Effects of Signal Interference in VNA Measurements

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INTRODUCTION

There are many circumstances where we are trying to measure phase and magnitude of a signal with a Vector Network Analyzer (VNA), in the presence of a smaller interfering signal at the same frequency. Generally, the interference results from isolation problems, or from unwanted reflections within the test circuit. The purpose of this paper is to get a ballpark estimate of the extent of errors that we can expect with interference of various levels. We first create a table showing the maximum errors that can occur in dB and phase measurements, and then consider interference arising in several types of measurements.

ERROR SIZE FOR VARIOUS INTERFERENCE LEVELS

The Basic Vector Relationships

Consider a main signal (A) experiencing interference from a significantly smaller signal (I). The two signals combine to form a net signal (B). We want to determine the extent to which the magnitude and phase of B may differ from that of A. Figure 1 shows vector diagrams for the sum of signals A and I for two different phase relationships between A and I.

Maximum phase change occurs with interfering signal (I) perpendicular to the combined signal (B), which also makes I approximately +/-90 degrees out of phase with main signal (A).

Maximum magnitude change occurs with interfering signal (I) in phase or 180 out of phase with main signal (A).

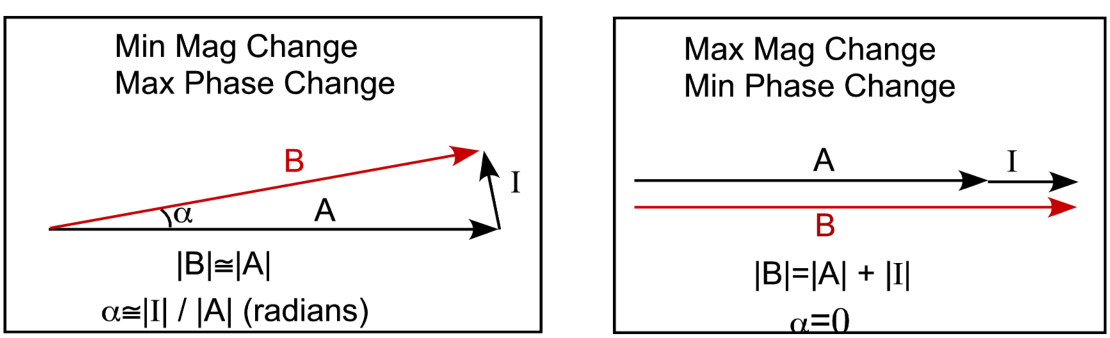

Figure 1—Vector diagrams of combined signals A and I, producing B. A is the actual signal of interest. B is what we measure.

On the left side of Figure 1, the interfering signal is approximately 90 degrees out of phase with the main signal. If I is less than about 10% of A, the magnitude of the resulting signal B will be approximately equal to that of the original signal A. Also, the phase difference (in radians) between B and A will approximately equal the ratio of I's magnitude to that of A (or to that of B), because A and B are nearly equal and the sine and tangent of small angles is approximately equal to the angle, in radians. Signal I can be as big as 1/3 of A, and the error in these approximations is still less than 5%.

On the right side of Figure 1, signals A and I are in phase, so the magnitude of their sum B equals the sum of the magnitudes of A and I, and the phase of B is the same as that of A. The amount of change will be the same if B is exactly out of phase with A.

In the analyses below, we will deal with known measurements of B in the presence of a signal I of some assumed maximum magnitude, but completely unknown phase. We are interested in how much error occurs. Let's define P to be the magnitude of I as a proportion of B:

$$\text{Define } P = |I|/|B|$$

Our first goal is to create a table showing the amount of error that can be caused by various levels of P. If you are in a hurry, you can skip the mathematics in the next section and go directly to Table 1.

The Math Behind the Table

The maximum amount of phase error is simple. Figure 1 states the error in radians, based on I and A. With the assumption that I is relatively small (<1/3) compared to A, A and B will be nearly equal, and we can state the maximum phase error in degrees as follows:

$$\text{Max Phase Error (degrees)} = P*57$$

The maximum amount of magnitude error is simply |I|, but we will normally make the magnitude measurement in dB, so we care about the maximum and minimum ratio of B to A, expressed in dB. Note that, while the maximum magnitude of error is the same for I at zero or 180 degrees relative to A and B, the ratio of B to A differs in the two cases:

$$\text{Max Ratio of B to A} = |B|/(|B|-|I|) = 1/(1-P)$$
$$\text{Min Ratio of B to A} = |B|/(|B|+|I|) = 1/(1+P)$$

With measurements in dB, the error in dB is the dB value of the ratio of B to A:

$$\text{Max Positive dB error (i.e. } |B|>|A|) = dB_+ = 20*Log(1/(1-P)) = -20*Log(1-P)$$

$$\text{Max Negative dB error (i.e } |B|<|A|)|) = dB_- = -20*Log(1/(1+P)) = 20*Log(1+P)$$

Note that the maximum negative error (dB_-) is here expressed as a positive number. Note also that our equations for maximum dB error do not rely on the assumption that I is much smaller than A, though they do implicitly rely on I being no bigger than B ($P \leq 1$).

With the equations above, if we measure B in dBm as B_{dB}, we know the true magnitude of A is in the following range:

$$B_{dB} - dB_+ \leq |A| \text{ (in dBm)} \leq B_{dB} + dB_-$$

dB_+ thus represents the extent to which the measured value B is a possible over-estimate of the actual value A, and dB_- is the amount of possible under-estimate. If I is relatively small compared to B, the values of dB_+ and dB_- will be nearly equal, but for large I they will differ considerably. Note particularly the extreme case where I has the same magnitude as B (i.e. P=1). In this case, if A and I are in phase, B will be twice A, for an over-estimate error of 6 dB, and if they are 180 degrees out of phase B will be zero, for an infinite dB error (under-estimation).

The Table of Errors

Now we can create a table showing the errors that can be caused by interfering signals of various strengths:

P dB	P ratio	dB under-estimate	dB over-estimate	Degrees error
0	1.0000	6	INF	---
-5	0.5623	3.9	7.2	---
-10	0.3162	2.4	3.3	18
-15	0.1778	1.4	1.7	10
-20	0.1000	0.8	0.9	6
-30	0.0316	0.3	0.3	2
-40	0.0100	0.1	0.1	0.6
-50	0.0032	0.03	0.03	0.2
-60	0.0010	0.01	0.01	0.06

Table 1—Errors for various levels of interference

These errors are all maximums, intended for worst-case analysis. P is the ratio of the interference magnitude to the measurement magnitude. For any given level of interference, the table shows the possible errors in the measurement of signal strength (dBm) and phase (degrees). Phase error is not shown for the highest levels of interference because those levels violate the assumptions on which our equations were based, and in any event the errors are so high that we are not likely to care about phase measurement at those interference levels.

For example, if we assume an interference signal of -100 dBm and we measure a signal at -80 dBm, the interference is 20 dB below the measurement and P is minus 20. Looking at the table entry for P=-20 dB, we see that the dB measurement of the signal may be as much as 0.8 dB low or as much as 0.9 dB high. As a practical matter, we could simply assume the dB error to be ±0.9 dB. The possible phase error is ±6 degrees.

If we measure a signal with interference and obtain a value of M (in dB), the true magnitude of the signal being measured is in this range:

M – Max Overestimate ≤ True Value (dBm) ≤ M + Max Underestimate

We are usually dealing with negative values for dBm, and the concepts of over- and under-estimation must be applied algebraically. For example, a measurement of -50 dBm is an under-estimate of a true value of -40 dBm, because -50 is less than -40.

Table 1 applies to signal levels measured in dBm, but it can be applied to dB values obtained in transmission and reflection levels, as long as the reference level against which dB is measured (e.g. the Through level for transmission) is not itself affected by the interference. It is normally reasonable to make this assumption. One caveat, however: The determination of the interference level P must be made by comparing the absolute interference level to the absolute measurement level. For example, a reflection of -40 dB may represent at signal strength of -60 dBm at the VNA input. If the interference signal is -90 dBm, then the relative interference P (in dB) is -30 dB, not -50 dB.

Also, if reflection is converted to return loss, negative dB values become positive dB values and what was a possible over-estimate becomes a possible under-estimate.

One important thing to notice in Table 1 is that significant errors can be caused by relatively low levels of interference. For any given level of interference, the phase error seems more significant than the dB error, though that may be a matter of taste.

Finally, note that it is possible to make meaningful measurements even when the interference level is as strong as the measurement, despite the fact that the possible over-estimate is infinite. If we measure a signal as -90 dBm in the presence of -90 dBm of interference, this tells us that the actual signal is -84 dBm or less. In many situations, we are simply hoping to verify that the signal falls below a particular level, and this measurement could do the job.

INTERFERENCE PROBLEMS IN SPECIFIC TYPES OF MEASUREMENTS

Let's consider a few different measurement situations to see how significant interference errors can be.

Transmission Measurements

Consider a straightforward transmission measurement where the test signal runs from the Tx port, through the DUT and to the Rx port. Assume the isolation is 100 dB. This means that an undesired interference signal bypasses the DUT, and is 100 dB below the level of the Tx signal. This signal may be passing directly from the Tx port to the Rx port, or it may actually be occurring inside the VNA.

If we measure a band pass filter which has 0 dB insertion loss and has skirts extending down past -90 dB, the interference will start to have some small effect at -40 dB, where the measured signal is only 60 dB above the interference. This puts us in the last entry of Table 1. By the time the measured signal is -90 dB, we are at the first entry of Table 1, where the error can be several dB and 18 degrees. Fortunately, however, for these sorts of measurement errors of a few dB at the lower levels are typically of little concern, and phase is probably of interest, if at all, only between the 3 dB points of the filter.

Suppose we are scanning a band stop filter instead of a band pass filter. Now the area we are primarily concerned with is the bottom of the dip in the filter response. Perhaps this is at -80 dB, which is only 20 dB above the interference. We now have potential errors of 0.8 dB and 6 degrees. By themselves, those may not be problematic errors. But consider that at the bottom of the filter response, the phase is likely changing rapidly. This means that the error may be changing rapidly—say, from 0.8 dB to -0.8 dB and back again with a small frequency change—which causes ripple in the response.

If we are trying to determine the parallel resonant frequency of a crystal, which occurs at a severe dip in the transmission response, rapid changes in the error may distort the shape of the dip and cause a shift in the apparent parallel resonant frequency. If we use common fixtures for measuring crystal parameters, which add significant attenuation, then the absolute level of the measured signal is reduced but the interfering signal is not. 80 dB attenuation by the crystal plus 20 dB attenuation by a fixture can make a mess of the measurement if the isolation is only 100 dB.

Reflection Measurements

The situation is usually a bit more favorable with reflection measurements. This is in part due to the fact that the range of meaningful reflection measurements is relatively small, typically no more than -40 to 0 dB. It is important to remember that there is generally very little significance to a change in reflection coefficient from -40 dB to -42 dB; in terms of impedance the difference is less than a quarter of an ohm. The lower you go with S_{11} ("lower" meaning more negative), the less you have to worry about errors. For example, there is no virtually no practical difference between S_{11} of -60 dB and S_{11} of -100 dB. Phase is also not very meaningful for values of S_{11} below -35 dB. If you are extremely close to 50 ohms on the Smith chart, a few degrees change in the direction of the deviation makes very little difference.

In reflection measurements, the equivalent of the isolation problem in transmission is "directivity". This represents the bogus signal that is generated by the bridge even when there is no real reflection. If, with a perfect 50-ohm load attached, a bridge produces a signal 50 dB lower than the signal it produces with an open circuit, its directivity is 50 dB. This is equivalent to the leakage signal from Tx to Rx in transmission measurements, though typically it is considerably stronger than the transmission leakage. If OSL calibration is used, the effects of directivity are greatly reduced, to the point where they have minimal effect on reflection accuracy. If only reference calibration is used, excellent results are generally achieved with directivity of 45 dB or better, which is easily achieved at frequencies below 100 MHz.

Consider a reflection measurement made with reference calibration (meaning the reflection signal generated by the DUT is compared to that generated by an open circuit), which produces a value of -40 dB. If the bridge directivity is -45 dB, then there is an interference signal 5 dB below the measurement. Table 1 shows that our measurement could be over-estimating by 7.2 dB or under-estimating by 3.9 dB. This makes the true reflection something between -52.2 dB and -36.1 dB. In many situations we simply want to verify that reflection is below (return loss is above) a certain level. If the target reflection level is -35 dB (return loss of 35 dB), then our measurement provides all the information we need.

Finally, Table 1 shows that whatever the directivity of the bridge, it can be used without OSL calibration to make measurements of return loss that are at least 20 dB below the directivity, with error of less than 1 dB. This is a good rule of thumb to keep in mind when evaluating the directivity of a bridge.

Interference from Reflections

If transmission measurements are made with a VNA whose Rx port does not have high return loss, the signal reaching the Rx port will partially reflect and return to the DUT. It may reflect off the DUT output and return to the Rx port. It may pass through the DUT all the way back to the Tx port, where it may partially reflect and make its way back to the Rx port. Worst case, the original reflection off the Rx port may return to the Rx port at full magnitude with any possible phase. Referring to Table 1 we can see that if the Rx port has return loss of 20 dB (meaning the reflection is -20 dB relative to the incident signal), the interference from the reflection can cause errors of ±0.8 dB and ±6 degrees in the measurement.

In most situations, only a portion of the reflection off the Rx port will ultimately return to cause interference. If the returning reflection can be kept to no higher than 40 dB below the original incident signal, the measurement error will be no higher than ±0.1 dB and ±0.6 degrees. This error level would likely only be bothersome when measuring insertion loss of very low loss DUTs, such as a high quality filter. It becomes more bothersome if the phase of the interfering signal changes rapidly over frequency (as it might if it passes through the filter). This causes ripple in the graph of the filter response, even where there is no ripple in the actual response.

At a minimum, we should hope for return loss of 20 dB or better at both the Tx and Rx ports. In this situation, the only way there can be a strong reflection resulting from the initial reflection off Rx and re-reflection back to Rx, is if the re-reflection occurs off the DUT output. This situation can arise in our example of the band stop filter (or parallel resonance of a crystal), where the reflections in the band of primary interest are likely very high. In this situation, a good attenuator is needed at the Rx input to improve the Rx return loss.

Interference from switches

Interference is a particular concern when switching mechanisms are used. For example, a VNA might have a switch to select between transmission and reflection. Or, it might have switches that can reverse the orientation of the DUT.

In the examples above, we assumed for illustration purposes that we had isolation of 100 dB. In a transmission measurement without switches, it is normally possible to achieve at least that level of isolation, unless there is significant leakage within the DUT itself, in which case the internal DUT leakage is actually a part of the DUT's behavior and properly included as part of the DUT's transmission.

However, when switches are added to the test setup, reaching 100 dB of isolation becomes more difficult. If we use a single SPDT relay to switch between reflection and transmission, we may achieve isolation in the 100 dB area for signals in the low MHz range, but the isolation may deteriorate rapidly, to perhaps 80 dB at 100 MHz. If we use a solid-state RF switch such as the PE4251, the low frequency isolation will start near 85 dB and deteriorate from there. Most RF switches have worse isolation than the PE4251. Therefore, it is generally necessary to use more than a single switch.

Isolation of a switch depends on the output having a load, typically 50 ohms, that will combine with the leakage resistance of the switch to attenuate the leakage. Simply cascading two SPST switches does not present much load to the first switch when both are off, and adds only about 6 dB to the isolation. The isolation of the cascaded switches can be improved considerably by adding a resistor between them, shunt to ground. For example, if the leakage resistance is 50 k-ohms, a 500 ohm shunt resistor will attenuate leakage through the first switch by 40 dB. If 500 ohms has too much effect on the signal when the switches are on, it can be raised to an acceptable level, with a reduction in the leakage attenuation. To achieve fully double the isolation of a single switch, it is usually necessary to use more than two switches. For example, a high-isolation SPDT switch can be obtained by a combination of 3 individual switches. This is particularly easy with solid-state RF switches, many of which route unselected signals to an internal 50-ohm termination, or to ground.

APPLICATION OF ALL THIS TO MSA TRANSMISSION/REFLECTION SWITCHING

Scotty's MSA has only a single input, so switching between transmission and reflection measurements requires an external switch arrangement. The bridge used for reflection measurements has the directivity measurements described above, and neither its Tx nor Rx ports have perfect return loss. Figure 2 shows a test set that is intended to address all these concerns at the low frequency end (perhaps to 100 or 150 MHz) of the MSA range.

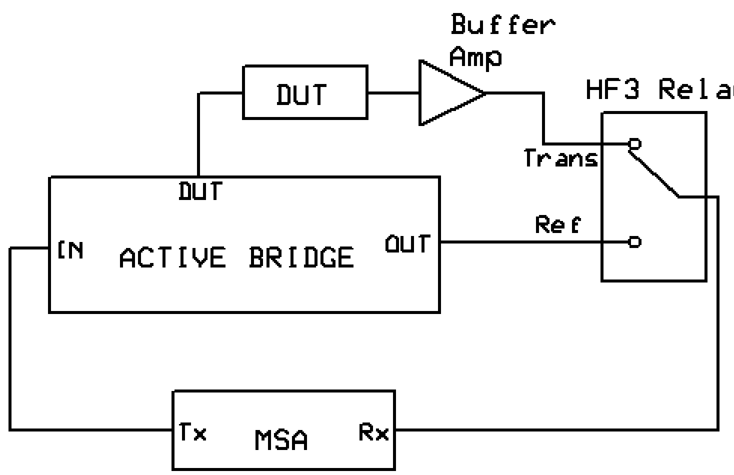

Figure 2—Transmission/Reflection Test Set for MSA

The test set contains the active bridge, a buffer amp, and a single relay. The active bridge has very good return loss at all ports. Up to 100 MHz, the return losses are all better than 30 dB—generally much better. The buffer amp has equally good return loss. These return losses dispense with issues of interference from reflections of the type described above. The directivity of the active bridge up to 100 MHz is better than 50 dB, so interference from its "bogus signal" is minimal for measurements of return loss up to 30 dB, even without OSL calibration. Per Table 1, using P=-20 dB, a 30 dB return loss would have a maximum error of less than 1 dB. (Phase would have an error of 6 degrees, but phase is not included in return loss.)

Note that the relay leaves the unselected input floating, presenting high impedance to the source. This has negligible effect on either the buffer amp or active bridge.

Finally, consider switching isolation. The isolation of the single HF3 ranges from 105 dB near 1 MHz to about 95 dB at 100 MHz. Let's analyze it as 100 dB. What effect does this have on measurements? Let's assume the transmission measurements produce actual output levels of -105 dBm to -5 dBm. That is, transmission of 0 dB produces an actual signal of -5 dBm. The output of the active bridge could be similarly high for 100% reflection, but it is purposely attenuated to, say, -30 dBm. This means the strongest reflection signal is 75 dB above the weakest transmission signal. With 100 dB isolation, the leakage signal resulting from that strong reflection would be 25 dB below the weakest transmission signal (which represents transmission of -100 dB). Table 1 shows that this could cause errors of about 0.5 dB and 4 degrees. Those errors could be significant in some circumstances, but generally at transmission levels of -100 dB phase is not even relevant, and an error of 0.5 dB does not mean much.

It would be possible to add an attenuator on the DUT input. A 10 dB attenuator would reduce the transmission by 10 dB but would reduce reflection by 20 dB, for a net 10 dB reduction in the reflection's interference with transmission measurement. If we added such an attenuator and saw little change in the transmission, we could conclude that the original measurement is not being affected by interference from the reflection signal.

So much for the reflection output interfering with transmission measurements. Let's look at the reverse. The strongest transmission signal would have an absolute level of -5 dBm. With the strongest reflection at –30 dBm, the weakest practical reflection signal would be perhaps 40 dB below that, or -70 dBm. (If we use OSL calibration, which is not required, we might be interested in weaker reflections from the calibration load, but in that circumstance there actually is no transmission signal, so this interference analysis is not even needed.) The strongest transmission is therefore 65 dB above the weakest reflection. That means the leakage from the strongest transmission signal through the switch, with 100 dB isolation, would be 35 dB below the weakest reflection signal. Based on Table 1, this would produce minor errors in reflection measurements. But when measuring return losses near 40 dB, errors of a few tenths of a dB or a fraction of a degree are almost meaningless. For example, the difference between return losses of 40 dB and 40.5 dB, when converted to impedance, is about 0.05 ohms.

CONCLUSION

We have developed Table 1 to use as a reference in determining how significant interference issues may be in our measurement system, and used it to analyze several common measurement situations. In doing so, it is necessary not only to estimate the extent of errors, but also to determine how significant the error may be to the type of measurement we are making.