the smaller variation of gain, the more accurate the system can be.
- The propagation delay can cause distortion due to the variation of the propagation delay in the system. A smaller variance in the on resistance (for example, a flatter response) will lead to smaller variations in the propagation delay. If the variations are small enough compared to the incoming signal's propagation delay, then it can be assumed that the variations are constant.
- Timing errors can be neglected if the system is not trying to read data during the transition period of the multiplexer and the resulting charge injection event after the switch.
- AC errors can be calculated based on the system's feedthrough – low frequency signals are typically attenuated out to the point of being able to neglect them. However, the signals on the disabled path must be checked to ensure that the device's maximum feedthrough can be calculated.
- DC errors, which mainly result from leakage currents, are limited by choosing parts that change the output by as small of a margin as possible with on resistances and low leakage currents.

All in all – the multiplexer can unlock flexibility in component selection, solution size, and solution cost. The multiplexer offers the designer these choices by allowing a greater amount of input sources than there are ADC channels available that use the multiplexer to switch in the correct signals. Less ADC channels on the board leads to less signal chain components because there are less channels. This reduces the solution size as the typical mux is not as large as the components to an ADC channel and the ADC itself. Also, the multiplexer is cheaper than the ADC in many instances, so there is a cost benefit to using it. Multiplexers do affect the end goal of the application. But, if proper care is used to understand the level of precision needed by the system and where the multiplexer will be placed into the system, then many of these deficits can be accounted for, and the full benefits of the multiplexer can be seen in these types of applications.

Table 3-1 shows the low voltage and mid voltage multiplexers that are good in ADC based applications.

Table 3-1. Low Voltage and Mid Voltage Multiplexers for ADC Based Applications

Part Number	Configuration	VDD Range	Signal Range	Niche
TMUX1108	8:1 – 1 Channel	1.08 V to 5.5 V or ± 2.5 V	VSS to VDD	LV Precision
TMUX1104	4:1 – 1 Channel	1.08 V to 5.5 V	0 V to VDD	LV Precision
TMUX1136	2:1 – 2 Channel	1.08 V to 5.5 V	0 V to VDD	LV Precision
TMUX1119	2:1 – 1 Channel	1.08 V to 5.5 V	0 V to VDD	LV Precision
TMUX1308	8:1 – 1 Channel	1.62 V to 5.5 V	0 V to VDD	LV General Purpose
TMUX1309	4:1 – 2 Channel	1.62 V to 5.5 V	0 V to VDD	LV General Purpose
TMUX6208	8:1 – 1 Channel	4.5 V – 36 V or ± 4.5 V to ± 18 V	VSS to VDD	MV Precision
TMUX7208	8:1 – 1 Channel	4.5 V – 44 V; or ± 4.5 V to ± 22 V	VSS to VDD	MV Precision
TMUX7209	4:1 – 2 Channel	4.5 V – 44 V; or ± 4.5 V to ± 22 V	VSS to VDD	MV Precision
TMUX7219	2:1 – 1 Channel	4.5 V – 44 V or ± 4.5 V to ± 22 V	VSS to VDD	MV Precision

4 References

- Texas Instruments, [TMUX13xx 5-V, Bidirectional 8:1, 1-Channel and 4:1, 2-Channel Multiplexers with Injection Current Control data sheet](#)
- Texas Instruments, [TMUX1108 5V / \$\pm 2.5\$ V, Low-Leakage-Current, 8:1 Precision Multiplexer data sheet](#)
- Texas Instruments, [Multiplexers and Signal Switches Glossary application report](#)
- Texas Instruments, [Using ADS8411 in a Multiplexed Analog Input Application application report](#)
- Texas Instruments, [Accurately Measuring ADC Driving Circuit Settling Time application report](#)

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