A Guide To RF Switching Systems

Whether you are designing an RF switching system or planning to purchase one, it is important to understand the fundamentals of these complex systems and the ways in which application requirements impact cost and performance.

BY SARA NAZEMZADEH

How do you design and develop a broadband complex RF switching system, or matrix, for your application that achieves great performance across the band? How do you select the best and most cost-effective RF matrix that meets your system requirements?

Whether your application is a ground system, test equipment, or a communication system, RF matrix design always begins with building blocks — discrete components such as switches, amplifiers or attenuators, power dividers, and couplers. As these building blocks are assembled, there are tradeoffs between switching speed and power handling, frequency and signal conditioning, and frequency and RF performance. In order to understand the challenges in a matrix design, it is important to understand the critical building blocks, as well as the important decisions that must be made along the way. This article will explain the requirements placed on switching systems and the tradeoffs that different choices will present.

RF Switching System Fundamentals

The main function of an RF switching system is to route RF signals between multiple inputs and outputs, where various signal routing topologies exist and signal conditioning is introduced.

There are two types of matrices:

- Electromechanical (EM) matrices, which use EM switches to interchange between signals
- Solid-state (SS) matrices, which use SS switches for routing signals

Before we get into the challenges introduced by these two designs and the critical steps to consider, it is essential to first understand what we mean by discrete components. Discrete components include passive components, such as power combiners/splitters (combine or divide two or more signals), directional couplers (direct the RF energy), circulators (split signals three ways), attenuators (decrease signals), isolators (omit signals), and filters (select signals). Discrete components also come in the form of active components, such as amplifiers (increase signals).

In addition, discrete components may include the brain of the system — the control circuit, which consists of a CPU (central processing unit) or microcontroller that allows local and remote control of the switching matrix. The discrete components, together with either EM or SS switches and cables, are the building blocks of an RF switching system.

DC Versus RF Signals

In order to recognize the challenges faced by an RF switching system, it is important to understand the difference between how signals propagate in a DC (direct current) system compared with an RF system. Since the routed signals (on the signal path) in DC systems are at low frequencies, signals at different points on a cable vary minimally. This is not the case with RF signals, whose frequencies can be much higher.

RF signal wavelength is small in comparison to the length of the cable, thus multiple cycles of the signal simultaneously propagate through the cable. As a result, the amplitude of an RF signal varies (since it is a wave), while it is constant for a DC signal. Compensation for signal degradation due to reflection and power losses must be made when working with RF signals. Also, as a matrix system cascades switches at least two levels, these RF properties increase in relation to each other and degrade the overall system performance, unless resulting tradeoffs are understood.

EM Versus SS Switching Systems

In many applications, the RF switch matrix has two critical functions — signal routing and signal conditioning. Prior to making critical decisions about these functions, a decision must be made between EM and SS matrices. In this section, we will take a closer look at the advantages and disadvantages of each system.

EM Switching Systems

EM switches have a number of advantages over SS switches. An EM switch can operate over a broader bandwidth (DC to 40 GHz or higher) with excellent signal linearity. Insertion loss is far lower, and the isolation between ports is far better in an EM system. Furthermore, an EM system can handle up to a few hundred watts CW (continuous wave) power. There are many EM switches on the market with various actuators, but latching switches are the best option since they maintain I/O (input/output) connectivity without AC (alternating current)/DC power present in the system. Hence, the last location of the switch will always be known at failure.

Figure 1: An electromechanical (EM) RF matrix

However, an EM switch also has some disadvantages:

- An EM switch has limited operating life, usually 1 or 5 million cycles.
- EM switches have much slower switching time (usually measured in milliseconds) than SS switches (microseconds).
- Since EM switches are larger than SS switches, the matrix box for a system requiring more than 12 switches on the input and output can easily increase to more than 4U (7 inches) in height.
- EM systems are more expensive than SS systems, since EM switches require more cables, and more interconnectivity signal conditioning is placed on the system (as shown in *Figure 1*).

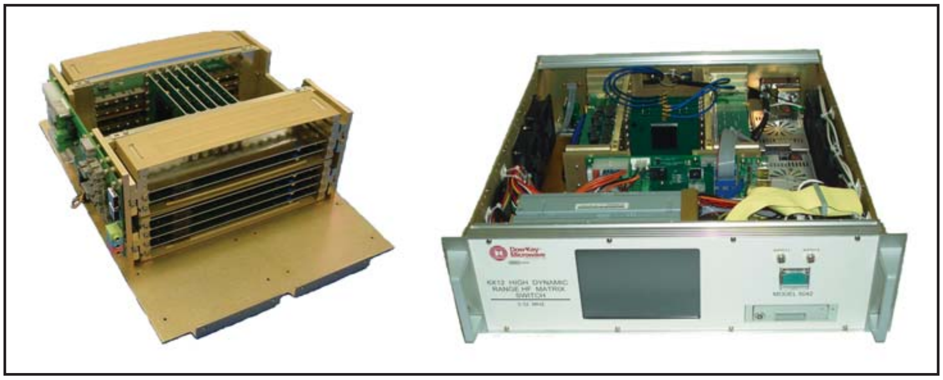

Figure 2: A solid-state (SS) RF matrix

SS Switching Systems

In SS switching systems, the switching capabilities are designed directly on a PCB (printed circuit board) at the solid-state level, where no mechanical parts are involved. PCB switching designs offer a number of advantages:

- SS switches are able to switch 100 to 1,000 times faster (in microseconds) than EM switches.
- Since SS switches are not restricted by mechanical parts, the number of switch cycles is infinite.
- Since multiple switches may be placed on a single PCB board (e.g. 4 x 8), the final size of an SS matrix is smaller. For instance, a 4U EM system can be reduced to a 3U (5.25 inch chassis) SS system. In addition, an SS matrix is less expensive than an EM system.

An SS matrix also has a number of disadvantages. It can handle only limited bandwidth — an SS matrix usually does not exceed 3 GHz (UHF band), while an EM matrix can easily handle DC to 18 GHz. Consequently, an SS system has limited operating power and limited linearity. Restricted isolation exists between input and output ports with higher RF losses. In addition, continuous power is required to maintain I/O connectivity; thus, a redundant power supply (for backup power loss) is advisable for sensitive applications.

Switching Topologies

Various switching topologies are available when designing a matrix system, each with its own advantages and disadvantages. The most common configurations are blocking and nonblocking, and more advanced topologies, such as nonblocking fan-in and fan-out matrices.

Blocking

A blocking matrix has switches on the inputs and outputs of the system, where each input signal can only be switched to a single individual output port at a time. One possible method of interconnection is shown in *Figure 3*.

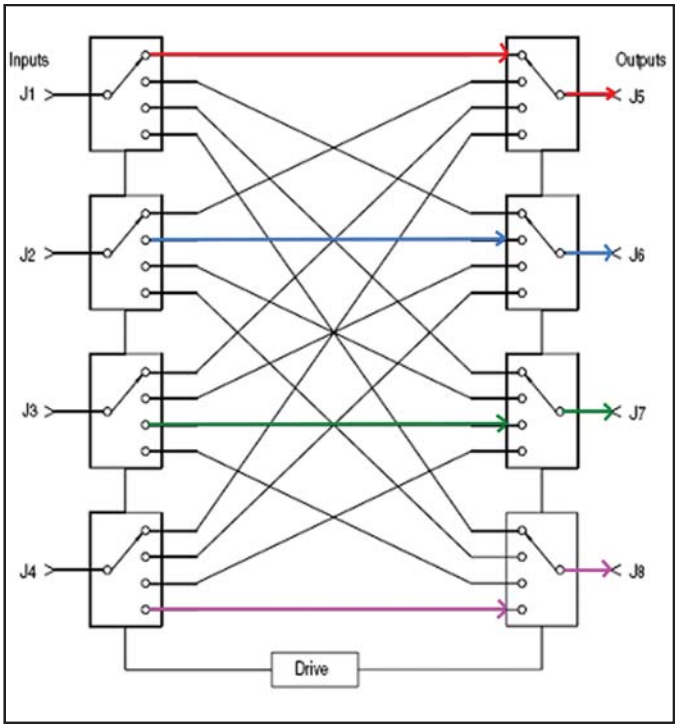

Figure 3: Interconnectivity — blocking configuration

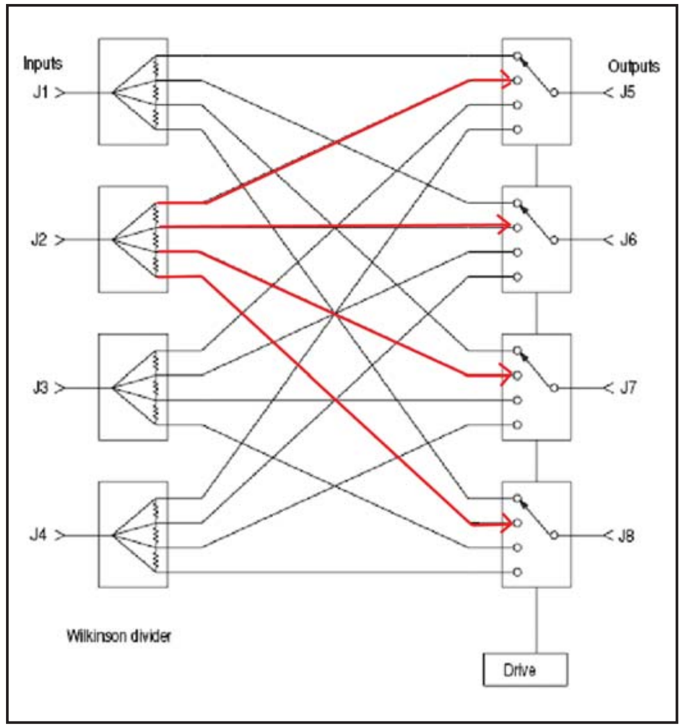

Figure 4: Interconnectivity — fan-out configuration

If an application requires an input to be available to more than one output simultaneously, then a nonblocking topology is required.

Blocking topology has some major advantages. Since no power dividers are involved, it is possible to maintain higher isolation and lower insertion loss from input to output, compared with other topologies. In addition, it allows higher bandwidth and provides bidirectional switching. However, it is not as flexible as the other configurations, because any input can connect to only one output at a time.

Nonblocking

Nonblocking topologies are manifest in at least two popular configurations: fan-out and fan-in. A nonblocking fan-out configuration has power dividers on the inputs and switches on the outputs as shown in *Figure 4*.

Hence, each input signal is divided between all output switches, which allows the user to select the signal at the outputs.

A nonblocking fan-in matrix uses the fan-out topology in reverse. It has switches on all its inputs and power dividers on all its outputs.

The major advantages of nonblocking systems are switching flexibility and high throughput between outputs connected to the same inputs. The tradeoffs are low isolation between output ports connected to the same input port and restricted bandwidth, which is limited by the isolation and the bandwidth of the power dividers.

In general, a nonblocking topology introduces an overall lower insertion loss into the system compared with a blocking matrix.

Signal Conditioning

It is important to carefully select the topology of the matrix. Each topology has its advantages and disadvantages as described in the previous section. In order to understand the tradeoffs presented by each configuration, it is necessary to comprehend how insertion loss, VSWR (voltage standing wave ratio), isolation, linearity, 1 dB compression point, phase matching, noise figure, and bandwidth are related, and how discrete components are used in a switching system.

Insertion Loss

Insertion loss is a measure of power loss and signal attenuation, and it varies with frequency. The parasitic capacitance, resistance, inductance, and conductance present in any system always result in some insertion loss.

Thus, power loss and voltage attenuation are a result of these physical factors. Insertion loss is highly dependent on frequency, therefore it is critical to know the bandwidth requirements imposed by your application in order to compensate for insertion loss.

VSWR, Phase Matching, And Return Loss

VSWR is a measure of the voltage of the reflected wave. Since at higher frequencies (RF), signals travel in waves and through different components (media), e.g. in a system, reflections always occur.

In a system, reflections may be the result of a mismatch between the impedance of the connector, the cable, and a single switch. A greater mismatch results in a worse (higher) VSWR. Also, it is important to note that VSWR is heavily dependent on frequency — VSWR increases as the frequency placed on the system increases. Hence, VSWR is a ratio of the maximum (when the reflected wave is in phase) and minimum (when the reflected wave is out of phase) voltage in a standing wave. Moreover, while VSWR is the measurement of reflected *voltage* ratios, return loss is the measurement of reflected *power* ratios.

Isolation

As it relates to a switching device, isolation is the measurement of the attenuated power traveling between the input and unconnected output in a system. The value is calculated at the unconnected RF output in terms of a power level difference expressed in dB.

Linearity

Linearity is the variation of a small signal gain given a varying signal input level, and it is typically measured in terms of nonlinearity, or deviation from the ideal. This means that an unwanted signal, which contributes to nonlinearity, will degrade the quality in signal band by causing interference and distortion. The greatest producer of nonlinearity in RF systems is the power amplifier.

There are three measurements commonly used to characterize linearity in RF systems: the 1 dB compression point, second-order intercept point (IP2), and third-order intercept point (IP3).

The 1 dB compression point is defined as the power at which the gain level falls below its ideal value by 1 dB (shown in RED in *Figure 5*).

IP2 and IP3 (shown in BLUE in *Figure 5*) represent the two most important linearity specifications of a receiver system. These measurements describe the susceptibility to interference by adjacent or nearby signals. This occurs when two input signals of slightly different frequencies are multiplied, such that their sum is raised to a power greater than unity. Intercept points (intermodulation) occur at a frequency equal to $2f_1$-f_2.

Discrete Components And Their Functions

Now that we have a better understanding of the types of signal conditioning that exist in a switching matrix as well as their definitions, let's look at the various discrete components that can be used to improve the RF characteristics of a matrix. These include directional couplers, power combiners/splitters, amplifiers, attenuators, terminations, circulators, and isolators.

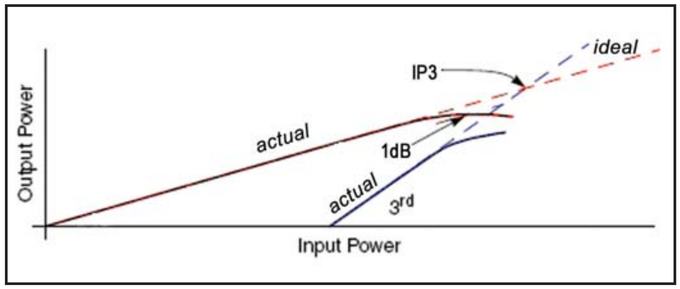

Figure 5: 1 dB compression point and third-order intercept point (IP3)

Directional Couplers

Directional couplers have two qualities: They allow high-power RF signals to be monitored and measured at a safe level without alternating the transmission line, and they determine the direction in which the RF energy flows.

In a matrix, directional couplers are mainly used for power level measuring (insertion loss) and detection of VSWR (voltage level measuring). This, in turn, will set alarms through the board that handles all software applications of the switching system.

Power Combiners/Splitters

Power combiners join two or more signals; power splitters divide two or more signals. These components are used particularly in nonblocking fan-in and fan-out switching topologies.

The key performance parameters for a power combiner or splitter are low insertion loss and lower (better) VSWR. In general, the performance parameters are a function of frequency. Hence, near the frequency band edges, isolation can further be improved at the expense of VSWR by adjusting the value of the internal load (using terminations). Another way in which isolation can be improved is by reducing the bandwidth of the power combiner/splitter to a narrower band for optimization purposes.

Power Amplifiers

Amplifiers are used to increase the amplitude of or maintain the RF signal from the input to the output path in a matrix. This power amplification also is known as gain, which is the ratio of output power to input power specified in +dB.

Power amplifiers often are used in a switching system on the input to compensate for losses through the switch and cables in a matrix. Maintaining the signal level, if that is required by a specific application, will result in a lower insertion loss and higher isolation.

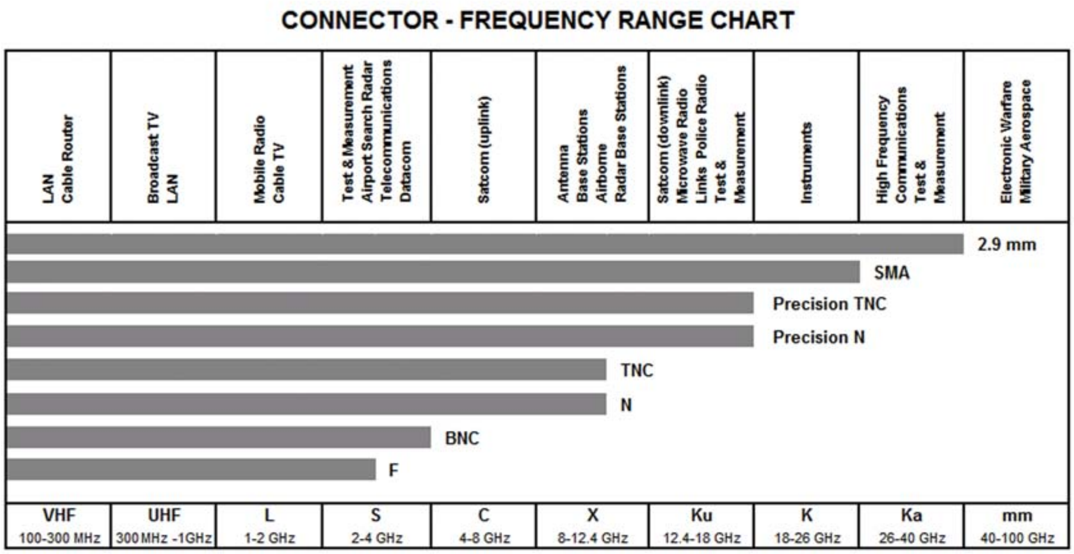

Figure 6: Connector frequency range chart

Attenuators

Attenuators have the opposite function of amplifiers. They are used to reduce the amplitude of the signal while maintaining the proper input-to-output impedance of all devices connected to the ports of the switching system.

There are two types of attenuators that should be considered when designing a matrix. A fixed attenuator reduces the input signal power by a fixed amount (e.g. 1 dB, 2 dB, 3 dB, etc.). A variable attenuator may vary continuously or in steps from 0 to 60 dB.

Attenuators often are used at the input of a receiver matrix, since the transmitted signal usually needs to be reduced before being processed. On the other hand, a transceiver unit usually needs to amplify the signal at the output before transmitting the signal to a satellite.

Terminations And Load Matching

Ideal load of impedance is often referred to as termination. In switching matrices, termination usually is either 50 ohms (most common) or 75 ohms (mostly used for video signals).

A termination is connected to the end of a transmission line whose characteristic impedance is also the same, and it absorbs all reflected power in the transmission line traveling toward the load. Hence, load matching is very critical in a matrix.

Fixed attenuators may be used for load matching since they reduce the power level of a signal by a fixed amount with little or no reflection. Thus, the output signal is attenuated relative to the input signal, while the input and output impedance is maintained close to 50 ohms (or 75 ohms) over the specified bandwidth. Hence, this device often is used to improve internal load matching.

Circulators

A circulator is a three-port component in which the adjacent ports are in one direction but isolated in the reverse directions. A typical application for this component is to separate the dual signals — transmit and receive — from an antenna. Hence, using a circulator in a switching system with antenna signals at the inputs, the matrix will be able to separate the transmit signal from the receive signal of the antenna.

Circulators have low electrical losses and can handle high power — well into kilowatts. They usually operate over no more than an octave bandwidth and are purely an RF component.

Isolators

An isolator is a component that allows microwave energy to travel in one direction but absorbs and attenuates energy traveling in the opposite direction. A typical application is to place an isolator between a signal source and a transmission line.

Thus, if an impedance mismatch occurs down the transmission line, the isolation will not allow any reflection back to the source.

By terminating one port, a circulator can become an isolator. Thus, by isolating components in a matrix, a high VSWR value on one input-to-output path can be prevented from causing a ripple effect throughout the system.

Connectors

The last critical RF components to consider when designing or buying a switching system are the connectors. What many people do not know — or pay enough attention to — is the limitations each connector puts on the RF parameters of a system.

The eight most common female connectors used in a matrix are F, BNC, N, TNC, Precision N, Precision TNC, SMA, and 2.9 mm connectors. *Figure 6* shows the frequency ranges for each connector type. The SMA connector is the most commonly used because it can handle up to 26 GHz signals, which is sufficient for most applications.

If a TNC or N connector (each handle signals up to 10 GHz) is on a matrix with DC to 18 GHz capability, the upper band frequency will be limited to the cutoff frequency of the connector type (which is about 90% of the rated connector frequency). Hence, the switching unit will operate around 10 GHz (refer to *Figure 6*) instead of 18 GHz. Therefore, choosing an appropriate connector for one's application is critical.

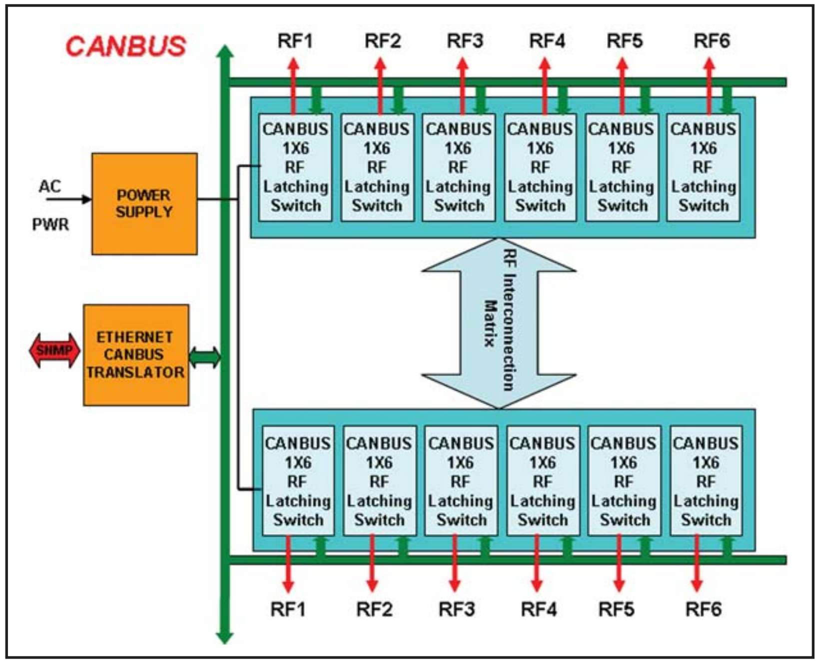

Figure 8: CANbus control interface

Control Interface

Now that we have addressed the critical decisions in terms of RF tradeoffs, let's explore the types of control interfaces to be considered when designing or purchasing a matrix. These include CANbus (Controller Area Network), Ethernet, GPIB (General Purpose Interface Bus), RS-232, and RS-485.

CANbus Interconnection Interface

CANbus is a serial bus that has become a popular interface for interconnecting multiple switches in matrix integration. Since this interface is used internally, it is transparent to the user. *Figure* 7 shows a Dow-Key SP6T EM switch with a CANbus interface. This interface

Figure 7: Dow-Key SP6T CANbus EM switch

features a high-speed communication rate (up to 1 Mbits/sec), real-time control, error confinement, and error detection. These attributes make it reliable in noise-critical environments, such as in a switching system.

External Interfaces

The Ethernet interface is the widely known interface used in LANs (local area networks). If an interface is required to connect a switching system to a network through a hub or router, then having Ethernet capabilities is a must, due to its speed. When sending commands over a network to remotely control a switching unit, Ethernet provides the fastest method of communication.

Another communication interface widely used with a matrix unit is GPIB, also known as IEEE-488. It communicates over a parallel bus and is widely used in test equipment. However, unlike the Ethernet interface, GPIB cannot be connected to a network.

RS-232 and RS-485 are interfaces that communicate in serial. Therefore, the speed of transmitting and receiving data (for remote control purposes) over these types of interfaces is much slower than with Ethernet and GPIB.

Most switching units come with either the combination of an Ethernet and an RS-232, or a GPIB and an RS-232. It is up to the user — based on preference and application needs — to determine which option to use for remote control of the switching system.

Figure 8 summarizes how CANbus interconnections are used together with Ethernet as the external communication interface for a 6 x 6 matrix.

Cost Analysis And Tradeoffs

The final, yet extremely important, decision to make is the cost of the solution. The questions that need to be asked are: Do you really need a smaller matrix or one that can accommodate future system requirements? Do you need a broadband frequency range? Do you need a flexible matrix system with fan-out topology? All of these options have price tags attached.

Matrix Size Requirements

The critical question to consider when making a decision about the size of a switching unit is: Is the size of the matrix required to support immediate needs or future system capacities?

When it comes to selecting a matrix for immediate needs, you should consider purchasing a standard-sized system with typical components, since these units are less expensive and custom modifications are not required. For instance, if you only need an 8 x 8 EM matrix that consists of SP8T switches, buying a 10 x 10 matrix (with two extra ports) may actually cost less, because SP10T switches are sometimes cheaper than SP8T switches. The cost of the SP10T and SP8T switches is dictated by the popularity of each switch and how often the manufacturers make them. The more switches manufactured, the less it will cost to make them.

If you believe you will need to expand your application with future matrices, then you should consider a matrix with capabilities that will support those requirements. Obviously, this approach is more expensive. If, on the other hand, you do not anticipate such future needs — and cost is a driving factor in your decision — select only what you need and not more. However, it is important to note that today most matrices are designed to accommodate future needs, and you are indirectly paying for it (even if you don't need it).

Frequency For The Right Price

Let's use an EM nonblocking switch matrix and an EM nonblocking fan-out matrix, each with a standard bandwidth of DC to 18 GHz, to demonstrate how frequency affects the price of the matrix.

Using a nonblocking EM matrix with the bandwidth DC to 18 GHz as a reference point, cost can be adjusted the following way. If the insertion loss is not too demanding, and more stringent RF specifications are required for lower frequency range or for a narrow band (rather than for the entire broadband), a reduction in cost is achievable.

On the contrary, by increasing the frequency range to 26.5 GHz as the upper limit, the cost of the matrix will increase between 30% and 50%, depending on the specified RF parameters and the matrix topology. By increasing the upper limit to 40 GHz, the cost of the matrix will double or even triple.

In an EM nonblocking fan-out matrix, the cost will further increase due to the necessary power dividers — and amplifiers if required — at all input ports. Power combiners and amplifiers (and EM switches) are the most costly components in a standard fan-out/fan-in matrix. It is critical to make sure a matrix is designed or purchased to meet the need of the specific application. A general rule of thumb is that power dividers are required for systems operating below 400 MHz, due to the lumped elements (parallel LC resonance in transmission line). For systems operating over 400 MHz, splitters are needed.

Cost Of Adding Amplifiers

Amplifiers (discrete components) are expensive, and most fan-out matrices are equipped with few of them. Hence, amplifier cost has a significant impact on the overall price of the matrix in broadband solutions. Price also is influenced by matrix RF specifications that impose demanding requirements on amplifiers.

For instance, demands are imposed on input power (1 dB compression point), linearity (IP2 and IP3), and noise figure. These requirements become more costly when a typical SS matrix requires at least two cascaded amplifiers, where one is placed on the input ports and the other on the output ports. However, amplifiers in most EM matrices are placed only on input ports.

Conclusion

Whether you are designing a matrix or planning to purchase one, it is important to understand how every decision makes a difference in the cost of the matrix and impacts RF performance.

The more components that go into a matrix, the more the system must compensate for signal loss and other RF parameters that are affected. As a result, integration of discrete components in switching systems is a complex, yet highly important, matter. ■

Acknowledgements

The author would like to thank Dr. Krzysztof Ciezarek (VP of engineering), Adolf Cheung (VP of sales and marketing), and Giuseppe Bondi (engineering manager) of Dow-Key for their support and insightful knowledge of RF systems design.

Sara Nazemzadeh *has been an applications engineer at Dow-Key Microwave Corporation since 2007 and works as the link between engineers, sales, and customers. She is responsible for technical inquires and design on the front end, with a focus on matrix switching systems. Previously, she worked at Vitesse Semiconductor Corporation designing switch hardware, and at Canoga Perkins working with testing and firmware design. She received her BS in computer engineering in 2005 and her MS in electrical engineering in 2007 from California State University, Northridge.*