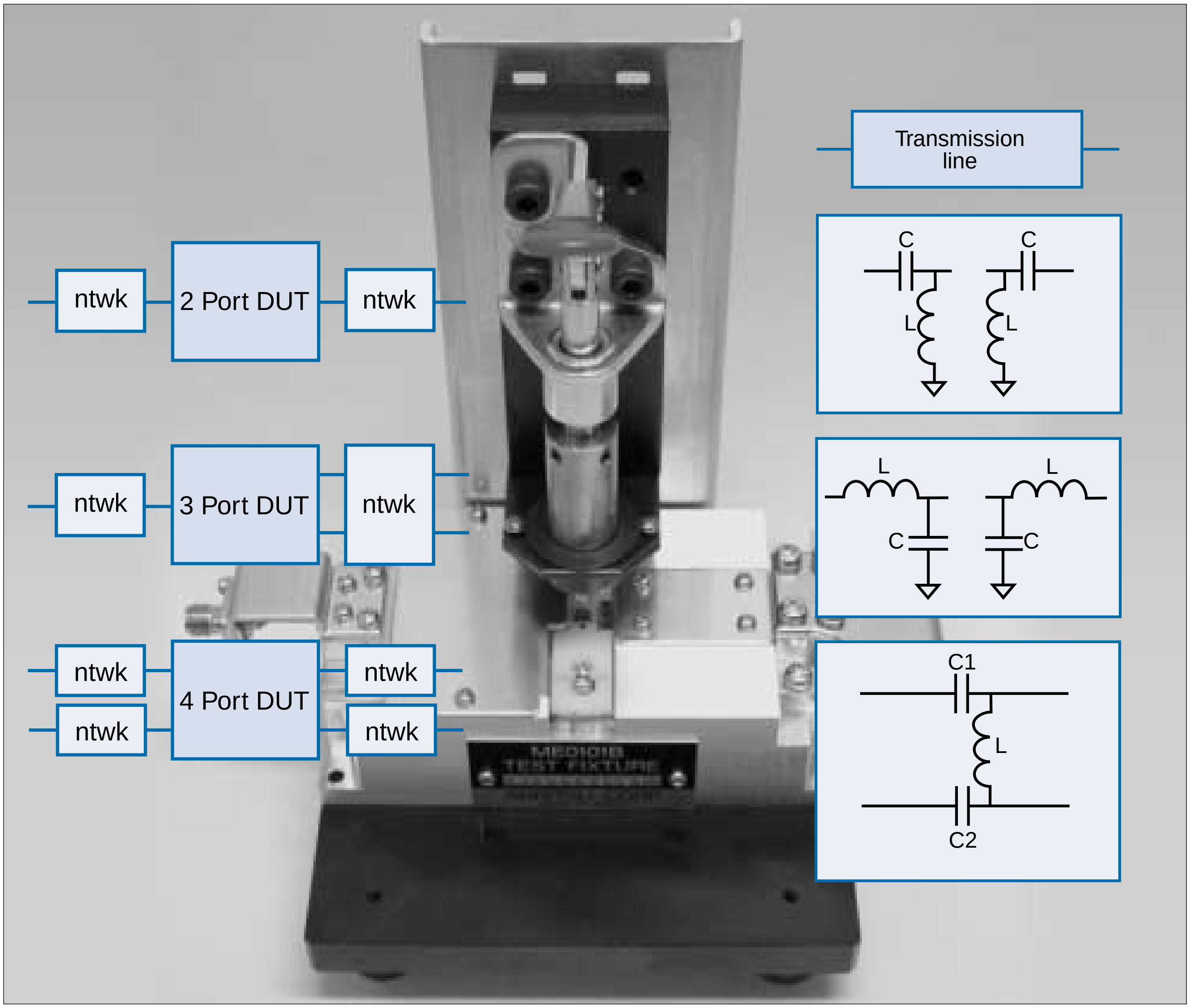
Anritsu

Application Note

Embedding/De-embedding

Scorpion®



Simulated Removal & Insertion of Fixtures,
Matching and Other Networks

Introduction

A frequent need in S-parameter measurements is to remove the effects of a fixture or virtually add in the effects of other networks (e.g., matching). Embedding and de-embedding are tools for virtually adding and subtracting networks to/from measured data.

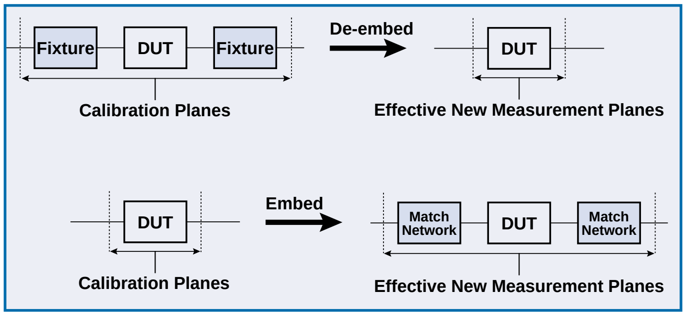


Figure 1*. The classical purposes of embedding and de-embedding are shown here. The idea is to virtually add or subtract networks to/from a measurement.*

In many S-parameter measurements, one would desire to make the measurement with some other setup than what one has. There may be a test fixture required between the normal coaxial calibration planes and the DUT; it may be useful to see the DUT performance with a certain matching network in place, it may be desired to see what the subsystem performance would be when the given DUT is inserted, etc.. One way of handling these chores within the instrument itself is through embedding and de-embedding: the process of mathematically adding or subtracting networks to/from the measured result. This technique has been around for many years (e.g., [1]-[5]) and has been subject to a number of refinements to improve accuracy and applicability. The purpose of this note is to explore some of the concepts of embedding and de-embedding, discuss the implementation in the MS462X, and to provide a number of examples and procedures to show how they can be used to get the required measurement results. There are references to 2, 3 and 4 port measurements in this document, obviously the N-port measurements require an N-port instrument so some of the features described do not apply to 2 and 3 port instruments.

Why Use Embedding and De-embedding?

The classical de-embedding problem is the removal of the effects of a fixture or wafer probe. If one can treat the fixture/probe as a simple length of 50 ohm transmission line, then the problem reduces to one of shifting the reference planes. This assumes that launch parasitics are small enough and usually that the frequencies involved are not too high. In this situation, a frequency-dependent phase shift is all that is required and can be done easily on most vector network analyzers. To determine how much the planes should be moved, the distance can be physically measured or it can be determined with the instrument. The latter can be performed with time domain reflectometry or with an automatic phase flattening function normally provided with reference plane adjustment utilities. Shorts (or opens if the capacitance is small enough) can be placed at the actual DUT planes and an ‘auto reference plane’ extension function can be used to calculate the distance required to put the reference plane exactly where the artifact was placed. This procedure is normally done by performing a linear fit of the phase vs. frequency function to remove the portion of the data that behaves like an ideal transmission line.

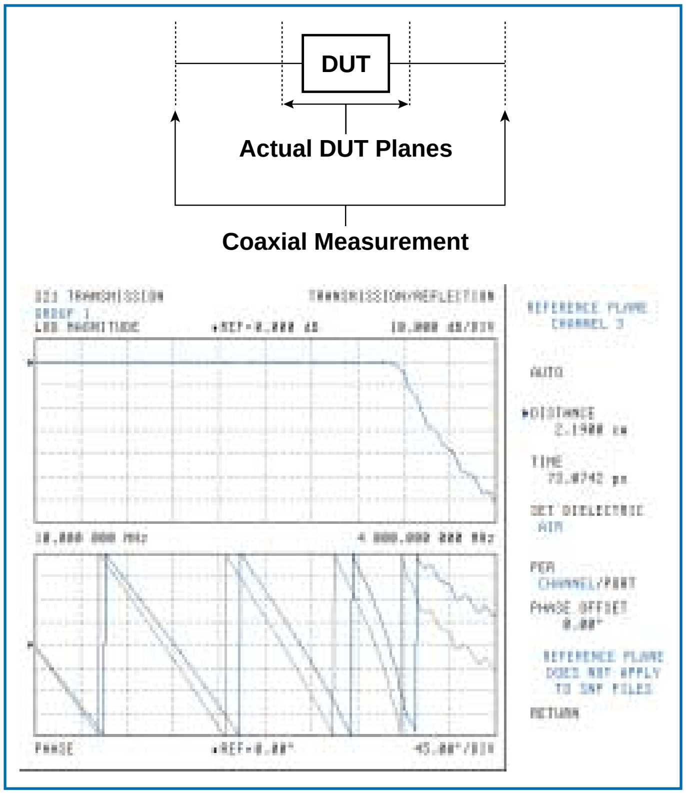


Figure 2. *The concept of reference plane extensions is shown here. The measurement is performed in a fixture that has an extra 2.19 cm of 50 ohm line length. The reference plane extension removes this (phase) effect.*

Figure 2 shows a filter measurement in a fixture with and without reference plane correction. In this case, the feed line length was 2.19 cm and upon removal one can see the phase has unwrapped slightly while the magnitude is unchanged. Often one will get the N reference plane extensions (on an N-port DUT) and simultaneously correct all N^2 parameters (using the per port option in the menu bar above). Note that an air equivalent dielectric was used in the above.

This is primarily of importance if the user enters a physical length as it is really the time that is the fundamental quantity being removed. In some cases, the reference plane shifts can affect magnitude as well. An example is when the port reference impedances are different from 50 ohms when the line whose length is being changed has a characteristic impedance of 50 ohms (reflections will be altered by changing the feed line lengths).

If the fixture is more complicated (with bond wires or complex packaging such as BGA), then this simple model of the fixture as a pure 50 ohm transmission line may be unacceptable. This is where more complete de-embedding is used to mathematically remove the fixture effects. The trick of course is that the fixture must be characterized before it can be removed from the data. The simplest version of de-embedding is that of a one term approach (quasi-scalar) in which just the loss and phase shift of the fixture are removed. The simplest approach in the past has been to connect a thru at the device plane, measure the total insertion loss and phase shift and arbitrarily assign a portion of it to each of port 1 and port 2.

This has its limitations in that it does not handle match effects and the ‘thru’ used to connect the fixture halves may introduce oddities of its own. Similar approaches have been done using shorts and/or opens on the fixture halves. One problem with this is that the impedance that can be generated at the DUT plane is rarely a perfect short or open so the basis for the calculation is flawed. This approach also fails to take into account reflections within the fixture assembly so there may be standing wave complications.

Another, somewhat more acceptable, approach with wafer probes is to perform an analog of adapter removal [6] in which multiple calibrations are used to remove probe effects. This technique relies on stability of a wafer probe thru connection as well as some knowledge of the probe characteristics [7]. The two calibration steps are shown in Figure 3.

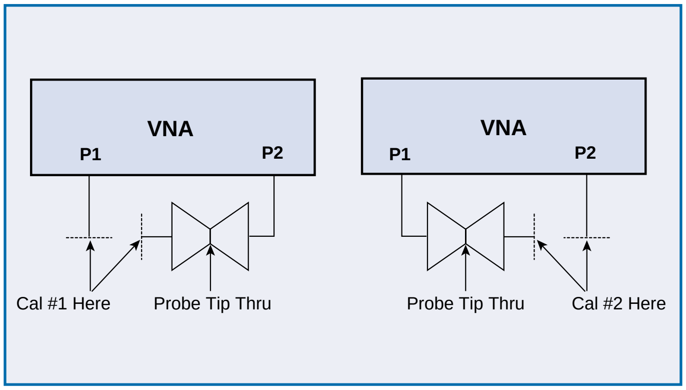


***Figure 3**. A two-calibration approach to remove the effects of a probe/fixture setup. The pair of calibrations provides enough information to remove probe effects if the ‘thru’ is sufficiently stable.*

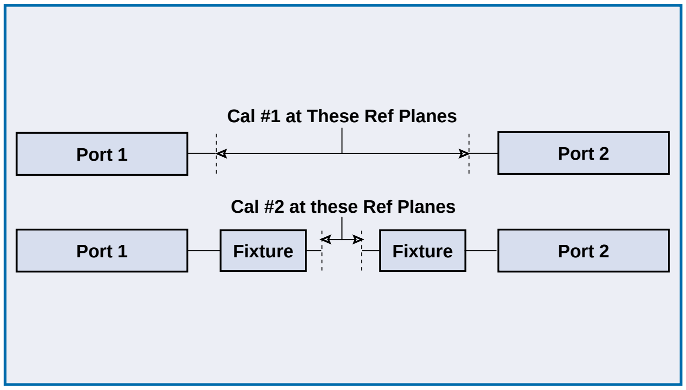


***Figure 4.** The extraction process (related to adapter removal and Figure 3) is shown here. Again the concept is to use a pair of calibrations to get information about the fixture in which the real measurement will be made.*

The most complete, although certainly not the easiest, route is to fully extract fixture S-parameters either iterative simulation or multiple calibrations. The former is easier to understand in that a model for the fixture is generated (either from first principles or by trial and error) and the values arrived at by simulating and comparing the results to measurements with known artifacts at the DUT plane. The multiple cal approach is termed extraction (see Figure 4) and relies on a cal at the coaxial plane and at the DUT plane. This obviously requires cal standards at the DUT plane, which can be difficult to implement and this issue is discussed in a later section. The concept is quite similar to that of adapter removal, the primary advantage here is that usually the thru is a well-defined concept in most fixtures.

Another de-embedding problem may be a matching network or filter that is present during measurement (perhaps because it is built into a fixture) and it would be useful to view data without it. Again this network must be characterized but this is often a simpler task than for the fixture.

Embedding problems often involve the desire to view the behavior of the DUT with a matching or other network present. This virtual network must be known and usually in the form of a circuit model or S-parameter data (from previous measurements for example).

Of course, sometime many of these problems occur all at once. The diagram in Figure 5 shows a 3 tier situation in which a fixture and an old matching network must be removed from the data and a new matching network that must be embedded.

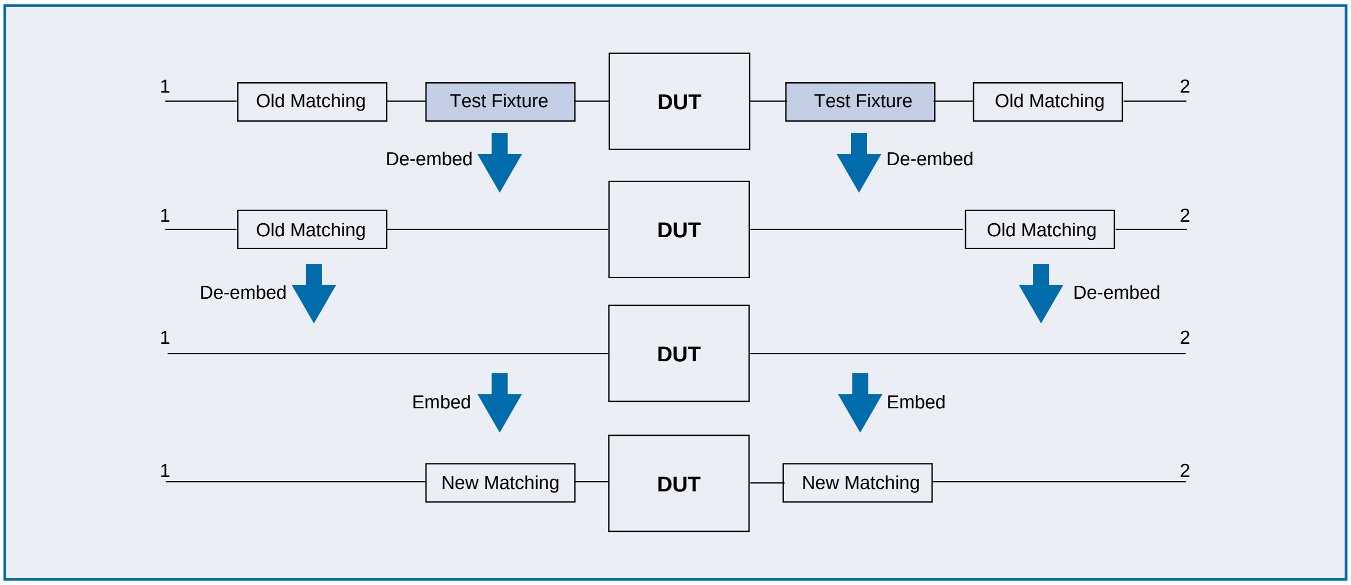
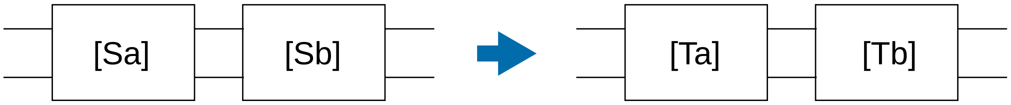


Figure 5. *A multi-tier embedding/de-embedding problem is shown here; as usual it starts with fixture removal. For production reasons, a certain matching network may be used in manufacturing test but the end customer may prefer to see the results as if a different matching network were present.*

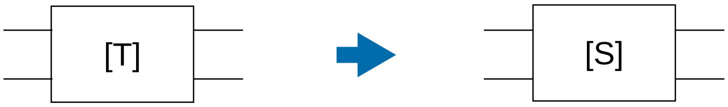
How Does Embedding and De-embedding Work

For anyone who has used a rf/microwave circuit simulator, the embedding process is conceptually very natural. The S-parameter data for the DUT is available from the measurement and the S-parameter data for the network to be embedded is available (either from an s2p file or from a circuit model) so the combination must simply be 're-simulated' within the instrument to produce the composite data to be displayed. Theoretically speaking, this turns into a problem of matrix multiplication where the scattering matrices are converted into T or transfer matrices (e.g., [8]) and matrix multiplication is equivalent to connecting the two circuits together.

First convert the starting S-matrices into T-matrices



Since T-matrices are cascadable, T=Ta*Tb. This result must then be converted back into scattering parameters…



De-embedding is not that much different. If multiplying one transfer matrix by another is equivalent to connecting in the new network, then multiplying by the inverse of that T matrix is equivalent to removing it ($T=Ta*Tb^{-1}$ to de-embed network b).
In actual implementation, variants on this algorithm may be used to avoid numerical issues but the principle will be the same.

The Implementation in the MS462X

The MS462X incorporates a variety of embedding and de-embedding functions and some utilities to make the task more tractable. The purpose of this section is to explain the choices that must be made when setting up a task and provide some guidance on how to formulate the problem.

The first question, to embed or de-embed, is quite straightforward. If this is to be a multi-tier operation (some embedding, some de-embedding, etc.) as pictured earlier, the operation closest to the DUT should be entered first (always working out from the DUT). The various networks entered are tracked in a log file for each port (or port pair). This log will track at least the last 10-20 entries made for that port/port-pair although it is expected that this limit will rarely be exceeded. Note that this printable/savable log keeps track of many networks but only the last one entered (on that port/port pair) may be edited.

The next group of questions is related to the number of ports on the device and how the networks (to be attached or removed) are configured. For two port devices, it is fairly obvious that a network can be attached to each port (feedback networks are not permitted). For three and four port devices, this is still possible and is usually appropriate for fixture de-embedding and many other problems. For three port devices with 1 balanced ‘port’ and four port devices with 1 or 2 balanced ‘port(s)’, there is another possibility where the ports should be considered in pairs. In this case, often with a matching network to be embedded or de-embedded, the network itself is balanced and has very different responses to differential and common-mode signals. As such, it really cannot be considered as two separate two-port networks but should be thought of as one four port network. In this case, the device ports are grouped as a pair and the embedding/de-embedding is operated on that pair. The menu path for four port devices is shown in Figure 6 while those for two and three port devices are shown in Figure 7. The help screen is shown in Figure 6 that gives some guidance on how networks are connected. Make special note of the distinction between number of ports on the DUT and number of ports on the network to be embedded/de-embedded.

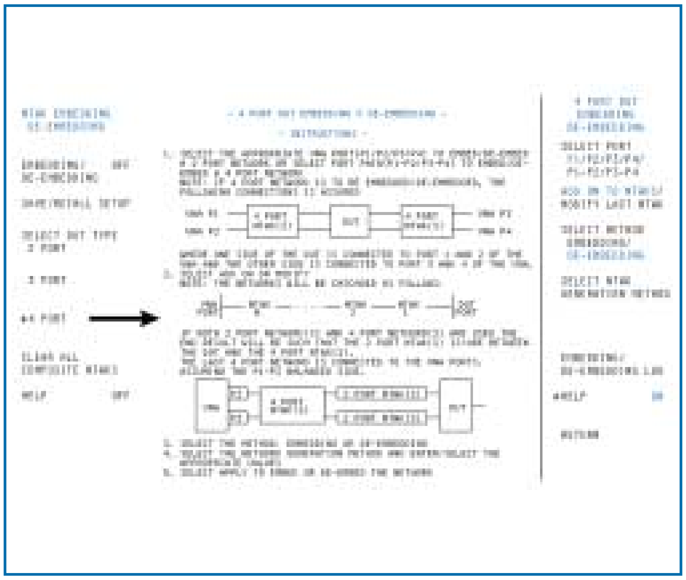


__Figure 6.__ The initial menu tree for 4 port DUTs is shown here along with a help screen. Upon selecting the DUT type as 4 port, the user must then select the port configuration (basically single-ended or balanced), what port(s) to work on, and embedding or de-embedding. The “network generation method” softkey leads to menus where the networks are entered. Note that in a balanced configuration, ports 1 and 2 are grouped as a pair and ports 3 and 4 are grouped as a pair.

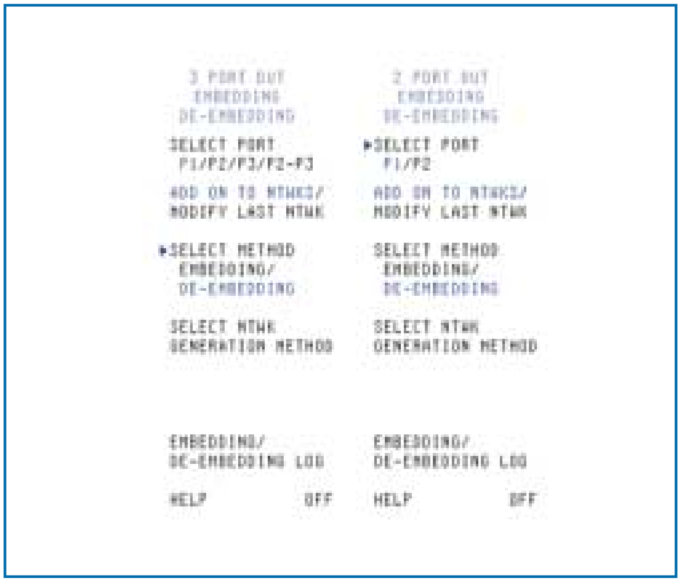


__Figure 7.__ The initial menus for two and three port DUTs are shown here. The choices to be made are basically the same as for four port DUTs except the configuration is strictly single-ended for two port devices and only ports 2 and 3 of a 3 port device can be considered balanced.

The next and most obvious question perhaps is what types of networks can be entered. The answer falls into two groups: .SnP files and simple circuit primitives. The most generic path is with the fairly universal .S2P and .S4P text file formats in which the S-parameters as a function of frequency of the network are entered directly. While these formats are presented in the appendix, they are available (for import or export) in almost all commercial simulators and almost all vector network analyzers. As such, the networks to be entered can come from simulations, previous measurements, or possibly measurements followed by subsequent modifications in a simulator. In the case of per-port networks, it is obviously an .s2p file that is of relevance while an .s4p file is important for the pairs-of-ports process. The extraction process, to be described later, also generates .s2p files for a fixture and is based on multiple calibrations in the fixture itself to allow for later de-embedding.

As an example to show some simple functionality, consider the matching network shown in Figure 8 that was designed in a simulator. The expected S22 (when port 1 terminated in 50 ohms of course) is shown in Figure 9. This .S2P file describing this matching network was taken to the MS462X as a network to be embedded on port 1. With the thru line still connected between ports 1 and 2, the resulting S22 is also shown in Figure 9. As expected, it matches the simulator result. In practice of course, the thru line would be replaced by some DUT and the displayed S_{ij} would represent the composite of the matching network and the DUT.

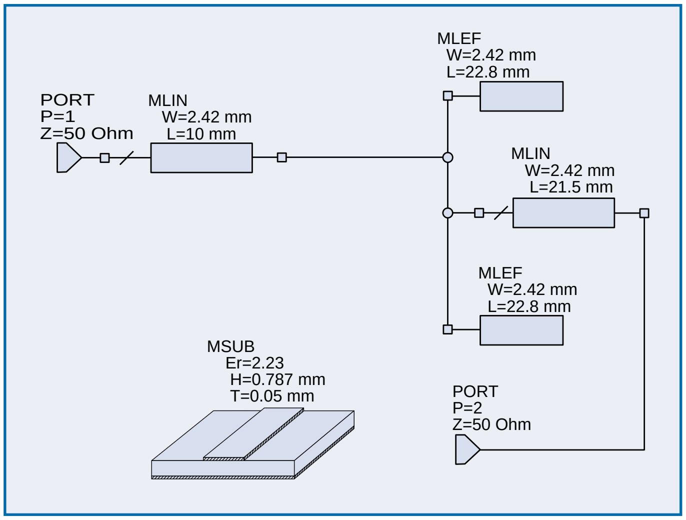


Figure 8. A simple network is shown here that was used to compare the embedding of the instrument to that which a simulator would generate. This network was used to create an .s2p file that was fed to both a simulator and the MS462X for comparison.

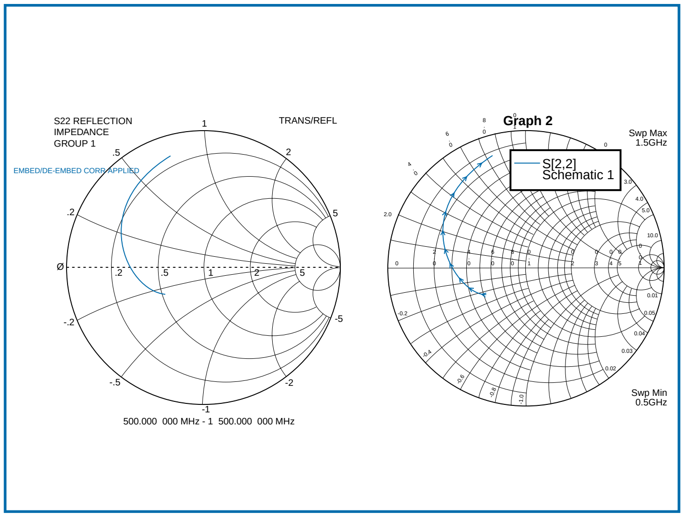


Figure 9. *A comparison of the S22 results from embedding and simulating the s2p file of Figure 8 are shown here. As would be expected, the results are the same.*

For some simple networks, it may be easier to directly enter the circuit elements (and values) into the system. For this purpose, a limited variety of circuit primitives are provided. The two port versions and one four port version are shown in Figure 10. The menus for selecting network type and entering values are shown in Figures 11 and 12. Again note the distinction between 2 port networks and 4 port networks refers to the circuit primitive (in this case), not the DUT. Pay special attention to which side of the network is connected to the DUT side and which is connected to the port (VNA) side; these labels are in the help screens to

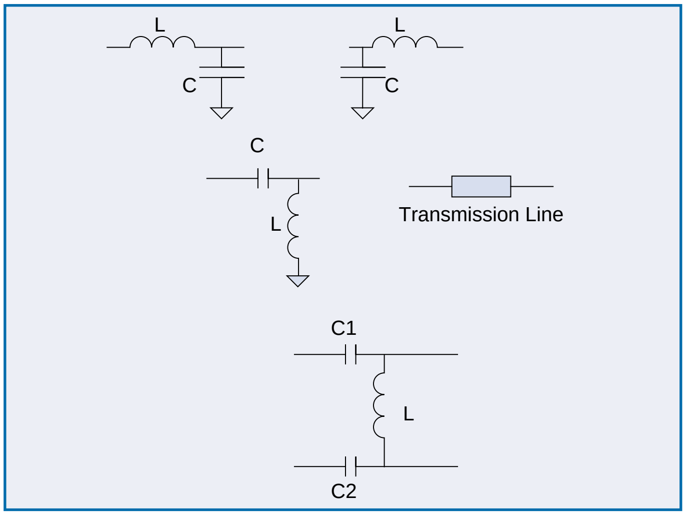


Figure 10*. The available circuit primitives within the MS462X are shown here. The right side of the circuits shown are connected to the DUT (for those that are asymmetric). The component values are entered discretely. The four port network shown is for balanced devices where the matching behavior in differential and common modes must be different.*

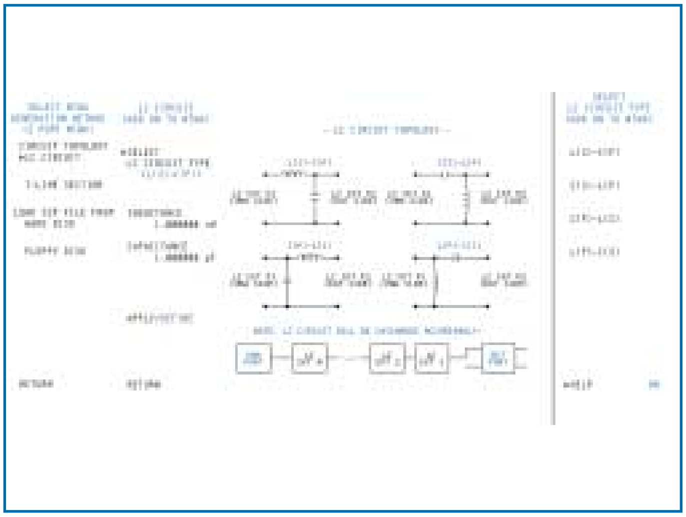
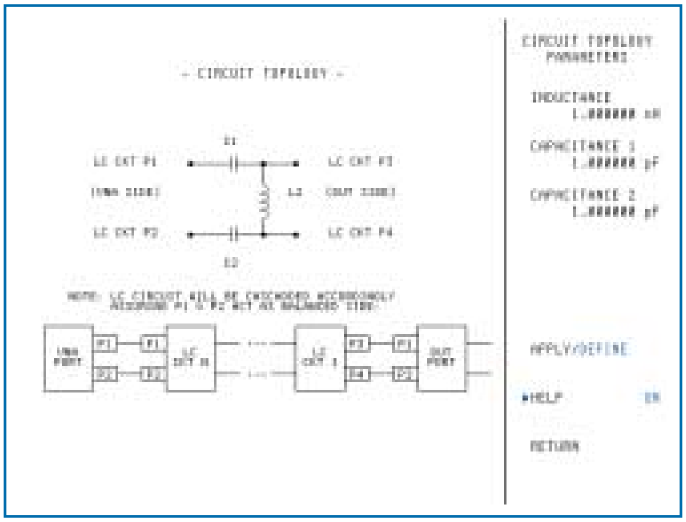


Figure 11*. The menu path for entering one of the two port LC circuit primitives is shown here (along with a help screen). Once the LC circuit class has been selected, the particular topology can be picked (far right menu) and the values entered (middle menu). Note that when multiple networks are entered on the same port, they build out from the DUT.*



```
NOTE: LC CIRCUIT WILL BE CASCADED ACCORDINGLY
      ASSUMING P1 & P2 ACT AS BALANCED SIDE.

INDUCTANCE
       1.000000 nH
CAPACITANCE 1
       1.000000 pF
CAPACITANCE 2
       1.000000 pF
```

Figure 12. *The menu for entering values on the four port LC primitive is shown here. Note the orientation relative to the DUT ports.*

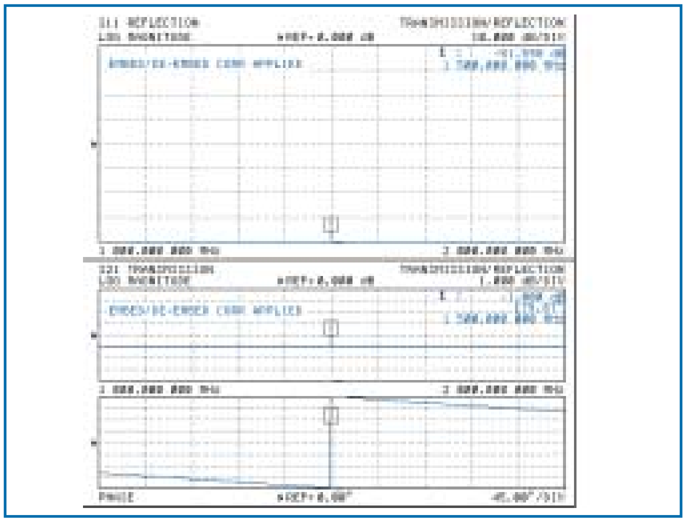
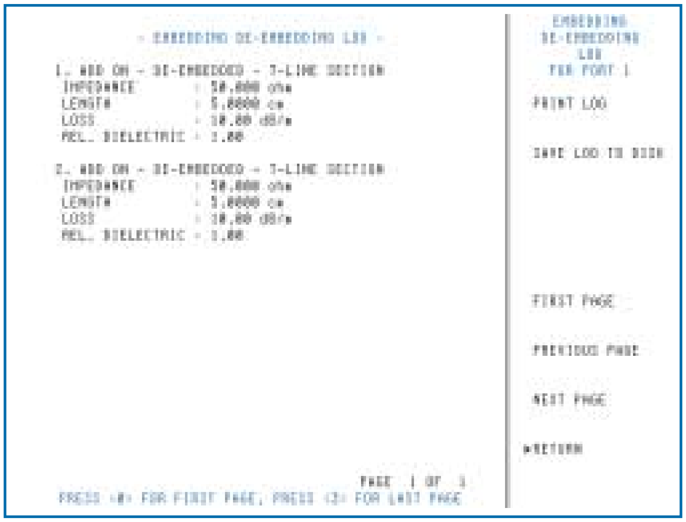


Figure 13. *The effect of embedding a 10 cm (air dielectric, 50 ohm, 10 dB/m loss) line onto a thru line is shown here. As expected, the match is basically unchanged but there is transmission loss and transmission phase shift.*

For the ladder structures, the L (1 pH to ~1 kH) and the C (1 fF to ~1kF) values can be specified (while it is not expected that the higher values will be used frequently, there are certain modeling situations where they can be helpful). These L-C structures can be used to create many different matching and filter circuits on DUT inputs and outputs (some examples shown later). The various combinations are to allow series-shunt reversals and order reversals. For ladder-type filter design, one of many books on the subject can be consulted (e.g., [9]-[10]). The four port primitive is a matching structure class sometimes used in balanced structures. This type of circuit has the advantage that it can provide different matching behavior for differential and common-modes. As such, it cannot be readily represented as a per-port network.

For the transmission line, the impedance, the physical length (or time delay), the loss per unit length and the relative (effective) dielectric constant can be specified. For pure TEM structures such as coax lines, the physical dielectric constant should be entered (often around 2.15 for Teflon). For microstrip and similar planar structures, an effective dielectric constant is required and can be found in many texts (e.g., [8]) or from various simulators. As with reference plane extension, the time delay is the basis quantity and the relative permittivity is used only in conjunction with a physical length. When one of the two 'length' variables is entered, the other (time or physical length) will be recomputed.

A number of examples using these embedding and de-embedding elements will now be presented. First consider embedding a lossy transmission line (50 ohm, 10 cm, 10 dB/m loss, relative dielectric constant of unity) onto a perfect thru (after cal). One would expect a loss of 1 dB and a phase shift of about 180 degrees at 1500 MHz. The result of embedding this primitive is shown in Figure 13 and is as expected. Note that the phase of S21 decreases with frequency as one would expect for an added length of line (e.g., [8],[11]). The match is excellent since the embedded line was also chosen to have 50 ohm characteristic impedance.



```
      - EMBEDDING DE-EMBEDDING LOG -

1. ADD ON - DE-EMBEDDED - T-LINE SECTION
  IMPEDANCE        : 50.000 ohm
  LENGTH           : 5.0000 cm
  LOSS             : 10.00 dB/m
  REL. DIELECTRIC  : 1.00

2. ADD ON - DE-EMBEDDED - T-LINE SECTION
  IMPEDANCE        : 50.000 ohm
  LENGTH           : 5.0000 cm
  LOSS             : 10.00 dB/m
  REL. DIELECTRIC  : 1.00

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Figure 14. *The log for a de-embedding problem is shown here. The entries show two 5 cm line sections (50, lossy, unity relative permittivity) to be de-embedded. One entry (of 10 cm) could have certainly be used; the two entries were used merely to illustrate simple cascading.*

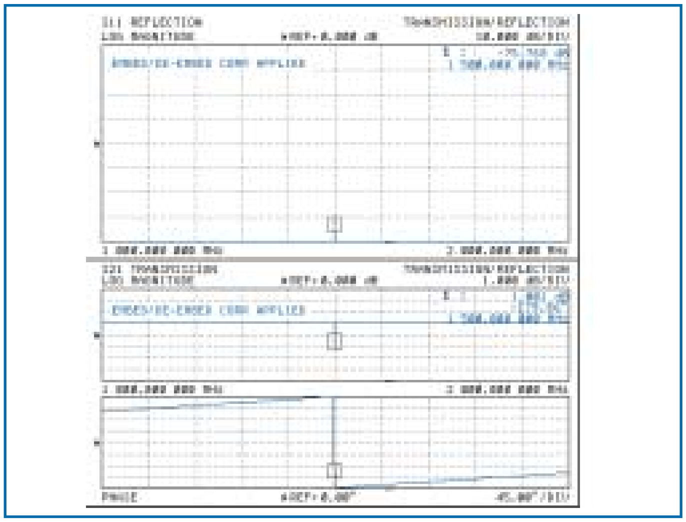
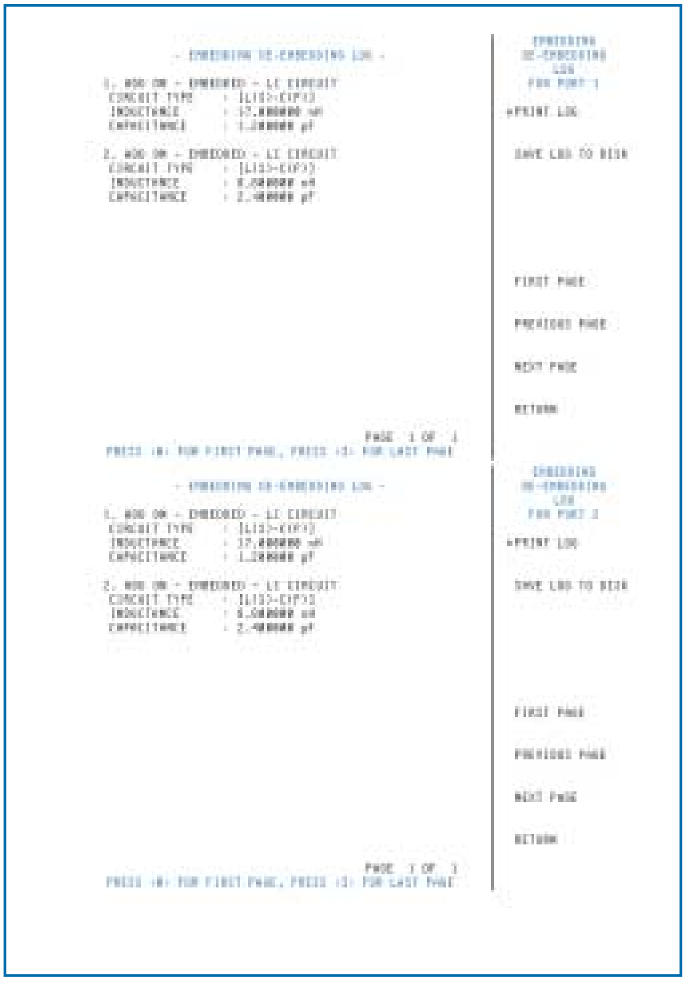


Figure 15. *The results of the (somewhat artificial) problem of de-embedding a lossy line from a thru line are shown here. After removing loss, the result is transmission gain and some reverse phase shift. As would be expected, the match does not significantly change.*

Now consider the opposite problem of de-embedding a lossy transmission line. This line is the same as above accept it was broken into two 5 cm pieces. The log is shown in Figure 14 to illustrate the value entries and the result (again operating on a thru line for clarity) is shown in Figure 15.

Note that now we see 1 dB of ‘gain’ (we removed a lossy, virtual transmission line from a thru line so the result should be gain). Also the phase is increasing with frequency, which should not be surprising, based on previous arguments. The match is still excellent since the starting measurement had almost perfect match (just after cal) and the line being de-embedded was chosen to have a 50 ohm characteristic impedance.

Next consider a network composed of the L-C primitives. The logs for ports 1 and 2 are shown in Figure 16; 2 primitives are used on each port and recall that these build from the inside out (first network entered is nearest the DUT on that port). This is a filter like structure and the results of embedding this network (into a thru line) are shown in Figure 17. Recall that the LC networks, as defined, have their second component nearest the DUT (thus L(S)-C(P) will have the shunt capacitor nearest the DUT no matter which port is being modified).



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          - EMBEDDING DE-EMBEDDING LOG -                    EMBEDDING
                                                          DE-EMBEDDING
   1. ADD ON - EMBEDDED - LC CIRCUIT                           LOG
    CIRCUIT TYPE      : [L(S)-C(P)]                        FOR PORT 1
    INDUCTANCE        : 17.000000 nH
    CAPACITANCE       : 1.200000 pF                       *PRINT LOG

   2. ADD ON - EMBEDDED - LC CIRCUIT                       SAVE LOG TO DISK
    CIRCUIT TYPE      : [L(S)-C(P)]
    INDUCTANCE        : 8.800000 nH
    CAPACITANCE       : 2.400000 pF

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          - EMBEDDING DE-EMBEDDING LOG -                    EMBEDDING
                                                          DE-EMBEDDING
   1. ADD ON - EMBEDDED - LC CIRCUIT                           LOG
    CIRCUIT TYPE      : [L(S)-C(P)]                        FOR PORT 2
    INDUCTANCE        : 17.000000 nH
    CAPACITANCE       : 1.200000 pF                       *PRINT LOG

   2. ADD ON - EMBEDDED - LC CIRCUIT                       SAVE LOG TO DISK
    CIRCUIT TYPE      : [L(S)-C(P)]
    INDUCTANCE        : 8.800000 nH
    CAPACITANCE       : 2.400000 pF

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Figure 16*. The logs for an LC embedding problem are shown here. A pair of LC circuits are added to both ports 1 and 2 to create a filtering structure.*

The schematic of the structure just embedded is shown in Figure 18. Note that since the embedding was done into a thru line, the resulting circuit looks just like a conventional low pass filter where the center capacitor was split into two. Carefully compare Figure 18 to the logs in Figure 16 to understand how the networks are ordered upon entry. To verify that the embedding process was done correctly, the results of an external simulation are shown in Figure 19.

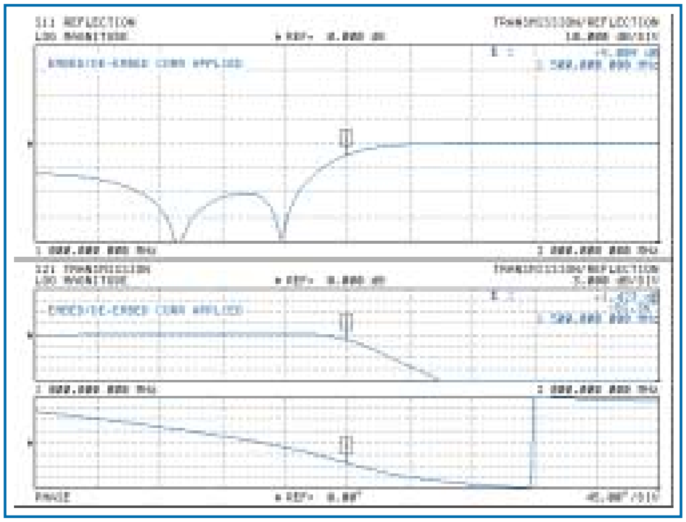


Figure 17*. The results of embedding the circuit described in Fig. 16 are shown here (|S11| and S21). The low pass behavior is quite evident.*

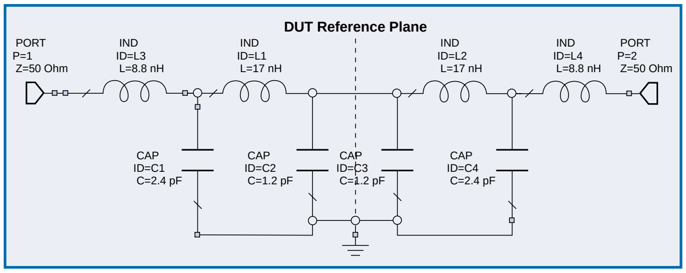


Figure 18. *Schematic of the complete structure embedded for Figure 17 is shown here. The original base thru line is in the middle.*

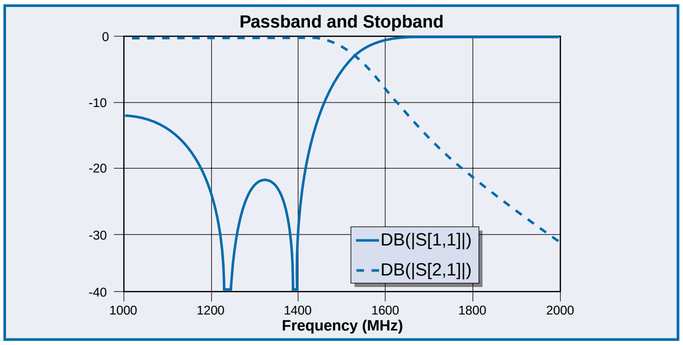


Figure 19. *Simulated result for the schematic in Figure 18. As one would expect, the results agree with that generated by embedding the elements into a thru line.*

Next consider the four port LC structure. As mentioned earlier, it is of use when different matching behavior for differential and common modes is desired. Two of these sections were cascaded on P1-P2 for embedding while nothing was done on P3-P4. The DUT in this case consisted simply of a thru between P1 and P3 and a thru between P2 and P4. As a result, a simple equivalent circuit, shown in Figure 20a (log in Figure 20b), is generated.

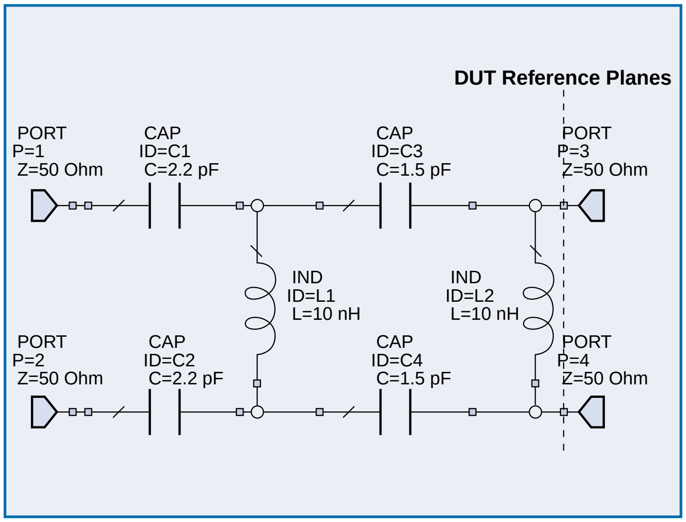
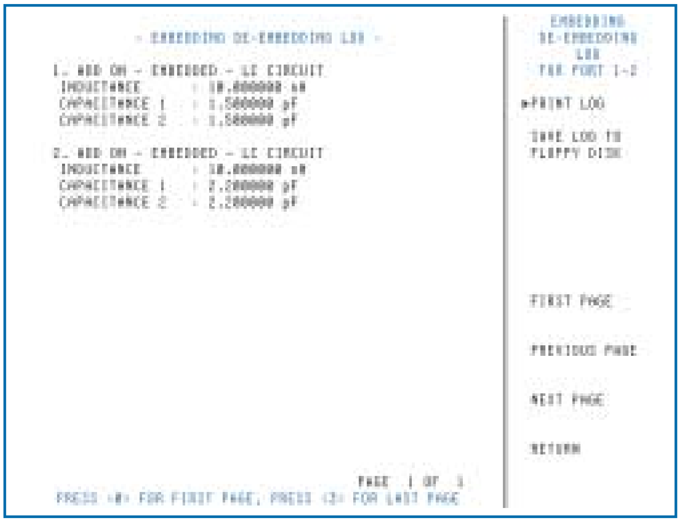


Figure 20a. *Equivalent circuit of an embedding example where two 4-port LC networks are cascaded at P1-P2, the DUT is a pair of thrus, and nothing is done on P3-P4.*



```
- EMBEDDING DE-EMBEDDING LOG -

1. ADD ON - EMBEDDED - LC CIRCUIT
 INDUCTANCE      : 10.000000 nH
 CAPACITANCE 1   : 1.500000 pF
 CAPACITANCE 2   : 1.500000 pF

2. ADD ON - EMBEDDED - LC CIRCUIT
 INDUCTANCE      : 10.000000 nH
 CAPACITANCE 1   : 2.200000 pF
 CAPACITANCE 2   : 2.200000 pF

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Figure 20b. *The log for the circuit of Figure 20a is shown here.*

The resulting common-mode (S_{C1C1}) and differential match (S_{D1D1}) are shown in Figure 21. If more information is needed on this class of mixed-mode S-parameters, consult the mixed-mode and 4 port application note [12], a related application note on impedance transformations [13] or other references (e.g.,[14]-[15]). As might be expected, the match levels in these two modes are quite different (in the design passband of course).

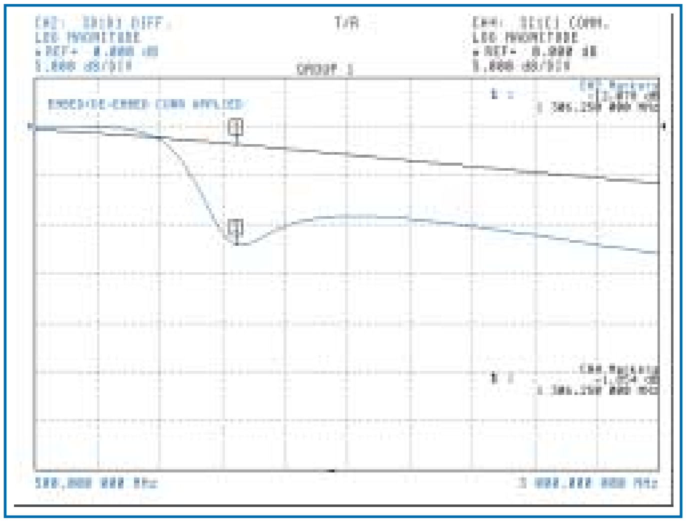


Figure 21. *Differential (darker trace) and common-mode (lighter trace) input match of the network in Fig. 20. The network was generated using embedding of a pair of simple LC circuit primitives.*

The next series of questions relate to 'editing' in the sense of how network information is entered and modified. Note the menu item ADD/MODIFY. In the ADD state, when network information is entered, it is added to (potentially) a chain of networks. This chain starts at the DUT port and works toward the measurement port. One can keep adding networks ad infinitum (log limited to five pages, keeping the last entries; only the last entry may be edited). A potential use for this is in multi-element matching structures or more complicated models for fixture behavior. In the MODIFY state, the last network entered (on the port currently being worked on) will be replaced by the next entry. This can be the same network type with just different parameters or it can be a completely different type (e.g., replacing and L-C structure with an S2P file). An important point is that only the most recent network entered (on the port in question) can be modified. If an entry further back needs to be changed, then CLEAR ALL COMPOSITE NTWKS must be used. Note that one cannot clear one port at a time. The logs are available for each port or port pair to indicate the networks stored up to that point. The networks (including the parameters and type) are listed in order working out from the DUT. These logs can be saved to disk or printed for future reference.

The collection of networks used for embedding and de-embedding ARE NOT saved as part of the front panel setup. They must be saved using the save/recall functions WITHIN the embedding/de-embedding menus. This save/recall function deals with all of the network configuration information for all ports.

PROCEDURES

To summarize some of the thoughts put forth, fairly general procedures will be de-lineated on how to perform embedding and de-embedding.

EMBED ONE OR MORE NETWORKS

1. Perform an N port cal for an N port device
2. Enter Embedding/De-embedding and clear all composite networks if necessary
3. Select the number of device ports and decide if port-by-port embedding is desired or pairs of ports (only for 3 and 4 port DUTs and only if a balanced structure is needed)
4. Select ADD TO NETWORKS and EMBEDDING
5. For each single port that is being embedded: select an .s2p file (from floppy or hard disk) or a circuit primitive (and enter the values). Enter the network nearest the DUT first for each port.
6. For each pair of ports that is being embedded: select an .s4p file (from floppy or hard disk) or a 4 port circuit primitive (and enter the values). Note that 2 port networks will be placed nearest the DUT, the four port networks will always be closer to the ports than the two port networks.
7. If multiple networks are to be embedded on a given port (or pair) keep ADDing. Recall that these networks work from the inside out.
8. Continue with all other ports (or pairs as appropriate)
9. Turn on embedding
10. If a mistake was made on the most recent network entered (wrong value, wrong file,…), go up a level and select MODIFY network and repeat step 5/6 for that network. Be sure to switch back to ADD when done. You can check the status of the current port/pair by looking in the log. If a mistake was made on an earlier network, you must CLEAR ALL COMPOSITE NTWKS and start over
11. Save the embedding/de-embedding setup if desired.

DE-EMBED ONE OR MORE NETWORKS

Perform the above steps substituting DE-EMBEDDING for EMBEDDING on item 4.

MULTI-TIER COMBINATIONS

This is similar to the above instructions. The only caveat is that you must select embedding or de-embedding before entering each network on each port/pair. Again recall that the first network entered on a given port/pair is nearest to the DUT and each successive network works toward the MS462X. ORDER IS IMPORTANT.

EXAMPLES

This section consists of a number of practical examples to help illustrate the use of this embedding-de-embedding engine with real circuits. The examples cannot cover every scenario but they should address a variety of topics.

Consider first a low gain amplifier in a simple fixture. The fixture's S-parameters were characterized separately since it was quasi-connectorized and the frequencies were low enough. The situation of a connectorized 'fixture' is not that unusual since it describes switch matrices and other multi-port test sets. De-embedding allows the measurement of a multiport devices using only a 2,3 or 4 port cal at the network analyzer planes together with de-embedding files for all test set paths.

The amp+fixture direct measurement along with the de-embedded result are shown in Figure 22. Because the fixture had a fair amount of loss (about 3 dB), the actual gain and mismatch are noticeably higher than with the combined DUT and fixture.

In the quasi-connectorized environment, it was also possible to calibrate at the DUT planes (the preferred method). The result of this cal along with the de-embedded result from the previous example are shown in Figure 23. As would be hoped, these results are quite close to each other. At least part of the small phase difference can probably be attributed to cable flex between the various measurements.

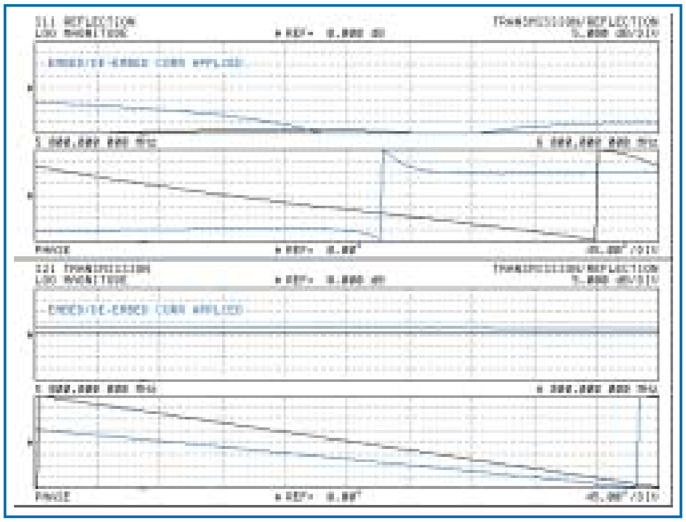


Figure 22. *Direct amp+fixture measurements (lighter trace) and de-embedded result (darker trace, upper magnitude trace in S21) are shown here. The fixture was fairly lossy so the de-embedded gain is much higher and the match worse at most frequencies.*

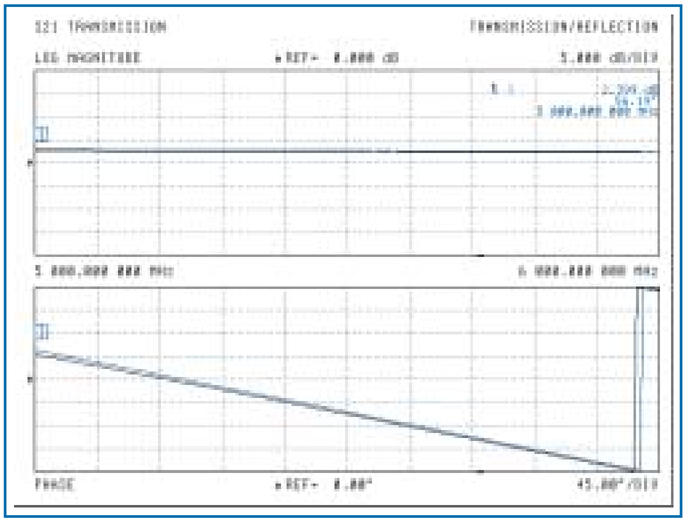


Figure 23. *A comparison of the de-embedded result of Fig. 20 along with the direct result when the calibration was performed at the DUT planes. Ideally there would be no difference but cable flexure between measurements resulted in some small shifts.*

Next consider a multi-tier example. A two port amplifier is measured within a test fixture. It is desired to de-embed the test fixture and then embed a high-pass network that will be connected to the amplifier in its actual application. The test fixture characteristics were arrived at through a combination of modeling and measurements and the S-parameters (finally extracted from a simulator) are available in the form of .s2p files. The high-pass network was measured separately and its .s2p file is also available. A situation in which this sequence may occur is in manufacturing where the same fixture is used from day-to-day (and was previously characterized) and the customer desires to see the data as if the extra network was connected (and it is too time-consuming to actually attach that network in production). The initial measured data is shown in Figure 24. The DUT has an integrated low pass filter so the sharp roll-off is expected. The net gain is near 0 dB suggesting that the fixture has considerable loss. The S-parameters of one side of the fixture are shown in Figure 25 and confirm the loss observation.

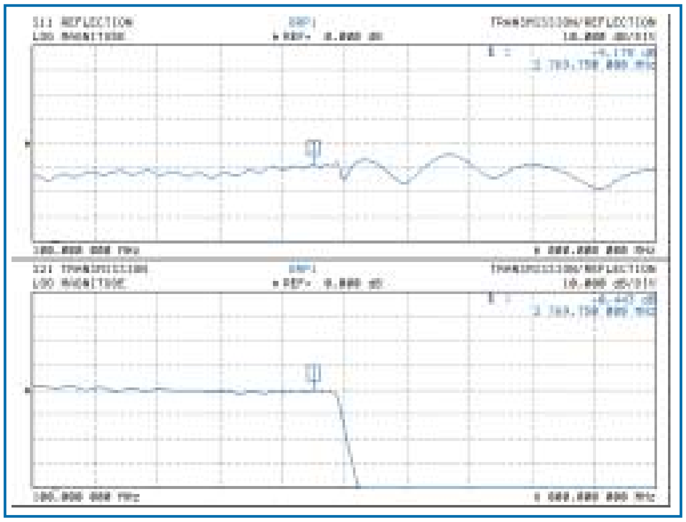


Figure 24. *Initial amp+fixture measurements are shown here. The amplifier has an integrated low pass filter. The low |S21| is indicative of substantial fixture loss.*

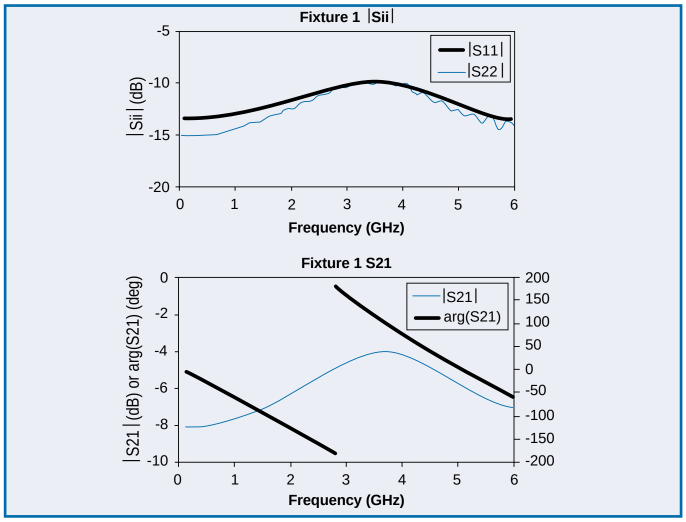


Figure 25. *The S-parameters of one side of the fixture (derived from modeling plus measurements) are shown here. The loss is substantial (as hypothesized) and unflat.*

The fixture on port 2 has parameters of similar order-of-magnitude although the frequency responses are slightly different. The performance after de-embedding the fixture segments is shown in Figure 26. The gain is closer to what was expected and the ripple is reduced. The input match is now better and closer to what might have been expected.

The next step is to embed the high pass network and the results are shown in Figure 27. For comparison purposes, the data prior to embedding and de-embedding is also shown. The high pass behavior of the complete structure should now be evident. As would be expected, the match has worsened in the stop-band of the high pass network but it has not changed dramatically in the common passband.

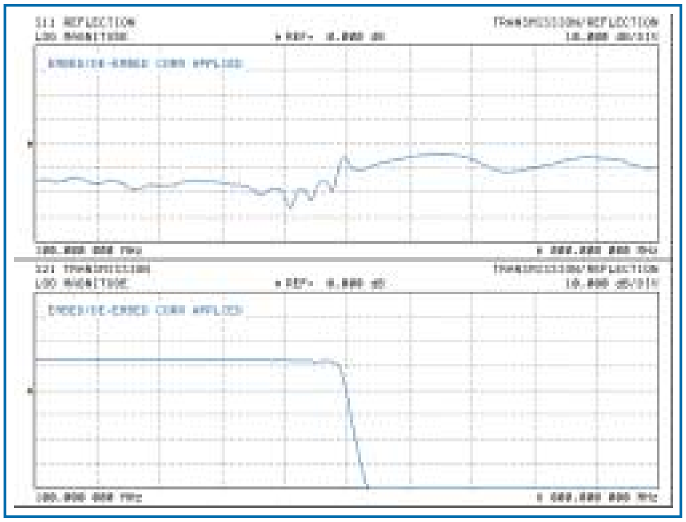


Figure 26. *The results after de-embedding the fixture from the results of Fig. 24 are shown here. As might be expected, the actual gain is much higher and flatter than that prior to de-embedding.*

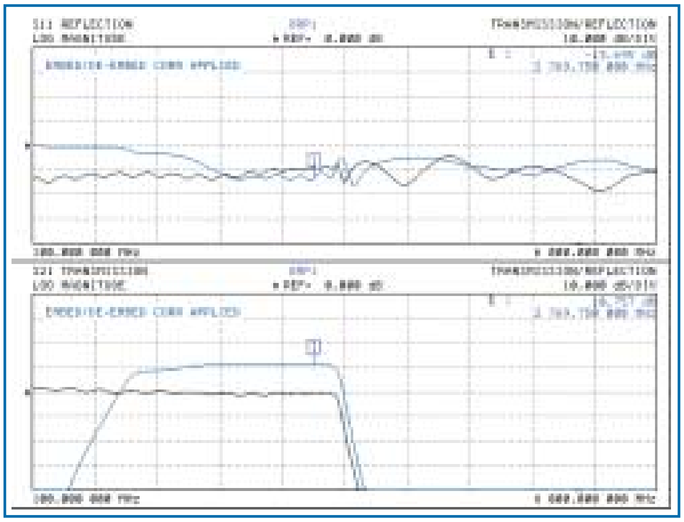


Figure 27. *The effect of the final embedding of the high pass structure on the de-embedded results is shown here (blue trace). The original measured data (black trace) is also shown for comparison.*

Extraction

An important step towards de-embedding the effects of a test fixture is to measure the S-parameters of the test fixture. Extraction is the name given to a process using a pair of calibrations to determine these S-parameters. The idea is to perform a full cal at the coaxial plane and then to perform another cal at the DUT plane with the fixture in place. There is then enough information to extract the fixture S-parameters, up to a point, in the form of a .s2p file for every port. One limitation is that only $S_{nm}S_{mn}$ is extracted (per port) and not the individual transmission parameters S_{nm} and S_{mn}. This ends up not being a problem for de-embedding since only the product is needed for that step. Since the .s2p file format requires the two separate parameters, however, a reciprocity assumption is made during that file creation step. As such, the files should be interpreted carefully if done outside the venue of de-embedding.

The two calibration files are stored to disk (hard disk or floppy). The calibration files can be 2 port (full 12 term), 3 port (full 24 term) or 4 port (full 40 term) but of course both files must be of the same type. The extraction algorithm takes these two files and generates an S2P file for every port that can again be stored onto disk for later use. For a full four port extraction then, four .s2p files would be generated. Each file described the path between the inner plane and the outer plane for that port.

While the outer calibration is presumably coaxial and probably straightforward, the inner cal at the DUT plane may be more complicated. Often this environment will be a pc board or similar planar structure and cal standards will need to be constructed. Ignoring traceability issues for the moment, the first question must be algorithm choice. A brief summary of calibration algorithms is below but the user may which to consult more detailed references (e.g., [16]).

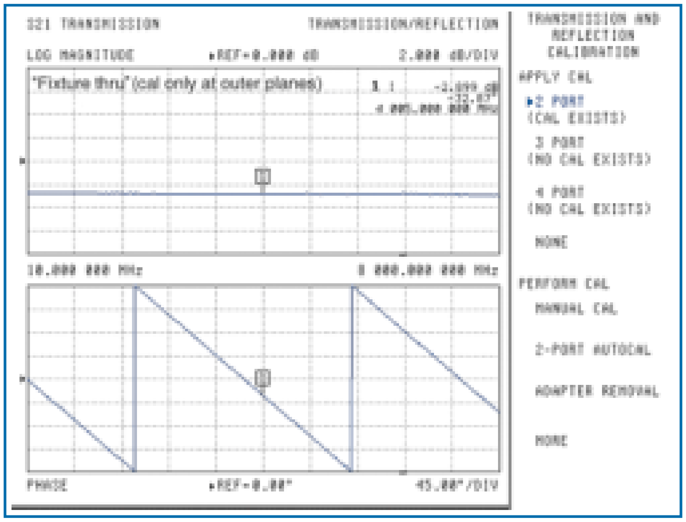
SOLT – must characterize open. This can be done to a certain degree using the coaxial cal if the fixture can be considered lossless (or at least constant loss). Otherwise an additional fixture may be necessary. Note that the standard model used is a 3rd order polynomial in frequency to describe the effective fringing capacitance. Fitting algorithms can be used on swept reflection data of the 'open' and note that the coefficients so derived are usually not unique.

$C_{open}(f) = C_0 + C_1 f + C_2 f^2 + C_3 f^3$

LRL- no opens to characterize but line length choices may be a physical layout problem. The difference in line length must be electrically significant at the lowest cal frequency and in general no more than a 9:1 frequency range can be covered with two lines (more lines can be used)

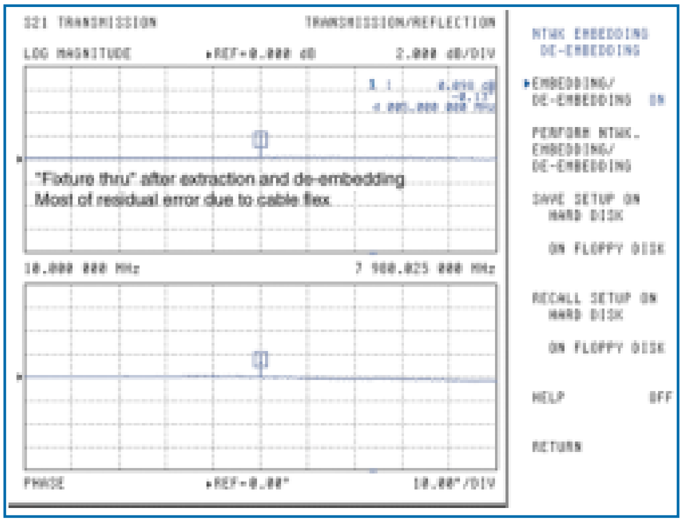
LRM- be careful with the load model. This only requires a thru line so layout geometry is less of an issue than with LRL. Board level loads (usually SM or chip resistors) often have a fair amount of package inductance that can be significant as the frequencies increase. This inductance can be included as part of the model within the instrument. Note that the use of two 100 ohm resistors shunted to ground is a common implementation that keeps some symmetry and reduces effective inductance.

As a confidence building example, an extraction will be performed based on a pair of cals and the resulting s2p data immediately fed back into a de-embedding engine. The outer cal will be applied and the thru with the fixture in place will be connected. If everything is functioning properly, the results should be an S21 of 0 dB and 0 degrees. The only error would be due to some slight drift or repeatability error between when the cals were originally done and when the de-embedding is performed. To start, consider the fixture thru with the outer cal applied. In this example, the S21 is shown in Figure 28 (some loss and some phase length). With the extraction performed, the s2p data is then sent to the de-embedding engine. This result is shown in Fig 29. Indeed in this case, the S21 has been reduced to basically the expected zero-length thru.



"Fixture thru" (cal only at outer planes)

Figure 28. *S21 of the fixture (thru connected) is shown here (cal at outer planes). This fixture will be extracted using the procedure discussed in the text with a pair of calibrations.*



"Fixture thru" after extraction and de-embedding
Most of residual error due to cable flex

Figure 29. *The fixture discussed in Fig. 26 was extracted and its full S-parameters generated (in the form of one s2p file for each port). These files were then used to de-embed the data of Fig. 26. As would be expected, the result is nearly a perfect thru with some residuals due to cable flexure.*

Conclusions

This note has attempted to present some of the purposes of embedding and de-embedding and how these techniques can be used to get desired measurement results in a variety of physical situations. The techniques themselves have been presented as well as how they have been implemented in the MS462X series of analyzers. In addition to the means of network entry available and the operational questions to be answered, a number of examples have been presented to both illustrate the mathematical process and to provide some ideas on the measurement sequences that might be employed in practice.

Appendix

.SnP and related file formats

The .s2p, .s3p and .s4p file formats have generally been accepted by simulator and instrumentation manufacturers ([18]). The formats are listed here primarily as a convenience. In all cases any white space separation is normally allowed but tab delimited is probably the most common. Usually no more than 4-5 significant figures are carried per field although there are exceptions. A header beginning with a # is required which specifies the frequency units (GHz, MHz,…), parameter type (S for S-parameters), format (MA for magnitude-angle, RI for real-imaginary, DB for log magnitude-angle), reference type (R for resistance), and reference impedance value (50 typically). Most simulators do not support the use of arbitrary impedance-referred S-parameters.

.s2p

```
# GHz S MA R 50 (required header, frequency units, type of parameter, data format, term type and value)
5.81          0.975         75.8          0.218         -131          0.218         -131          0.975    -158
```

(freq S11 S21 S12 S22)

RI is also allowed as is dB for log-mag and phase

.s3p

```
# GHz S MA R 50
2.3           0.15709       -105.78       0.6088        31.754        0.55165       -17.864
              0.6088        31.754        0.25912       -110.54       0.57848       -7.7228
              0.55165       -17.864       0.57848       -7.7228       0.2658        111.7
```

(here the order is S11 S12 S13 S21 S22 S23 S31 S32 S33 as one would expect in a true matrix formulation)

.s4p

```
# GHz S MA R 50
0.52        0.95541    -29.33     0.21828    65.996     0.12632    75.892     0.15361    71.995
            0.21828    65.996     0.95541    -29.33     0.15361    71.995     0.12632    75.892
            0.12632    75.892     0.15361    71.995     0.97405    -22.6      0.10809    77.995
            0.15361    71.995     0.12632    75.892     0.10809    77.995     0.97405    -22.6
```

(here the order is S11 S12 S13 S14 S21 S22 S23 S24 S31 S32 S33 S34 S41 S42 S43 S44 as one would expect in a true matrix formulation)

.m3p and .m4p

Closely related file formats allow the storage of mixed mode S-parameters. While not standard in the simulator industry, these formats at least allow complete export of mixed mode data for spreadsheet or other analysis. These formats, since not restricted my convention, also allow the presentation of data in an arbitrary impedance environment. The header has been modified to accommodate this with 6 fields for .m3p and 8 fields for .m4p (a real and imaginary field for the impedance of each port).

```
FILENAME
DATE: 08/31/01
CORRECTED DATA
# GHz MS DB R 50.000            0.000        50.000              0.000        50.000              0.000
0.010000000     -9.533554E+00   176.970      -5.456931E+01       30.074       -4.873734E-01       -2.825
                -4.655542E+01   176.606      -8.739791E-02       172.742      -4.565174E+01       -179.441
                -4.356444E-01   -2.746       -5.404599E+01       -79.141      -9.400748E+00       -2.589
0.021237500     -9.522542E+00   173.258      -5.041196E+01       0.325        -4.612945E-01       -5.855
                -4.534632E+01   145.615      -2.599994E-01       165.229      -4.740926E+01       161.587
                -4.121463E-01   -5.935       -4.526606E+01       -18.056      -9.446059E+00       -5.372
```

(The parameter order for .m3p is S_{11} S_{1D} S_{1C}; S_{D1} S_{DD} S_{DC}; S_{C1} S_{CD} S_{CC}. The structure is analogous for .m4p with the parameter order being S_{D1D1} S_{D1D2} S_{D1C1} S_{D1C2}; S_{D2D1} S_{D2D2} S_{D2C1} S_{D2C2}; S_{C1D1} S_{C1D2} S_{C1C1} S_{C1C2}; S_{C2D1} S_{C2D2} S_{C2C1} S_{C2C2}).

Interpolation

Because it is likely that the .SnP files input will not have exactly the same frequency points as the instrument setting at the time, interpolation is an important process. Obviously if the .SnP point density is very low relative to that of the instrument setting, then one can expect inaccuracies to increase. Even if the point densities are comparable, the interpolation must be handled correctly to avoid problems. Some of the issues involved are discussed below mainly for reader interest but the important point is that the closer the point systems are aligned, the lower the probability of error.

Complex interpolation

Since the numbers being interpolated are complex, there are an infinite variety of ways to perform the interpolation. Consider the two frequency points and data shown below; the desire is to find the value of X at 1.5 GHz.

1.000 GHz	X= 1+j2
2.000 GHz	X=-1-j1.9

If one were to just interpolate the real and imaginary parts separately, one would get X=0+j0.05. While mathematically this seems perfectly legitimate, it has some physical problems. Implicit in all S-parameters and error coefficients is a certain degree of the concept of energy conservation. If X represented gain or reflection coefficient, it also represents a certain amount of energy being transmitted or reflected. The amount of energy involved should smoothly change from frequency to frequency assuming non-linearities involved are not abrupt. In the above example this would clearly not be the case. Since the magnitude of X is most closely related to the energy content present (in the case of S-parameters certainly, also in the case of error coefficients since they can directly be tied to reflected or transmitted signals as well), it is more reasonable to interpolate in magnitude and phase. In this case, the value of X at 1.5 GHz would instead be 1.954-j1.003.

Phase wraps

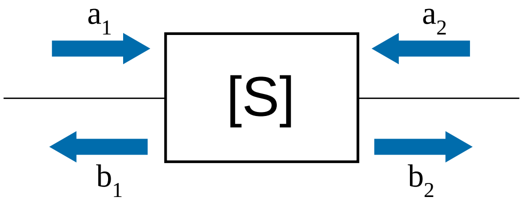
While continuous energy is a physical requirement, continuous phase is usually assumed. Normally this is not an issue but can occasionally get confusing due to the practice of phase wrapping. Usually the phase of a complex number is expressed over the interval of –180 degrees to 180 degrees. Interpolation is normally not an issue but if the two neighboring points are in the 2nd and 3rd quadrants, then the interpolation will mistakenly put the midpoint result somewhere in the 1st or 4th quadrants. For this reason, the phase should be wrapped (not constrained to +/- 180) prior to interpolation. For display purposes, the data can then be re-wrapped.

This section has dealt only with variants of linear interpolation. There are more advanced interpolation techniques, such as rational function or spline methods, that can handle S-parameter interpolation as well (often with fewer issues). The user may which to consult other sources on this subject (e.g. [17]).

T-matrices

The transfer matrices are defined in a manner analogous to S-parameters except the dependencies have been switched to enable the cascading discussed in the text. In both cases the wave variables are defined as a_i for the wave incident on port *i* and b_i for the wave returning from port *i*. For a two port network, the S-parameters are defined by:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

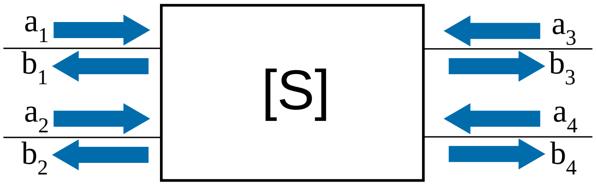


The T-formulation (e.g., [8]) is a bit different to allow for cascading: this forces b_2 and a_2 to be the independent parameters instead of a_1 and a_2. This does change the operation of the circuit, just the situation under which the parameters are measured. Since the T parameters are rarely measured directly, this is usually not a concern.

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

Note the arrangement so that when two networks are connected together that b_2 of the network on the left maps directly onto a_1 for the network on the right (similarly for a_2 and b_1). For a four port network, a similar structure can be generated. The four port S-parameters are defined in the obvious way:

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}$$



There are a number of ways one could define the T-formulation, but for our purposes here the primary application is in using the four port as a device with two balanced ports. As such, it makes sense to pair off the ports such that ports 3 and 4 of one device would connect to ports 1and 2 of the next device (respectively). That leads to the following structure

$$\begin{bmatrix} a_1 \\ a_2 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & T_{13} & T_{14} \\ T_{21} & T_{22} & T_{23} & T_{24} \\ T_{31} & T_{32} & T_{33} & T_{34} \\ T_{41} & T_{42} & T_{43} & T_{44} \end{bmatrix} \begin{bmatrix} b_3 \\ b_4 \\ a_3 \\ a_4 \end{bmatrix}$$

Transformations are relatively easy to generate between these formulations.

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