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1 Introduction

This application note describes the different types of switch matrix products available for IF, RF and microwave switching. It also discusses many of the important tradeoffs that should be considered when selecting a switch matrix to fit your application.

Many installations and facilities use switch matrix products throughout the entire signal chain. This paper is focused on those portions of the system where the signals being switched are (typically) modulated carriers. The type of modulation is not important to our discussion, since the switch matrix only has to pass the signal without degrading it. We are interested in the portions of systems passing RF signals that are already modulated (on the transmit side) or not yet demodulated on the receive side. Signals received from an antenna or down-converted by a LNB, for instance, are part of our discussion. So are multiple carrier multiplexes being prepared for transmission.

But we exclude switches designed for baseband or digital signals such as RS-232, ECL, RGB video, audio and similar signals. Although some of these signal types can cover many MHz of bandwidth, they require switch matrix designs that are substantially different than those of an RF, IF or microwave switch.

For the purposes of this paper, we will assume that the application is a satellite communication ground station. The process of selecting a switch can be applied equally well to other application areas, but it is convenient to use one of the most common applications, because it provides a variety of possible switching configurations for our discussion.

1.1 Key Definitions

A glossary of terms is included at the end of this document. In this document, we will need to distinguish the switch matrix from an individual switch element inside the matrix. We will refer to the switch matrix as a whole, by the term “matrix”. We will refer to an individual switch element inside a matrix, as a “crosspoint”. In this way, we will minimize the use of the term “switch” with its potentially ambiguous meaning.

Unless we specify otherwise, when the following discussions refer to “RF” signals, we mean any frequency, so that IF, RF and microwave signals are all being considered.

1.2 Organization

Section 1 of this paper will encourage you to read with your own application in mind. Some key questions are listed, which will allow you to make your own tradeoffs as you read.

Section 2 covers some basic switch matrix terminology and looks at block diagrams of contrasted architectures.

Section 3 describes the different types of physical switching elements (crosspoints) that are found in switch matrix products. Those technologies are compared in a number of categories and generalizations are made regarding the suitability of each for various application requirements.

Section 4 looks at the switch matrix as a complete system. The discussion focuses on tradeoffs in such areas as physical packaging, method of control, maintainability, and other system level issues.

1.3 Know Your Application

The first thing to that will affect your selection is the matrix's location in the signal chain sequence. Location implies things about signal characteristics and its importance to the overall system.

- Will it be located in the receive or the transmit side of the signal chain?
- Will the signals be very low levels or will they have been amplified to very high levels when they reach the matrix?
- Will the signals passing through the matrix be revenue generating (or otherwise critical to you or your customer) or will they be monitor and test signals used for maintenance?

The second thing that will influence your decision is the anticipated size of the switch matrix.

- How many inputs and outputs are required?
- How much physical space is available for the matrix?
- Is significant expandability required? Can a small percentage of spare inputs and outputs be adequate to cover future needs for the life of the matrix?

2 Switch Configuration Tradeoffs

Like many engineering problems, there are multiple solutions to the problem of switching signals. Several typical configurations have been used in the industry, each with its own merits. Vendors will optimize their own designs, of course, but in general, the respective product offerings can be grouped by a few characteristics of their internal design.

For our discussions, we will take an example switch matrix that has 4 inputs and 4 outputs. This matrix would be designated as a 4X4 configuration. A switch matrix can have any number of inputs and outputs, designated as NxM. A 4X4 configuration is unusually small, but it reduces the complexity of the drawings.

2.1 Directionality

Switches can be unidirectional or bi-directional. Few RF applications require true bi-directionality in the matrix, because the upstream and downstream equipment typically only moves the signal in one direction. If the switch has gain elements (amplifiers) it typically cannot be bi-directional.

Almost all bi-directional switches have a single input or single output. So they are 1xN or Nx1 configurations. For our purpose here, we will not consider bi-directional switches since they are rare and typically very small.

2.2 Blocking vs. Non-Blocking

A primary differentiator for switch matrices is whether they have a “blocking” or a “non-blocking” architecture. Blocking is the situation where the user wants to connect a particular input to a particular output, but the switch matrix is not able to do so, because that input is already committed to another output. So the request cannot be satisfied *without changing other connections or outputs*.

Some systems tolerate rearrangement of existing channels, so a blocking characteristic is acceptable. The public switched telephone system is one example. In commercial or military satellite environments, the momentary interruptions associated with any path re-arrangement would be unacceptable.

The figure below shows a simple 4x4 blocking switch matrix. The heavy lines show that input 1 is connected to output1, input 2 to output 2, etc. The inputs all pass through 1-to-4 switches on the left side of the diagram. The outputs of these four switches are connected to mirror-imaged 4-to-1 switches at each of the outputs. There are a total of 4x4=16 interconnections required to give every selected input a path to each of the outputs.

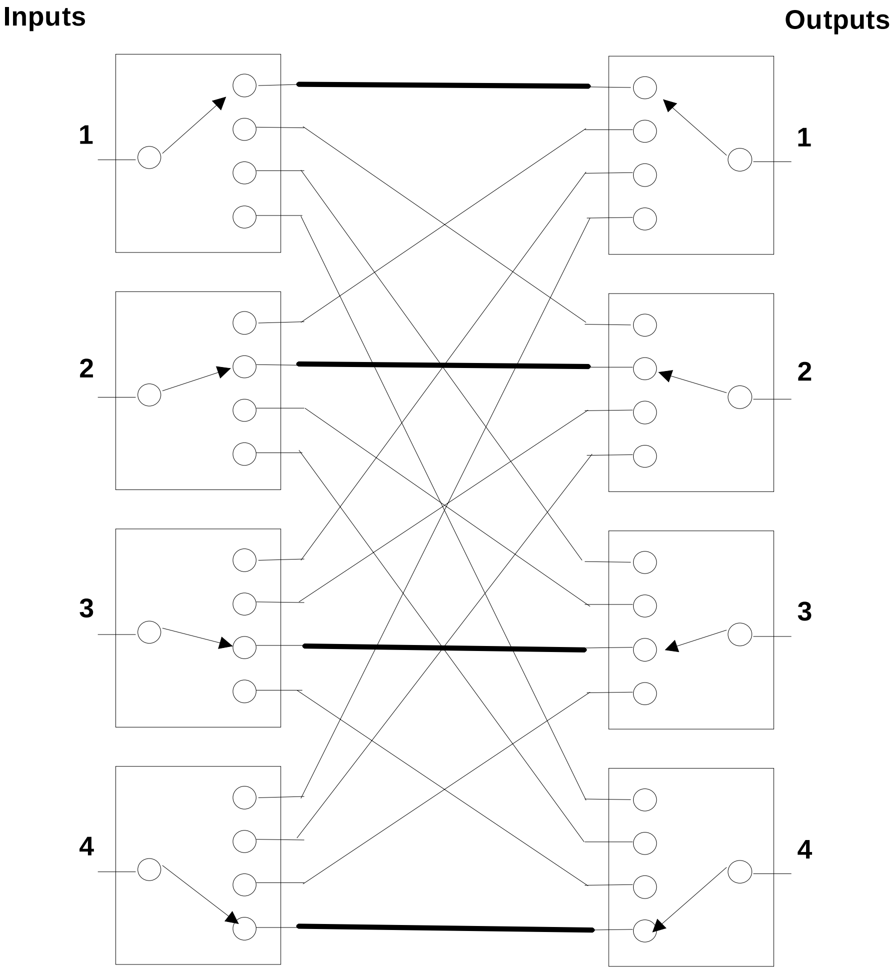

Figure 2-1 : 4x4 Blocking Switch Matrix

So far, this switch has accomplished 4 connections. But if the user of Output 2 needed to look at input 1, the switch could not service the request. The figure below shows this situation:

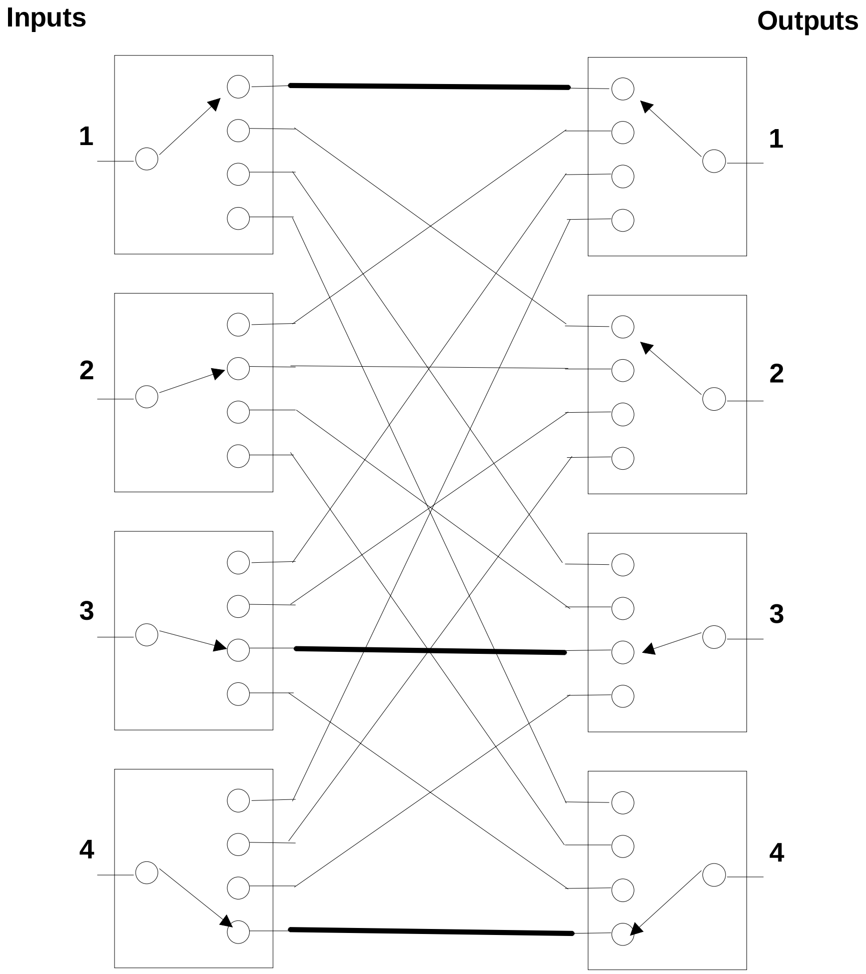

Figure 2-2 : 4x4 Blocking Matrix with Output 2 Blocked

Output 2 cannot be connected to Input 1 unless Output 1 relinquishes its own connection to Input 1. This configuration can only connect an input to (at most) one output at a time. We say this configuration has a fan-out of 1, and this matrix design is not “full-fanout”

A non-blocking switch is one where no request for a connection is ever blocked. This requires that each input signal be handled in such a way that it can be sent to many destinations simultaneously. If we replace the input 1-to-4 switches with 1-to-4 power dividers, we can overcome the blocking situation. The figure below shows a full fanout, non blocking 4x4 switch matrix. The power divider is shown as a transformer with multiple secondaries. Each output of the power divider is an independent copy of the input, though it is at a reduced power level (the incoming RF power was divided equally among the N outputs)

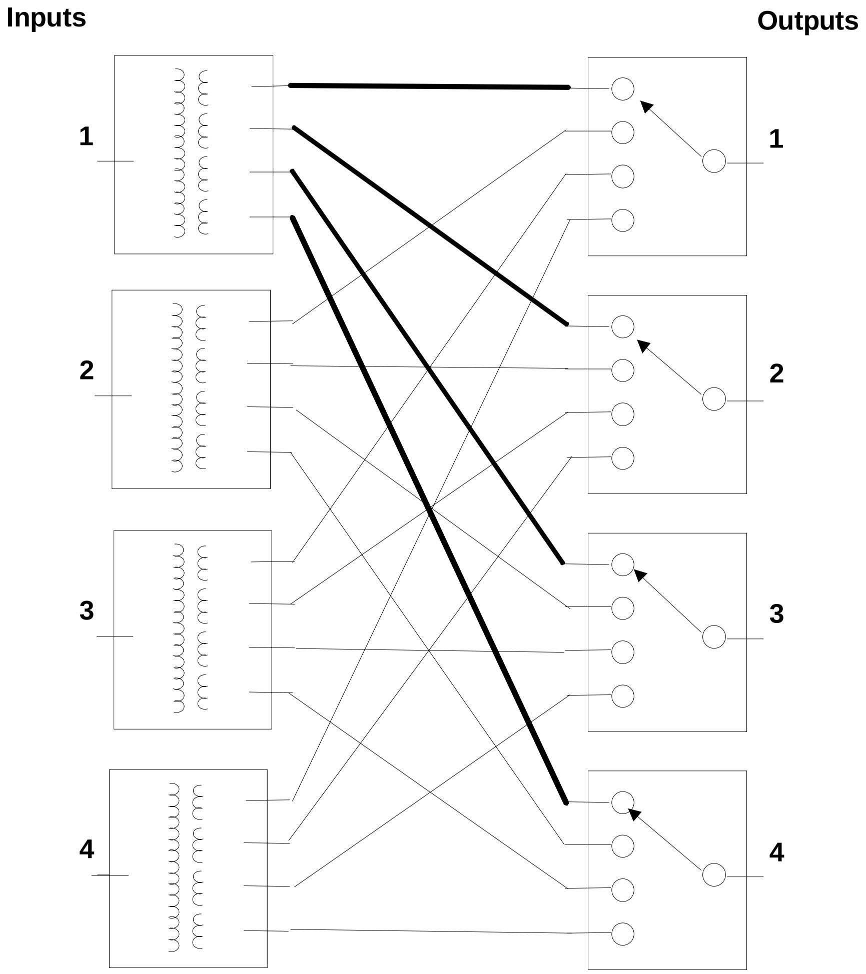

Figure 2-3 : 4x4 Non-Blocking Switch Matrix

The total number of interconnects between the power dividers and the switches is the same as in the blocking switch. For an NxM switch matrix, each input power divider will need M outputs, and each output selection switch will need N inputs.

Full fanout, non-blocking matrices are very common. The price paid for the non-blocking feature is the signal path losses in the power dividers. A blocking switch matrix can often be completely passive, since the only losses are two switch contacts and some interconnecting cable. It is possible to have total losses under 2 dB for a 16x16 blocking matrix. Lower loss also yields better bandwidth, better flatness, lower noise, lower distortion and higher power handling.

But most applications require a non-blocking architecture. The non-blocking matrix usually requires amplifiers to recover the signal attenuation of the power dividers. This means higher power consumption, some loss in signal fidelity, and increased complexity. But with proper design, the performance can remain excellent over a wide dynamic range.

2.3 Fan-In vs Fan-Out

The non-blocking switch matrix block diagram in Figure 2-3 shows that it is possible for an output to connect to only one input at a time. However, any input can be connected simultaneously to multiple outputs, because of the power dividers. This type of matrix is called a fan-out matrix. It is the most common configuration. It is used mostly in receive-side applications, where a signal may need to be routed to multiple destinations simultaneously.

A fan-in configuration is a mirror image of the fan-out. The figure below shows a 4x4 fan-in non-blocking switch matrix. Output 1 is connected so that it provides the summation of all 4 input signals. The Fan-in configuration finds its usefulness in uplink paths, where multiple carriers (at non-overlapping frequencies) may be multiplexed together by the power combining property of the power divider.

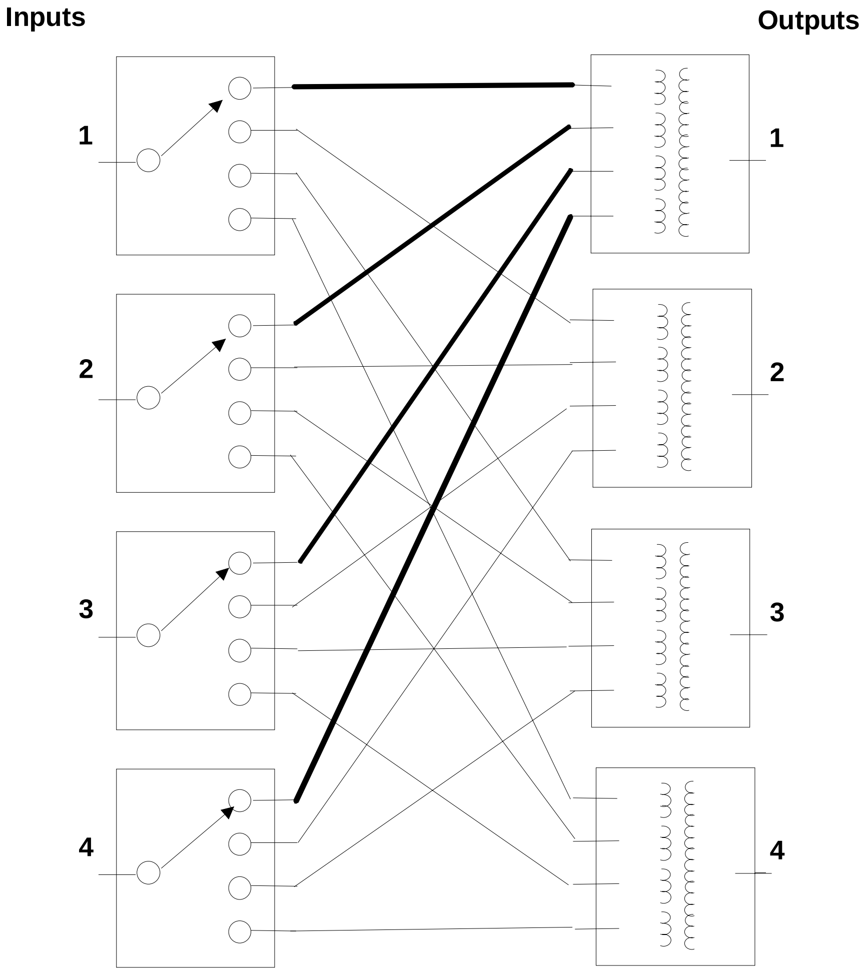

Figure 2-4 : 4x4 Full Fan-In Non-Blocking Switch Matrix

2.4 Single vs. Multi-level

Switching occurs in multiple stages within a large matrix. It is usually not possible to build a single multi-pole switch that has enough capacity for all the signals. Instead, switching components are cascaded until the full capability is realized. For instance, semiconductor crosspoints are limited by the number of pins that can be mounted on a single integrated circuit. The practical limit at high frequencies is about 8 inputs. So a 32 way switch will require multiple 8 pole switches to achieve its required capability.

A large switch matrix can be built up from smaller complete matrices. This is typically how vendors proved their largest switch offerings. So a matrix switch typically has a core switch size and a core power divider size that become the building blocks for all matrices in a product line.

The 4x4 matrix in our examples above is a single level switch matrix. All the power dividing occurs before any switching occurs. If you were to trace aany connection path, you would encounter a total power division ratio of M before encountering any switches. Then you would encounter N selction switches without encountering any more power division.

A multi-level switch breaks the matrix into smaller independent non-blockign full fanout matrixes. When tracing a path from an input to an output, the signal would be divided by less than M, then selecgted by a switch that was less than N wide, then power divided some more, then down-selcted some more, until the total power division was at least M and the total selection was at least N. A diagram will make this clearer.

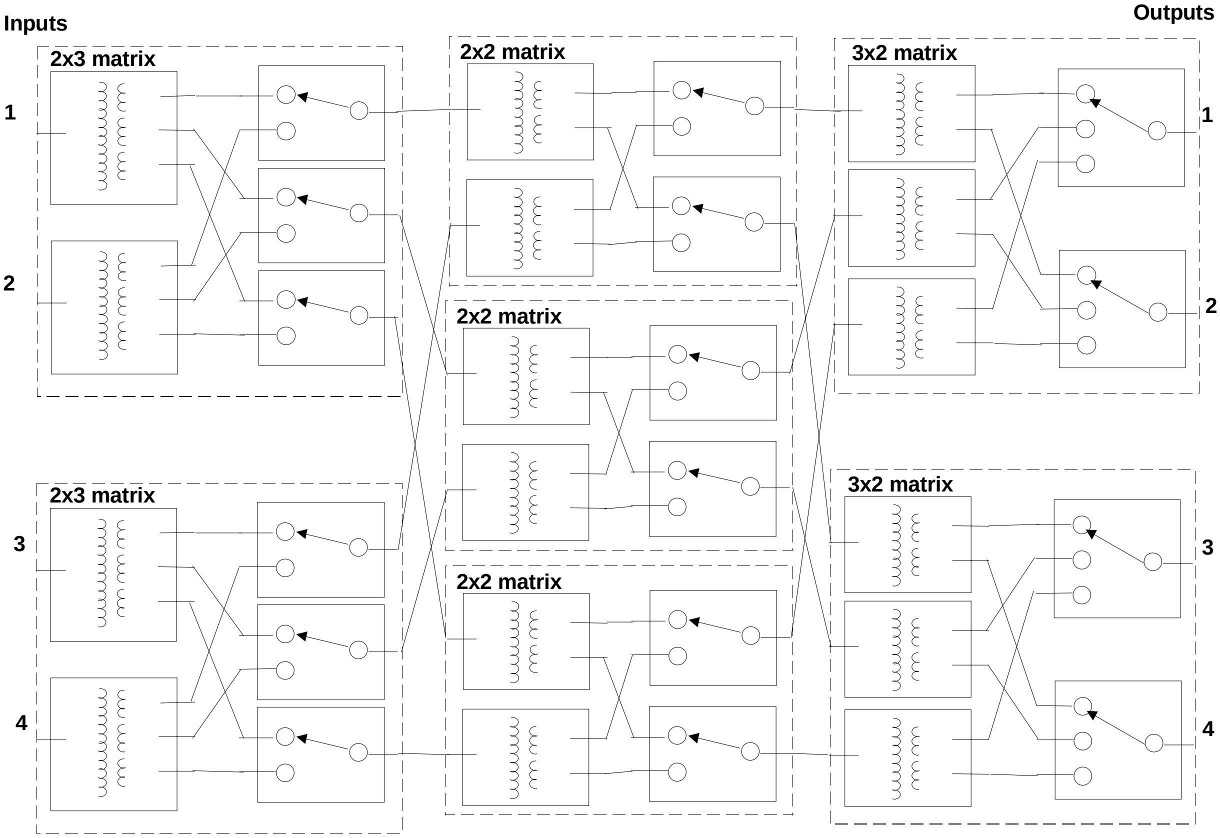

Figure 2-5 : 4x4 3-Level Non Blocking Matrix

A 4x4 matrix is too small to achieve any benefit from a 3-level architecture, but for simplcitiy we use it anyway. In fact, there is a significant cost penalty associated with 3 level switches, until the total matrix size reaches about 32x32.

The 4x4 is shown as interconnections of smaller NxM matrices. A 2X3 matrix is used at the input, a 2X2 matrix is used in the center column, and a 3X2 matrix is used at the output. This configuration meets the mathematical criteria for a minimal size 3-level 4x4 non blocking switch. All output requests can always be satisfied, without rearranging any other paths. [for a discussion of the mathematical criteria for 3-level non-blocking switches, see Benes, reference 1).

Compare the 3 level switch to the single level switch matrix. The single matrix required 16 interconnecting paths between power dividers and switches. The 3-level version requires 48. The total power division ratio (power loss) for the single level switch was 4 (6 dB). For the 3-level switch, that loss ratio is 12 (11 dB).

The benefit to the 3 level switch are two-fold. In very large switches, the total switch crosspoints can be reduced to less than NxM. This results n substantial cost savings in a large switch. The second benefit is that there are redundant paths between any input and output pair. This redundancy can only be used if paths are permitted to be reconfigured, but in critical applications, this redundancy may be worth the extra complexity.

3 Switching Technology Tradeoffs

3.1 Crosspoint Types

There are 4 major types of electronic switches that are applicable to the RF/IF environment. Two are solid state devices, and two are electromechanical devices. The electromechanical devices are coaxial relays and reed relays. The solids state devices are GaAs MESFETs and PIN diodes. CrossPoint Technologies can provide any of these switching elements in a matrix. The most common is the GaAs FET, followed by the microwave coaxial relay. The reed relay is popular at lower frequencies, and the PIN diode is requested in only a few applications.

The sections that follow will give a comparative overview of these switching technologies. Most of the comparisons are shown graphically, but the numeric scales should be treated as approximations only. Manufacturers are constantly extending the performance of their components. The limits are intended to show relative strengths, rather than specific performance limits.

In the graphs and discussions that follow, only the crosspoint components themselves are under consideration. The impact of amplifiers, power dividers, cables, etc are not considered unless explicitly stated.

3.2 Frequency

The electromechanical devices have the potential to pass DC and very low frequencies. However, if amplifiers are used in the matrix, the low frequency capability is usually lost. The dotted line in the reed relay shows that some relay vendors claim usable performance beyond 1 GHz, but most matrix products seem to limit themselves to 500 MHz or so.

The GaAs FET and PIN diode both operate above 10 GHz. Low frequency performance of the solid state solutions is often limited by the biasing networks, which tend to interfere with, or distort the signals. GaAs FET distortion tends to increase dramatically in the lower MHz region, though GaAs is still usable in some low frequency applications. The ease of biasing and low power (see below) are often more important than low distortion

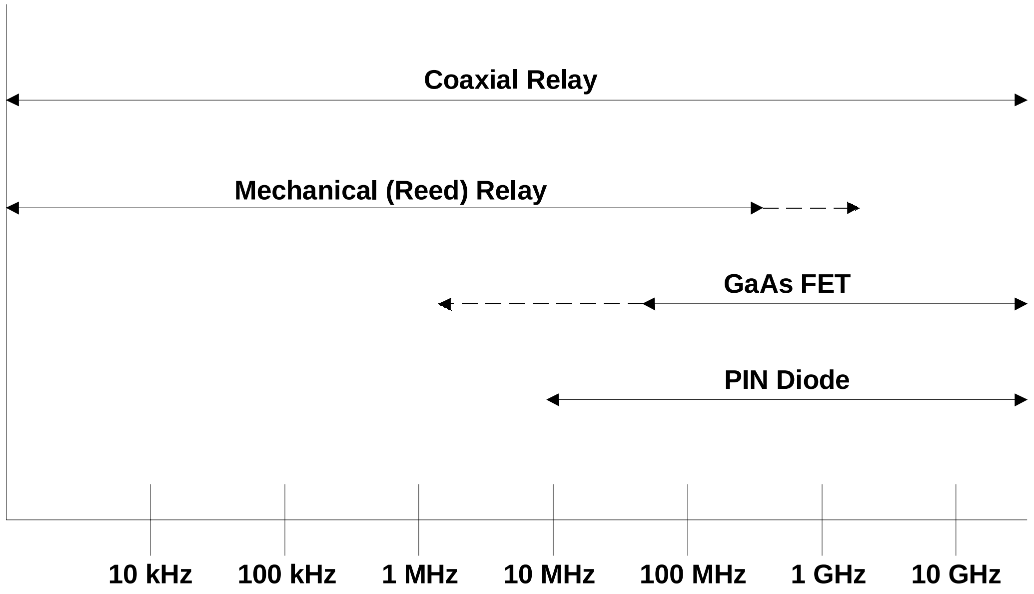

Figure 3-1 : Frequency Ranges

3.3 Flatness and Bandwidth

All the devices we are considering are very broadband. PIN diodes tend to be the only technology that ends up with octave bandwidths. This is because of the typical biasing network and quarter wave transformers used for matching. The device itself can be used over a very broad range.

The bigger contributors to loss of flatness tend to be cable slope (especially in large coaxial matrices where cable lengths are very long) and amplifiers. Occasionally, customers require filters in a switch matrix, but typical COTS matrix products are very broadband.

Because the matrix does not have filtering, phase accuracy and group delay tend to be excellent. Adding a switch matrix to a satellite signal chain does not typically influence the overall phase linearity of the customer's passband.

3.4 Isolation

The chart below shows the range of isolations of a single switch element, against the frequency range. Isolation of all devices degrades with increasing frequency. The coaxial switch is substantially better than all the other solutions. This means that a coaxial relay matrix only requires a single switch to achieve the total isolation. The other technologies usually have to put several devices together to build up enough isolation for the application.

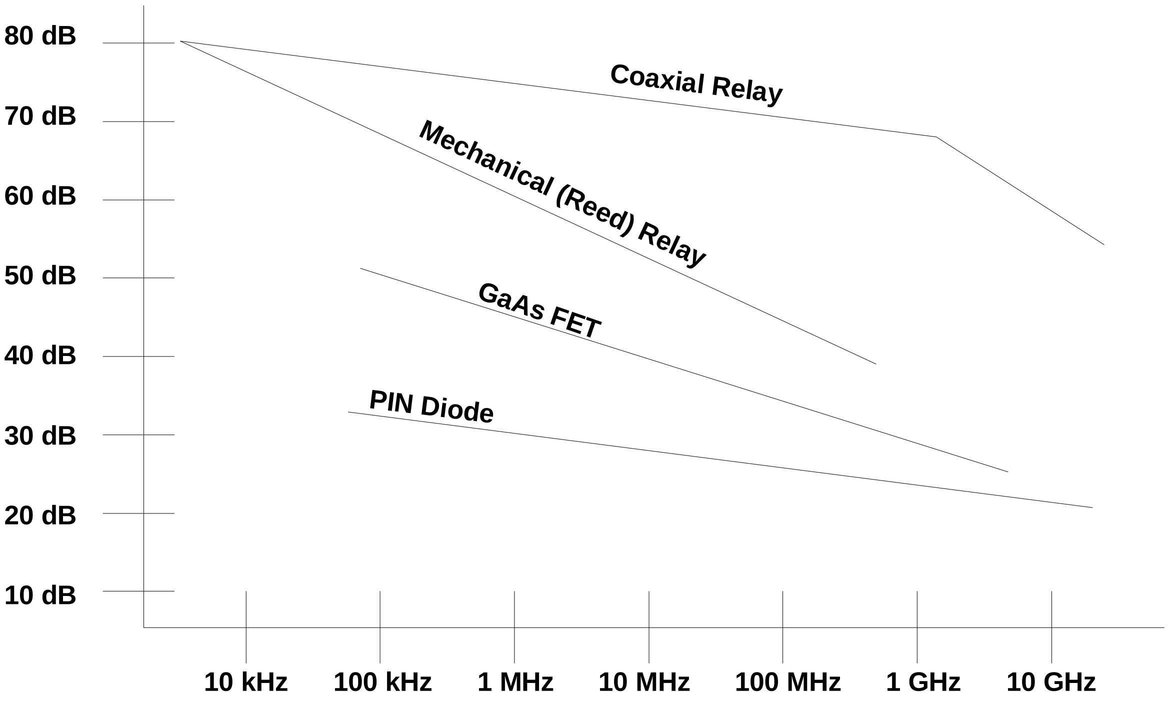

Figure 3-2 : Single device Off-Isolation

3.5 Signal Power Handling

Signal power level is important to the solid state devices. IF the signal levels are too high, distortion will result. The electromechanical devices can handle much higher CW power. Most ground station applications with signal levels in the <10 dBm range can be served by any of the technologies.

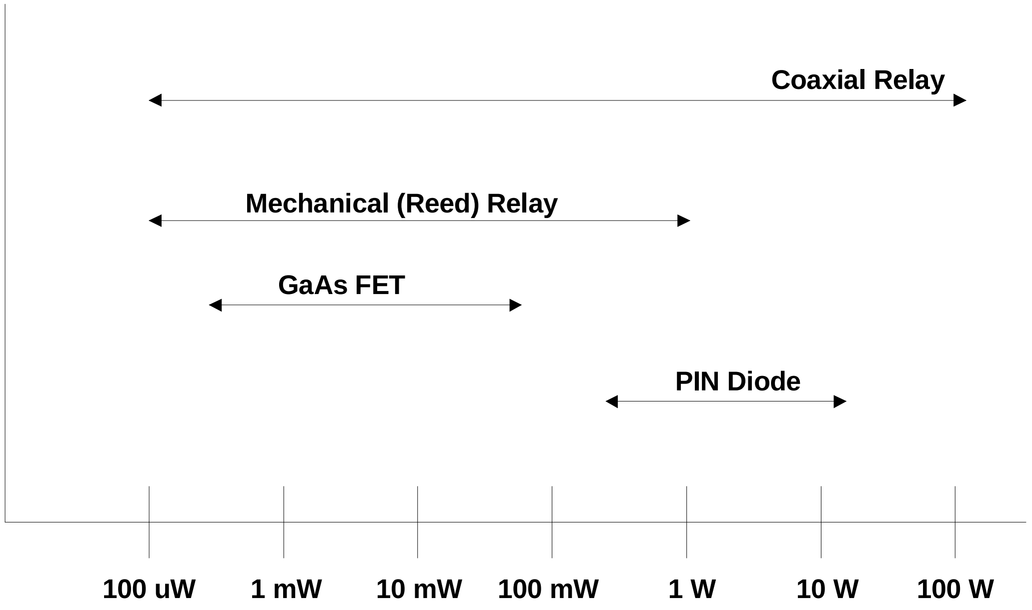

Figure 3-3 : Signal Power Handling

3.6 DC Power

The amount of DC power required to operate a signle stage device is compared below. The coaxial relay is shown in two configurations. The standard coil arrangement requires power continuously, while the magnetic latching configuration can change state with a pulse. Power is not running continuously no matter what state the switch is commanded to.

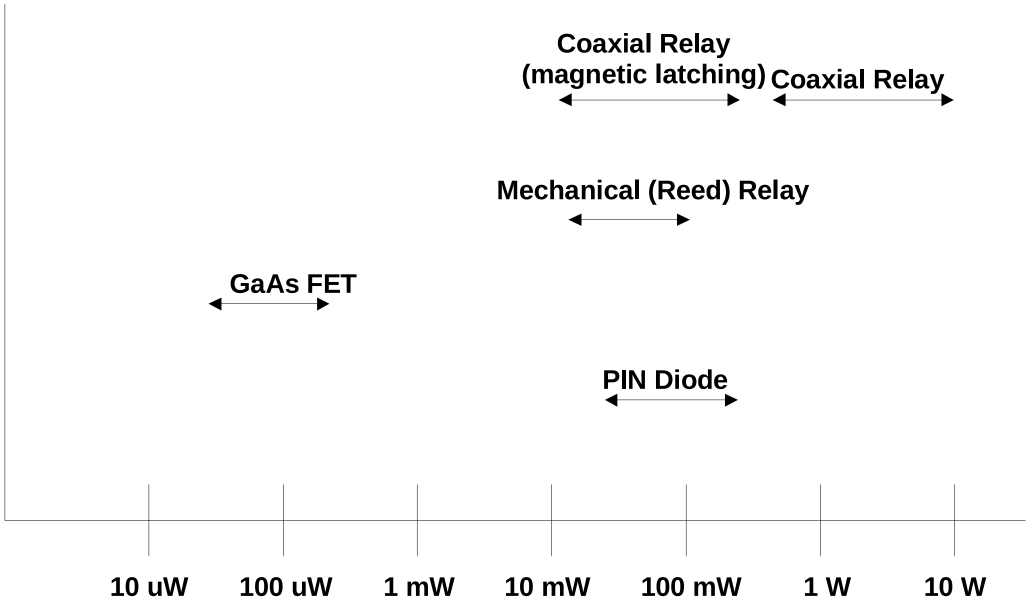

Figure 3-4 : DC Power Consumption

3.7 Switching Speed

The solid state devices are faster, as one would expect. This comparison is for the device itself, not the overall matrix switching speed. This graph does not account for driver rise times, control delays, etc.

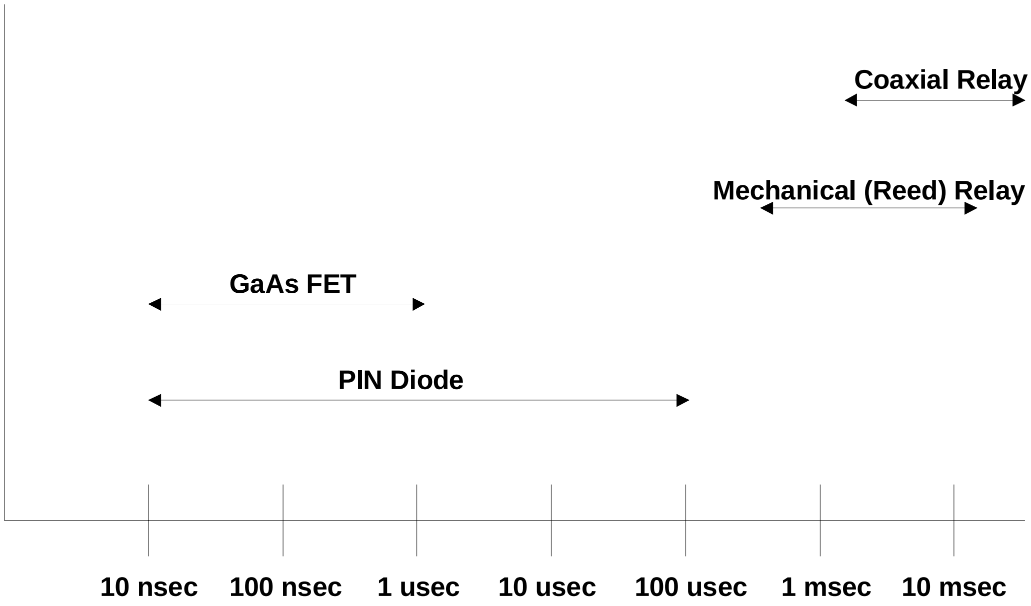

Figure 3-5 : Switching Speed

3.8 Size

This chart shows the range of physical volume of the devices themselves, scaled to a single crosspoint. Driver circuitry is not considered. PIN diode driver circuitry is much larger than GaAsFET driver circuitry.

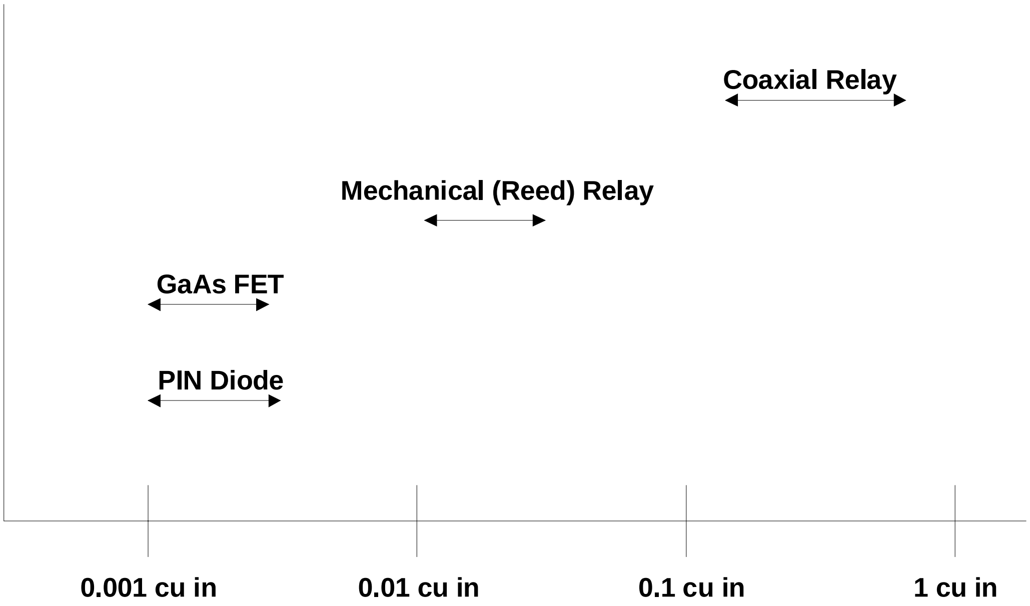

Figure 3-6 : Switch Physical Volume per crosspoint

3.9 Lifespan

Lifespan of the solid state devices is very large, the scale numbers are arbitrary. On the other hand, electromechanical devices have specified life spans (operating cycles). Coaxial relays are typically specified at 1 million operations. The usual end of life condition is electrical performance degradation (resistance rise), not mechanical failure. For matrices with only occasional path changes, electromechanical devices can provide many years of trouble-free service.

When considering MTBF, remember that a solid state switch may use a number of devices in series to achieve isolation as well as to make a multi-way switch. But the coaxial switch is a single multi-pole device.

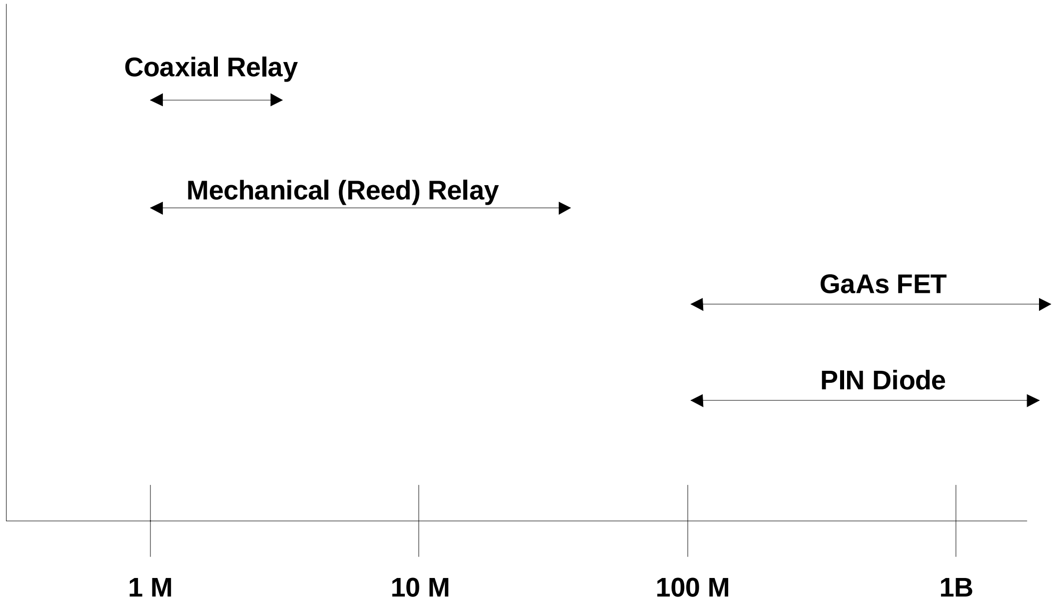

Figure 3-7 : Device Operations

4 System-Level Tradeoffs

In this section, we discuss system-wide factors that influence design and specification decisions. The 4X4 non-blocking configuration is embellished in the drawing below, to show one way in which amplifiers are incorporated into a matrix.

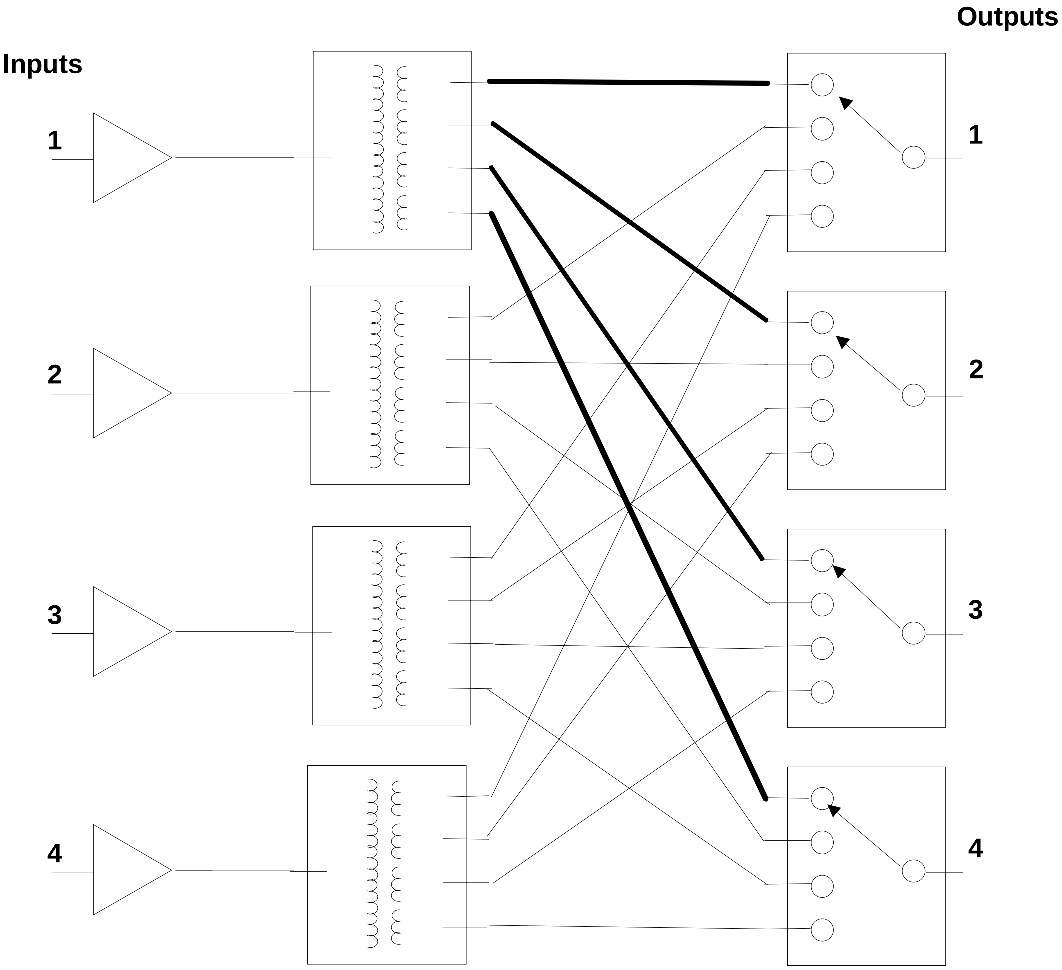

Figure 4-1 : Amplified 4X4 Non Blocking Matrix

4.1 Signal Level, Gain and Dynamic Range

We have already mentioned that the power dividers introduce loss that must be counteracted for most applications. Large matrix installations will also have significant loss in the switches and the interconnecting cables. The typical switch matrix application requires unity gain (0 dB). Adjustable gain or attenuators may also be provided to allow flexibility. When the matrix is used in the receive side, the system noise figure is typically fixed before the signal arrives at the switch matrix. So the matrix does not usually need an extremely low NF. Values in the range 6-12 dB are often adequate.

As with any RF system, the gain and noise performance are tradeoffs against power handling and distortion. Increasing gain improves noise but degrades distortion and compression performance. Specifying intermodulation distortion and output compression points that are adequate for the task, but not over-specified will keep costs down.

Compression point and intermod distortion points are very dependent on amplifier transistor bias points. Increasing the compression point by 10 dB will raise the DC power of an amplifier by about a factor of 10. In a GaAs FET matrix, the amplifier power tends to be a large part of the total power consumption, since the GaAsFET's themselves operate with virtually no power consumption.

When possible, allow the signal to be attenuated through the matrix. This increases noise figure, but generally pays dividends in relaxing the IP3 requirements. And many systems can tolerate the noise figure increase without serious detriment to the signal to noise ratio presented to the demodulator.

4.2 Reliability

In military and commercial satellite applications, high-value signals are continuously passing through the switch matrix. Continuous operation is the norm. Therefore, reliability is a very important criteria. When the matrix is used for maintenance and test, some reduction in reliability may be tolerable to reduce cost.

4.2.1 Power

The most common feature to improve system reliability is redundant DC power supplies. The failure rate of the AC/Dc power supply tends to be one of the largest contributors to final MTBF. A typical AC/DC supply can have a specified MTBF of 100,000 hours. By using redundancy, that MTBF value is effectively squared, which tends to remove the effect of a power supply failure from the MTBF computation.

One important aspect of redundancy is to ensure that the circuit elements that sum the power supply outputs are either replaceable or testable. In a typical low cost scheme, series diodes are used in the outputs of each supply. If the series diode fails open, that supply cannot provide any current when the other supply dies. But monitoring that condition in a live circuit is difficult. In cases where MOSFET’s provide this function, the situation is similar. When swapping out a failed power supply, the best systems will also swap the summing elements, to ensure that all the potential failures are removed. Parallel diodes are another technique to address some of the risk of diode failure.

The ease of swapping the supply is discussed below

4.2.2 Switching

A single level non blocking switch has no redundant switching paths. A three level switch will have some amount of redundancy, depending on the actual design. Having alternate paths during failures can protect critical outputs. But the firmware complexity grows to accommodate this fact. It also means that either the three level switch must determine the path failure on its own (Built In Test Equipment - BITE) or there must be a manual method of selecting alternate paths when a failure is spotted by external equipment.

BITE to test paths typically involves signal generation, a potential interferer for adjacent channels. Power sensors are required for all inputs and outputs.

4.3 Environmental

4.3.1 Cooling

4.3.2 Shock and Vibration

4.4 Control

4.5 Maintainability

4.5.1 Modularity

4.5.2 Hot Swapping

4.6 Expansion

5 References

Benes,