# $R_{ON}$ Modulation in CMOS Switches and Multiplexers; What It Is and How to Predict Its Effect on Signal Distortion*

By John Wynne

A single CMOS switch or a single channel of a CMOS multiplexer essentially consists of an N-channel and a P-channel MOSFET transistor in parallel. Figure 1a shows this basic arrangement. The respective drains and sources of the two transistors are tied together to become the switch terminals while the gates of the two transistors are usually driven with the power supply voltages, $V_{DD}$ and $V_{SS}$, to control the on/off action of the switch.

Essentially, the N-channel is on for positive gate-to-source voltages and off for negative gate-to-source voltages while the P-channel is vice versa.

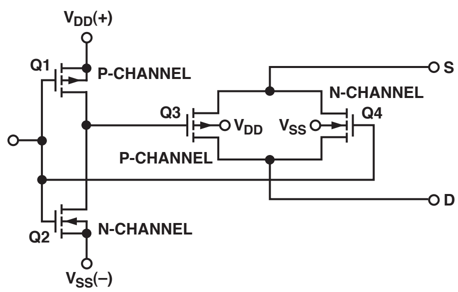


*Figure 1a. Basic CMOS Switch*

With a fixed voltage on the gate the effective drive voltage for either transistor varies in proportion to the polarity and magnitude of the analog signal passing through the switch. In Figure 1b, where $R_{ON}$, the resistance of the on switch, is plotted against applied analog switch voltage, $V_S$ or $V_D$, the resistance of the N-channel increases with positive voltage and the resistance of the P-channel increases with negative $V_S$ or $V_D$. The resultant parallel combination of these two characteristics (heavy line in Figure 1b) results in the well-known crown or twin-peak characteristic. This variation in on-channel resistance with input signal is termed $R_{ON}$ modulation, and the actual spread of maximum channel resistance to minimum channel resistance over the signal swing of interest is represented by $\Delta R_{ON}$.

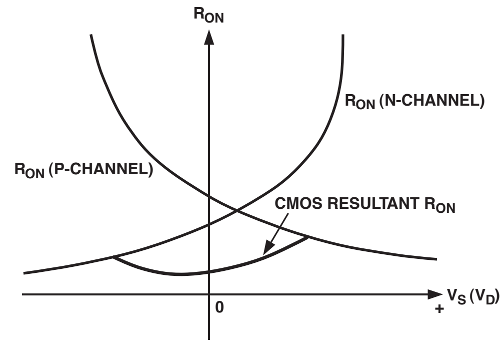


*Figure 1b. Individual MOSFET $R_{ON}$ Profiles vs. $V_S(V_D)$*

Figure 2 shows typical $R_{ON}$ profiles for Analog Devices ADG508A/ADG509A multiplexers. Three $R_{ON}$ curves are shown for three power supply ranges. As might be expected, both the absolute value of the channel $R_{ON}$ and the $\Delta R_{ON}$ increase as the power supplies are reduced. It is instructive to compare the $R_{ON}$ profiles from this generation of multiplexers with devices from recent generations. Figure 3 shows the $R_{ON}$ profile for the 4-/8-channel ADG608/ADG609 multiplexers. Due to the use of a 3 μM, 12 V process, these devices are limited to ±5 V operation rather than the ±15 V operation of the ADG508A/ADG509A series, which is built on a 6 μM, 44 V process. More modern examples of the emphasis within ADI to reduce $R_{ON}$ modulation are single SPDT switches, ADG619/ADG620, running off of ±5 V supplies or a single +5 V supply. The typical $\Delta R_{ON}$ for these switches is below 1 Ω with a typical on resistance of 4 Ω.

*Based on Application Note AN-251, which appeared in the ADI Applications Reference Manual of 1993.

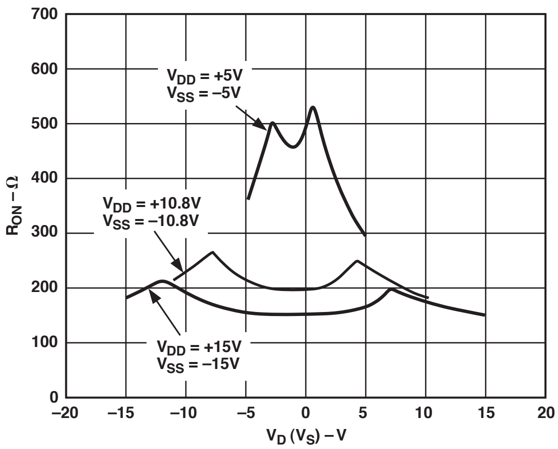


*Figure 2. $R_{ON}$ as a Function of $V_D(V_S)$: Dual Supply Voltage, $T_A$ = 25°C, ADG508A/ADG509A*

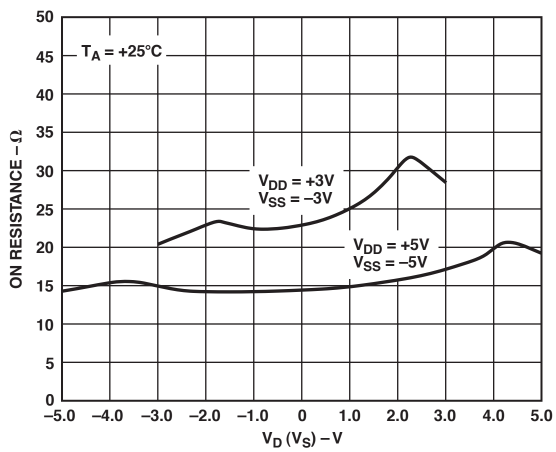


*Figure 3. $R_{ON}$ as a Function of $V_D(V_S)$: Dual Supply Voltage, $T_A$ = 25°C, ADG608/ADG609*

## MODELING THE DISTORTION EFFECT

Configuring the signal conditioning circuitry so that the switch or multiplexer operates directly into a summing junction of an op amp will obviously ensure a very low voltage across the switch which in turn virtually eliminates $R_{ON}$ modulation problems. However it is not always possible or desirable to do this; many applications require high level signals to be passed through the channel.

Figure 4 shows a typical situation where high level signals are multiplexed into a common load resistance, $R_L$. In this situation, $R_{ON}$ modulation can be kept to a minimum if the analog input signal range is restricted. For instance, for the ADG508A operating on ±15 V power supplies, $\Delta R_{ON}$ is typically less than 20 Ω, with a ±5 V input signal range, increasing to over 50 Ω, for a ±10 V signal range. In contrast, for the ADG608 operating on ±5 V supplies, $\Delta R_{ON}$ is typically less than 3 Ω within its specified ±3 V signal range, increasing to approximately 21 Ω for a ±5 V signal range.

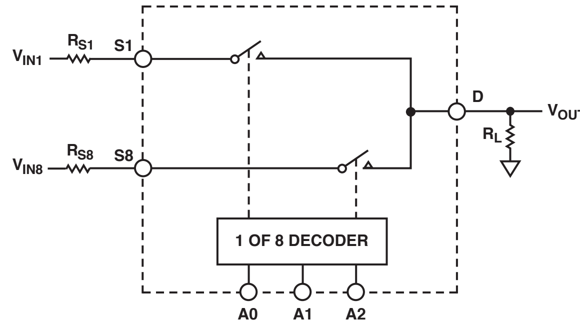


*Figure 4. Multiplexing High Level Signals*

Also included in Figure 4 are any source resistances, $R_{SX}$, which may exist for each channel. Over the signal range of interest, the amount of distortion generated through any one channel is proportional to the ratio of $\Delta R_{ON}$ to total minimum channel resistance:

$$Distortion \propto \Delta R_{ON} / \left(R_L + R_{SX} + R_{ON}\ min\right)$$

For any given multiplexer or switch with a given value of $R_{ON}$ min and a maximum value of $\Delta R_{ON}$ over the signal range, the distortion generated can be kept low by choosing a relatively large value for $R_L$, which does not compromise the performance of the circuit due to the additional thermal noise.

## PREDICT DISTORTION GRAPHICALLY

Figures 5 and 6 show nomographs that can be used to quickly predict, to a first order, the distortion generated through a single channel. The nomogragh scaling is based upon the circuit configuration of Figure 4. The left-most scale represents the total channel resistance from source through to load and including the switch $R_{ON}$ value at 0 V analog input. The middle scale represents the total harmonic distortion (THD) and the right-most scale represents the $\Delta R_{ON}$ over the signal range of interest.

To use a nomograph, locate the total channel resistance on the left-most scale and the $\Delta R_{ON}$ on the right-most scale. A straight line is drawn between these two points, and where the line intersects with the middle scale is the approximate THD to be expected from the system. Figure 5 is scaled for switches and multiplexers exhibiting a $\Delta R_{ON}$ from 10 Ω to 100 Ω; Figure 6 is scaled for more modern switches and multiplexers that exhibit a $\Delta R_{ON}$ from 1 Ω to 10 Ω.

Consider a switch with $R_{ON}$ = 15 Ω at $V_S(V_D)$ = 0 V and $\Delta R_{ON}$ = 3 Ω over the signal range of interest. With $R_S$ = 0 Ω and $R_L$ = 1 kΩ and using Figure 6, the THD through the channel is approximately 0.08% or –62 dB. Increasing the load resistor to 10 kΩ improves the THD to 0.0122% or –78 dB.

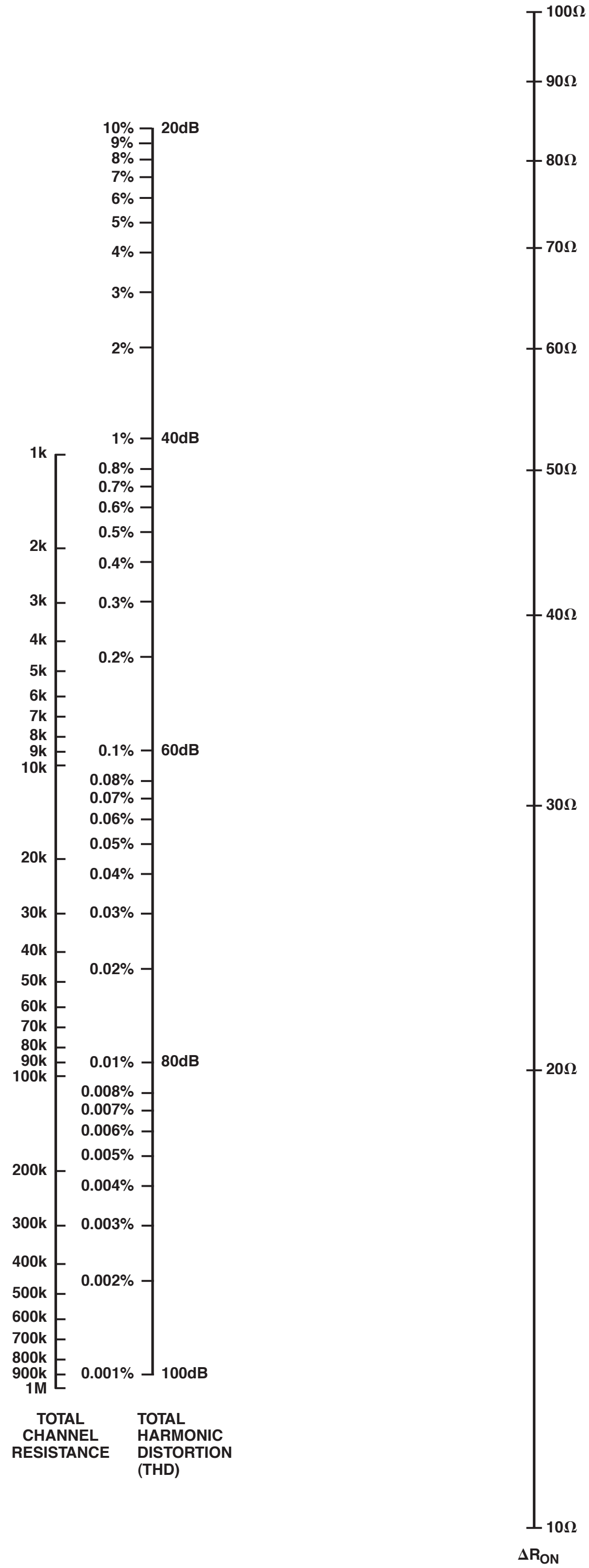


*Figure 5. Nomogragh to Determine THD Through a Single Switch or Multiplexer Channel, $\Delta R_{ON}$ from 10 Ω to 100 Ω*

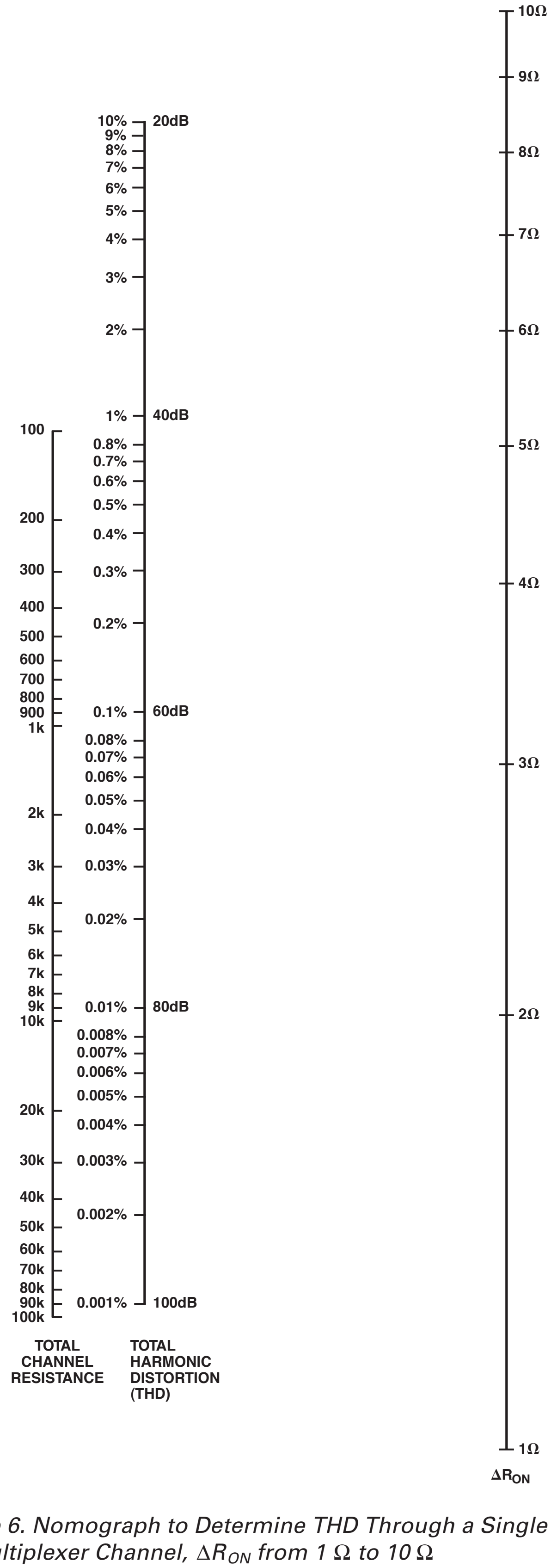


*Figure 6. Nomograph to Determine THD Through a Single Switch or Multiplexer Channel, $\Delta R_{ON}$ from 1 Ω to 10 Ω*