Understanding Key RF Switch Specifications
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In the world of high-speed instruments, a product’s bandwidth is often equated to its 3 dB frequency, the frequency in which a signal’s power is 3 dB, or 50%, below maximum. The bandwidth specification of an RF switch however isn’t necessarily its 3 dB point. Rather, it is the highest-frequency signal that the manufacturer believes you can route through the product with acceptable performance. Because the definition of “acceptable” varies, you may find that the performance of a 3 GHz switch also varies.

The ambiguity associated with the bandwidth specification of an RF switch mandates the assessment of lower-level specifications such as characteristic impedance, insertion loss, voltage standing-wave ratio, and isolation when comparing products from different vendors. But evaluating a product based on these specifications first requires a thorough understanding of their implications on product performance. The purpose of this article is to help you understand these implications through various examples and illustrations.

Before discussing characteristic impedance and other RF switch specifications, you must first understand the difference between how signals propagate in DC circuits versus RF systems. In DC circuits, or circuits where frequency of the propagating signal is low, the voltage of the signal at different points in a cable is likely to remain constant. With RF or high-frequency signals where wavelength of the signal is minute in comparison to the length of the cable, multiple cycles of the signal propagate through the cable at any given time, which gives rise to fluctuations along a cable’s length.

You can better understand the relationship between cable lengths and signal wavelength by comparing the propagation characteristics of a 1 MHz wave to that of a 1 GHz wave through a 1 m coaxial cable. Wavelength for both signals can be calculated using the formula:

\[ \lambda = VF \frac{3 \times 10^8}{f} \text{ m} \]

Here, \( \lambda \) is the wavelength of the signal, \( f \) is its frequency, and \( VF \) is the velocity factor of the cable. Assuming the type of cable in both systems has a velocity factor of 0.66, you get the following results:

Signal 1 (\( f = 1 \) MHz):

\[ \lambda_1 = 0.66 \frac{3 \times 10^8}{1 \times 10^6} \text{ m} = 198 \text{ m} \]

Signal 2 (\( f = 1 \) GHz):

\[ \lambda_2 = 0.66 \frac{3 \times 10^8}{1 \times 10^9} \text{ m} = 0.198 \text{ m} \]
Figure 1. High- and Low-Frequency Signals Propagating through a 1 m Coaxial Cable

Figure 1 and the signal calculations show that the length of the coaxial cable is considerably small in comparison to the wavelength of signal 1. Therefore, the variation in potential of signal 1 at different points in the cable is negligible. This is not the case for signal 2, where the length of the coaxial cable is much longer (almost five times) than the wavelength of the signal itself. Therefore, at any given time, multiple cycles of the signal traverse through the cable simultaneously. Signal 2 therefore propagates through the cable in the form of a wave and hence encounters power loss and reflections when traveling between varying media (wave theory). In the case of electrical circuits, this change in medium takes place when the signal (wave) is made to pass through system components that have varying characteristic impedances. Therefore, to minimize reflections and power loss, RF systems must be constructed using suitable components with matched impedances.

**Characteristic Impedance**

Characteristic impedance is a transmission line parameter that is determined by the physical structure of the line and helps determine how propagating signals are transmitted or reflected in the line. You can calculate characteristic impedance of the transmission line shown in Figure 2 as follows:

\[ Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \]

Figure 2. Characteristic Impedance of a Transmission Line

In the above formula:

- \( Z_0 \) = Characteristic impedance
- \( L \) = Inductance per unit length of the RF transmission line caused due to magnetic fields that are formed around the wires when current flows through them.
\( C \) = Capacitance per unit length of the RF transmission line. This is also the capacitance that exists between two conductors
\( R \) = DC resistance per unit length of the RF transmission line
\( G \) = the dielectric conductance per length
\( \omega \) = frequency (radians/s)

Because an ideal cable has no resistance or dielectric leakage, you can calculate its characteristic impedance can to be:

\[
Z_0 = \sqrt{\frac{L}{C}}
\]

Since all components in an RF system have to be impedance matched to minimize signal losses and reflections, component manufacturers specifically design their equipment to have characteristic impedances of either 50 or 75 \( \Omega \). 50 \( \Omega \) RF systems form the bulk of the RF market and include most communications systems. 75 \( \Omega \) RF systems are small in number and are prevalent in RF video systems.

**Insertion Loss**

Significant power loss in the signal occurs if the length of the transmission line it is made to propagate through is greater than 0.01 times its own wavelength. The “insertion loss” specification of a switch module is a measure of this power loss and signal attenuation. Insertion loss of a switch module at a particular frequency can be used to calculate the power loss or voltage attenuation caused by the switch on a signal at that frequency.

\[
\text{Insertion Loss (dB)} = 10\log_{10}\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right) = 20\log_{10}\left(\frac{V_{\text{out}}}{V_{\text{in}}}\right)
\]

Insertion loss occurs due to parasitic capacitance, inductance, resistance, and conductance that reside in the circuitry of the switch. These parasitic components combine to attenuate and degrade the signal that the switch routes. The power loss and voltage attenuation caused by these components varies with frequency of the input signal and can be quantified by the insertion loss specification of the switch module at that frequency. It is therefore critical to ensure that the insertion loss of a switch is acceptable at the bandwidth requirement of the application.

Imagine that you are in charge of selecting a switch to route eight 3 GHz video signals to a channel on a vector network analyzer with less than 30 percent attenuation (insertion loss should be less than 3 dB at 3 GHz). You are evaluating three RF switches from different vendors for the task. All three switches have a 75 \( \Omega \) characteristic impedance which makes them ideal for routing video signals, have the same topology (8x1 multiplexer) and use the same connectivity options. The modules from vendor ‘A’ and ‘C’ have a bandwidth specification of 3 GHz while that from vendor ‘B’ has a bandwidth specification of 2.5 GHz. After comparing the higher level banner specifications (bandwidth and topology) of all three products you determine that modules from Vendor ‘A’ and ‘C’ meet the requirements of your system but the one from Vendor ‘B’ does not
(its bandwidth is less than 3 GHz). However, a more detailed analysis of the insertion loss specification reveals otherwise. The graph in Figure 3 displays insertion data from 160 MHz to 3 GHz collected on all three switch modules through extensive tests.

![Insertion Loss Comparison](image)

**Figure 3. Insertion loss comparison for switch modules from 2 different vendors**

The graphs shows that at 3 GHz, insertion loss of the 2.5 GHz module from Vendor ‘B’ is approximately 1.78 dB while that of the 3 GHz module from Vendor ‘C’ is closer to 5.64 dB. The subsequent voltage and power loss caused by all three modules is shown in the table below.

<table>
<thead>
<tr>
<th>Vendor</th>
<th>% Voltage Attenuation at 3 GHz</th>
<th>% Power Loss at 3 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vendor ‘A’</td>
<td>13.9</td>
<td>26</td>
</tr>
<tr>
<td>Vendor ‘B’</td>
<td>18.3</td>
<td>33.3</td>
</tr>
<tr>
<td>Vendor ‘C’</td>
<td>47.8</td>
<td>72.7</td>
</tr>
</tbody>
</table>

*Table 1. Voltage and Power Loss Percentage Comparisons*

The calculations shown above imply that at 3 GHz, a 1 V pp sine wave, when made to pass through modules A, B, and C would be attenuated down to 0.861 V, 0.817 V, and 0.522 V respectively (see Figure 4). This means that the 2.5 GHz module B causes less signal degradation than its 3 GHz counterpart C. The example demonstrates the importance of considering the lower-level switch specifications such as insertion loss in addition to higher-level ones such as bandwidth, when choosing an RF switch for a particular
application. The 3 GHz module A and the 2.5 GHz module B meet the needs of the aforementioned application but the 3 GHz module C does not.

**Figure 4.** Attenuation Caused on a 1 Vpp Sine Wave by 3 different RF switch Modules

Voltage Standing-Wave Ratio (VSWR)

VSWR is the ratio of reflected-to-transmitted waves. As mentioned earlier, at higher frequencies, signals take the form and shape of waves when passing through a transmission line or cable. For this reason, just as in the case of sound and light waves, reflections occur when such signals traverse over different media (such as components with unmatched impedances). In a switch module, this mismatch occurs due to slight variances in characteristic impedances of the connector, the PCB traces, and the actual relay itself. The reflected wave, when summed with the input signal either increases or decreases its net amplitude, depending on whether the reflection is in phase or out of phase with the input signal. You can calculate VSWR as the ratio of the maximum (when reflected wave is in phase) to minimum (when reflected wave is out of phase) voltages in the "standing wave" pattern. To understand how to calculate VSWR and return loss in an RF system, let us consider the RF transmission line shown in Figure 5.

**Figure 5.** Comparison of Attenuation Caused on a 1 Vpp Sine Wave

In the circuit in Figure 5, the impedance of the load (50 Ω) is not equal to that of the source and the transmission line (40.9 Ω). For this reason, some portion of the signal...
propagating through the transmission line is reflected back from the load. You can measure this reflection by calculating VSWR using the formula:

\[ VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \]

In the above formula, \( \Gamma \) is the reflection coefficient and can be calculated using the following formula:

\[ \Gamma = \frac{Z_L - Z_o}{Z_L + Z_o} \]

For the circuit in Figure 5, you can calculate VSWR to be:

\[ VSWR = \frac{1 + \frac{Z_L - Z_o}{Z_L + Z_o}}{1 - \frac{Z_L - Z_o}{Z_L + Z_o}} = \frac{1 + 0.1}{1 - 0.1} = 1.22 \]

To visualize what is happening in this example, let us imagine that the signal being sourced in the RF system is a 1 Vpp sine wave. Because the reflection coefficient for the system is 0.1, we can determine that the magnitude of the reflected is 0.1 x 1 = 0.1 V or 100 mV. Figure 7 displays the maximum and minimum amplitudes of the resultant signal which occurs when the reflected wave is in phase and 180 deg out of phase with the input signal, respectively.
As stated earlier, VSWR is the ratio of maximum voltage to minimum voltage in the standing wave pattern. Using this definition, you can calculate VSWR from Figure 6 to be:

\[
VSWR = \frac{1.1}{0.9} = 1.22
\]

**Bandwidth**

Bandwidth is the maximum estimated frequency signal that a switch can route with acceptable performance. Because bandwidth is only an approximation, it is important to appraise it in conjunction with more absolute specifications such as insertion loss and VSWR which can be found in most switch module datasheets. Remember that bandwidth of an RF switch is not necessarily its -3 dB point. While some switch vendors use -3 dB as a benchmark for specifying bandwidth, others specify bandwidth at a frequency where insertion loss is typically less than 1.5 dB and VSWR is typically less than 1.4.

In Figure 5, insertion loss of the 2.5 GHz module B is approximately 1.5 dB at its bandwidth. In fact, the -3 dB point of this product is closer to 3.5 GHz. The reason why some vendors specify bandwidth at a frequency where loss is less than 3 dB stems from the fact that the RF switch is usually part of a larger system. In some cases, multiple switch modules are used for routing signals within a single system. If each switch were to add 3 dB of loss (cause 30% attenuation on the signal it is being used to route), total loss within the system could easily exceed 10 dB which is unsuitable for most RF applications.

**Isolation and Crosstalk**

Isolation is defined as the magnitude of a signal that gets coupled across an open circuit. Crosstalk is defined as the magnitude of a signal that is coupled between circuits (such as separate multiplexer banks on an RF module). Just like insertion loss and VSWR, isolation and crosstalk specifications of a switch module vary with frequency. You can find isolation and crosstalk specifications in most module datasheets.
You must evaluate the rise time specification of an RF switch module if you plan to route signals with multiple frequency components, such as square waves, through it. For example, when routing a square wave, which is made up of a fundamental frequency along with numerous odd harmonics, you must ensure that the bandwidth of the switch is high enough to cause minimum attenuation on all harmonics. In general, if the 3 dB frequency of the switch exceeds the frequency of the 7th harmonic of the square wave, its bandwidth is sufficient for routing that wave. This, however, isn’t always the case. If your application requires analysis of the nth harmonic of a given square wave, then the 3 dB frequency of the switch module must be higher than the frequency of that harmonic.

Figure 9 displays the rise time measurement for the 5th harmonic of a square wave. Assume that for your application this is the highest harmonic that needs to be routed through the switch. To determine whether a particular switch can successfully route the signal, you must compare rise time of the switch with the rise time of the harmonic. Sometimes this specification is not available for a switch module. In such cases, you must calculate the -3 dB point of this harmonic and compare it with the -3 dB point of the switch. You can do this using the formula:

$$3dB\ Point\ (dB) = \frac{0.35}{\tau_R}$$

where $\tau_R$ is the rise time of the switch module.
Using the rise time measurement of the signal in Figure 9, you can calculate the -3 dB frequency of the signal to equal 6.36 Hz (rise time is 0.055 s). Therefore, to make this measurement, you can use any switch that has an insertion loss specification of less than 3 dB at 6.36 Hz.

**Conclusion**

When selecting an RF switch, no individual specification is paramount. A switch with low insertion loss but high VSWR will minimize power loss and attenuation on the signal in the transmission line but can cause high-power reflections that could potentially damage the device under test (DUT) or source. Similarly, a system with low VSWR and bad isolation will minimize reflections but permit signals to bleed over between channels causing measurement errors. Finding the right RF switch is therefore an entailed task that requires you to pay due attention to all specifications, first individually and then cumulatively, in order to make an informed purchasing decision.

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