Telecommunications Industry Association (TIA)

TITLE:	**ANSI/ TIA 1183-1** ***MEASUREMENT METHODS AND TEST FIXTURES FOR BALUN-LESS MEASUREMENTS OF BALANCED COMPONENTS AND SYSTEMS Extending Frequency Capabilities to 2 GHz*****.**
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ABSTRACT: ***Specifications for test fixtures for making network analyzer measurements without the use of balun transformers in the measurement path. Extending measurement capabilities to 2.0 GHz***

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8-27-2014 Formatted figure numbering and table numbering. Accepted edits. Modified figure 6. Added explanation of 16-port matrix subscript numbering in Clause E.2.2.

NOTICE

{TIA staff to insert applicable text here.}

MEASUREMENT METHODS AND TEST FIXTURES FOR BALUN-LESS MEASUREMENTS OF BALANCED COMPONENTS AND SYSTEMS

LIST OF TABLES

LIST OF FIGURES

FOREWORD

(This forward is not a part of this Standard.)

This project was initiated in conjunction with the need to measure additional parameters for modeling of alien crosstalk in permanent links and channels of Category 6A and better cabling and components. The scope of the project has been broadened to higher frequencies and general testing purposes. The Standard is intended to be published as an independent testing reference.

This Standard was developed by TIA Subcommittee TR-42.7.

Approval of this Standard

This Standard was approved by TIA Sub-Committee TR-42.7, TIA Engineering Committee TR-42, and the American National Standards Institute (ANSI).

ANSI/TIA reviews standards every 5 years. At that time, standards are reaffirmed, rescinded, or revised according to the submitted updates. Updates to be included in the next revision should be sent to the committee chair or to ANSI/TIA.

Contributing Organizations

More than 30 organizations within the telecommunications industry contributed their expertise to the development of this Standard (including manufacturers, consultants, end users, and other organizations).

Annexes

Annex A is informative and not considered requirements of this standard.

Introduction

This standard describes test fixturing and methods for obtaining performance measurements of passive devices designed for differential signal transmission. The measurements are generally aimed at swept frequency response measurements where the source signal is provided by test equipment. A network analyzer is typically used for these types of measurements. The fixtures are not limited to use with network analyzers, though, and can be used with time domain measurement equipment (TDRs, Oscilloscopes) as well. The primary enhancement of these test methods and fixtures relative to conventional devices is the elimination of balun transformers for impedance matching between the device under test (DUT) and the measurement equipment.

Purpose

Removal of the balun transformers from the measurement circuit allows extension of the bandwidth of testing up to the inherent capabilities of the network analyzer and the associated test fixtures. Elimination of baluns also allows the DUT to be tested with both differential mode stimulus or response, or common mode stimulus or response. This enables testing of mixed mode parameters such as TCL, TCTL and cross-modal NEXT and FEXT couplings without reconfiguration of the DUT or the measurement setup.

Specification of criteria

Two categories of criteria are specified; mandatory and advisory. The mandatory requirements are designated by the word "shall"; advisory requirements are designated by the words "should", "may", or "desirable" which are used interchangeably in this Standard.

Mandatory criteria apply to performance and compatibility; they specify the absolute minimum acceptable requirements. Advisory or desirable criteria are presented when their attainment will enhance the general performance of the testing platform in all its contemplated applications.

A note in the text, table, or figure is used for emphasis or offering informative suggestions.

Metric equivalents of US customary units

The majority of the metric dimensions in this Standard are metric with soft conversions to US customary units; e.g., 4 inches (in) is the soft conversion of 100 millimeters (mm).

Life of the Standard

This Standard is a living document. The criteria contained in this Standard are subject to revisions and updating as warranted by advances in telecommunications technology.

1 Scope

Balun-less measurement methods, nomenclature, and fixtures are defined for measurement of transmission parameters of four-pair (16 port) devices typically utilizing multi-port network analyzers. The methods and fixtures have shown to facilitate measurement of all differential mode, mixed mode, and common mode transmission parameters up to 1 GHz. Test interface performance specifications above 1GHz are under study.

2 NORMATIVE REFERENCES

The following standards contain provisions that, through reference in this text, constitute provisions of this Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision; parties to agreements based upon this Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated. ANSI and TIA maintain registers of currently valid national standards published by them.

ANSI/TIA-568-C.2, *Balanced Twisted-Pair Telecommunications Cabling and Components Standard (2009)*

IEC 61156-1, *Multicore and Symmetrical Pair/Quad Cables for Digital Communications – Part 1: Generic Specification (2009)*

3 DEFINITION OF TERMS, ACRONYMS AND ABBREVIATIONS, AND UNITS OF MEASURE

3.1 General

For the purpose of this Standard the following definitions, acronyms, abbreviations and units of measure apply.

3.2 Definitions

cross-modal: related to conversion from differential mode to common mode or vice versa.

far-end crosstalk loss: A measure of the unwanted signal coupling from a transmitter at the near end into another pair measured at the far end, and relative to the transmitted signal level.

insertion loss: The signal loss resulting from the insertion of a component, or link, or channel, between a transmitter and receiver (often referred to as attenuation).

longitudinal conversion loss: A ratio, expressed in dB, of measured differential voltage relative to the common mode voltage on the same conductor pair applied at the same end.

longitudinal conversion transfer loss: A ratio, expressed in dB, of measured differential voltage relative to the common mode voltage on the same conductor pair applied at the same end.

mixed mode: Containing differential mode and common mode signals.

near-end crosstalk loss: A computation of the unwanted signal coupling from a transmitter at the near-end into a different receiver at the near end.

return loss: A ratio expressed in dB of the power of the outgoing signal to the power of the reflected signal.

screen: An element of a cable formed by a shield.

shield: A metallic layer placed around a conductor or group of conductors.

transverse conversion loss: A ratio, expressed in dB, of the measured common mode voltage on a pair relative to the differential mode voltage on the same pair applied at the same end.

transverse conversion transfer loss: A ratio, expressed in dB, of the measured common mode voltage on a pair relative to the differential mode voltage applied at the opposite end of the same pair, or on either end of another pair.

3.3 Acronyms and abbreviations

ANSI	American National Standards Institute
CM	common mode
DM	differential mode
DMCM	differential mode plus common mode
DUT	device under test
FEXT	far-end crosstalk
F/UTP	foil (surrounding) unshielded twisted-pairs
IEC	International Electrotechnical Commission
LCL	longitudinal conversion loss
LCTL	longitudinal conversion transfer loss
NEXT	near-end crosstalk
RL	return loss
SE	single ended
S/FTP	overall shield surrounding individually foiled twisted-pairs
SF/UTP	overall shield and foil surrounding unshielded twisted pairs
TCL	transverse conversion loss
TCTL	transverse conversion transfer loss
TIA	Telecommunications Industry Association
U/FTP	individually foiled twisted-pairs without an overall shield
UTP	unshielded twisted-pair
U/UTP	unscreened and unshielded twisted pairs (see UTP)

3.4 Units of measure

dB	decibel
in	inch
MHz	megahertz
mm	millimeter
Ω	ohm
V	volt

3.5 Variables

f	frequency, in MHz

4 General

This document describes the general configuration of and requirements for laboratory test equipment for measurement of generic copper cabling components and systems. The equipment configurations described are for measurement of cabling type devices consisting of four pairs of wires which present to the test equipment 16 ports for measurement divided into 8 ports at a defined near (local) end and 8 ports at a defined far (remote) end. For practical purposes all 16 ports connect to a single network analyzer for measurement, so the remote end is not physically removed from the local end. The least number of network analyzer ports considered in this standard is four, with external switching or manual connections to adapt the network analyzer to the cabling under test. The maximum (ideal) number of network analyzer ports considered here is 16, which would provide a fully calibrated measurement environment for a single four pair channel. A 32 port network analyzer would provide a fully calibrated measurement environment to capture all of the coupling parameters between two four pair channels in addition to the coupling parameters within those channels. 32 port systems will not be considered in this standard. In this document, the cable, channel, or other device under test will be referred to as the DUT.

The test fixtures described in this document are designed to present a generic interface between cabling devices which present a bare wire or wires to the test interface with a multi-port network analyzer. The test system may also include an intermediate RF switch to adapt the number of network analyzer ports to the number of DUT ports. The multi-port network analyzer allows for the elimination of balun transformers from the measurement path of devices that are designed for differential signaling. The network analyzer can drive any single-ended 50 Ω port, measure response from any single ended 50 Ω port and calculate the response in terms of mixed mode (differential and common mode) signaling environment. Full characterization of a two-port differentially signaled DUT is possible through stimulus and measurement of the four-port single-ended S parameters. The results include not only the commonly specified differential S parameters (insertion loss, return loss, NEXT, FEXT) and mixed mode S parameters (TCL, TCTL), but also common mode parameters such as common mode insertion loss and common mode return loss. In addition, the four port S-parameter data may be post-processed to provide equivalent test results for different mixed mode environments, for example different common mode impedances.

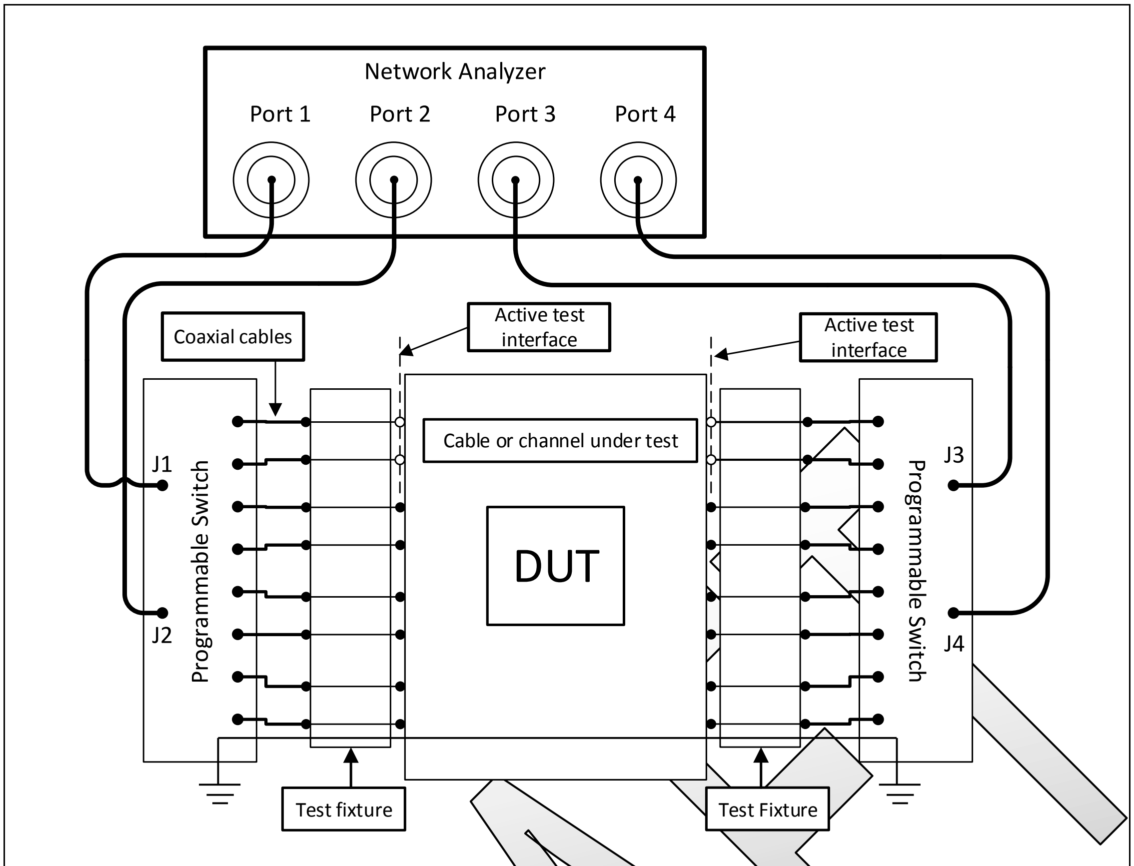


Figure 1 - Test system diagram for four port network analyzer

5 Test configurations

The test configurations in this document show connections between a four-port network analyzer and a 16 port DUT. The 50 Ω ports of the network analyzer are connected directly to each of the active pair(s) of the DUT under test. The far end of active ports which are not connected directly to the network analyzer and the inactive ports which are also not connected to the network analyzer are terminated with resistor terminations.

There are two types of resistor terminations, depending on their location in the measurement stream, not their physical configuration. The first type is the remote, or far-end termination of an active port under test. The second type is the termination of an inactive port that is only weakly coupled to the measurement path via pair-to-pair crosstalk couplings. This distinction can be made based upon the assumption that the DUT is composed of four pairs of conductors that are loosely coupled to each other. The optimal measurement configuration is for each of the ports of the device under test to be terminated with a network analyzer port. This allows for the residual effects of the terminations to be compensated through calibration. For a four port measurement, this allows fully calibrated measurements on one pair of a DUT. The measurements that can be made on a single pair would include insertion loss, near and far end return loss, TCL, TCTL, and delay. Measurements of a DUT with two pairs would include crosstalk between the two pairs of a DUT, near end and far end, in addition to the above parameters. This would require 8 ports to be connected to an 8 port network analyzer for fully calibrated measurements. Similarly, for a four pair DUT, a 16 port network analyzer could be fully calibrated for accurate measurements of all S-parameters.

If 8 port or 16 port network analyzers are not available for testing, the far end terminations of active ports should be constructed to provide a suitable termination that best approximates a fully calibrated network analyzer port. Deviation from this ideal will directly affect measurement accuracy. Similarly, the terminations of inactive pairs will affect the measurement accuracy depending upon the magnitude of the coupling parameters between those pairs and the pairs under test. Since these coupling parameters reduce the influence of these inactive pairs on the active pairs under test by the relative crosstalk couplings (roughly -20 dB), a more relaxed performance requirement for these terminations can be specified than for those directly in the measurement path. This is desirable to enable the use of network analyzers with fewer ports than the device under test, and to enable automatic switching between ports, rather than requiring manual placement of high quality terminations directly at each measurement port.

In the figures, boxes with dashed lines indicate the DUT, the far end resistor terminations, and the inactive pair terminations for 16 port (four pair) DUTs when tested using a four port network analyzer.

Post-processing after measurement is used to mathematically apply differential and common mode termination impedances as defined for a mixed mode environment. The mixed mode termination impedances for each pair of the DUT are generally specified in cabling standards as the reference differential mode and common mode termination impedances of the cabling system. See Clause 7 for description of termination impedances.

5.1 Test configuration

Figure 2, Figure 3, Figure 4, and Figure 5 show measurement configurations for a 16 port DUT with ports paired as 8 differential ports. The four-port network analyzer excites and monitors on four 50 Ω single-ended ports. The measurement results are defined in terms of single-ended 50 Ω S-parameters. The termination resistors shown are for single-ended 50 Ω S-parameter measurements. These test configurations are used to extract the full 16 by 16 S-parameter matrix to fully characterize the 16 port DUT, and can be expressed using appropriate algorithms to calculate the response with the mixed mode terminations specified for the cabling system.

Note: When two single ended ports are combined, forming the equivalent of one 100 Ω differential port in the mixed mode environment, the differential impedance between the signal pins will be 100 Ω and the common mode impedance with respect to ground will be 25 Ω. This common mode impedance differs from the 50 Ω common mode impedance commonly specified in cabling standards. Measurement results must be post-processed to obtain results consistent with standards requirements.

Measurement of all 16 ports of the DUT requires either the use of a switching matrix between the network analyzer and the DUT as shown in figure 1, or successive re-positioning of the DUT input and output port connections until all port combinations are tested. If a switching matrix is used, it must be configurable to allow all 16 ports to be connected either as inputs, outputs, or terminations. It is assumed that calibration at the DUT interface will correct for impairments in the switching and cabling. A unique calibration for each signal path is required.

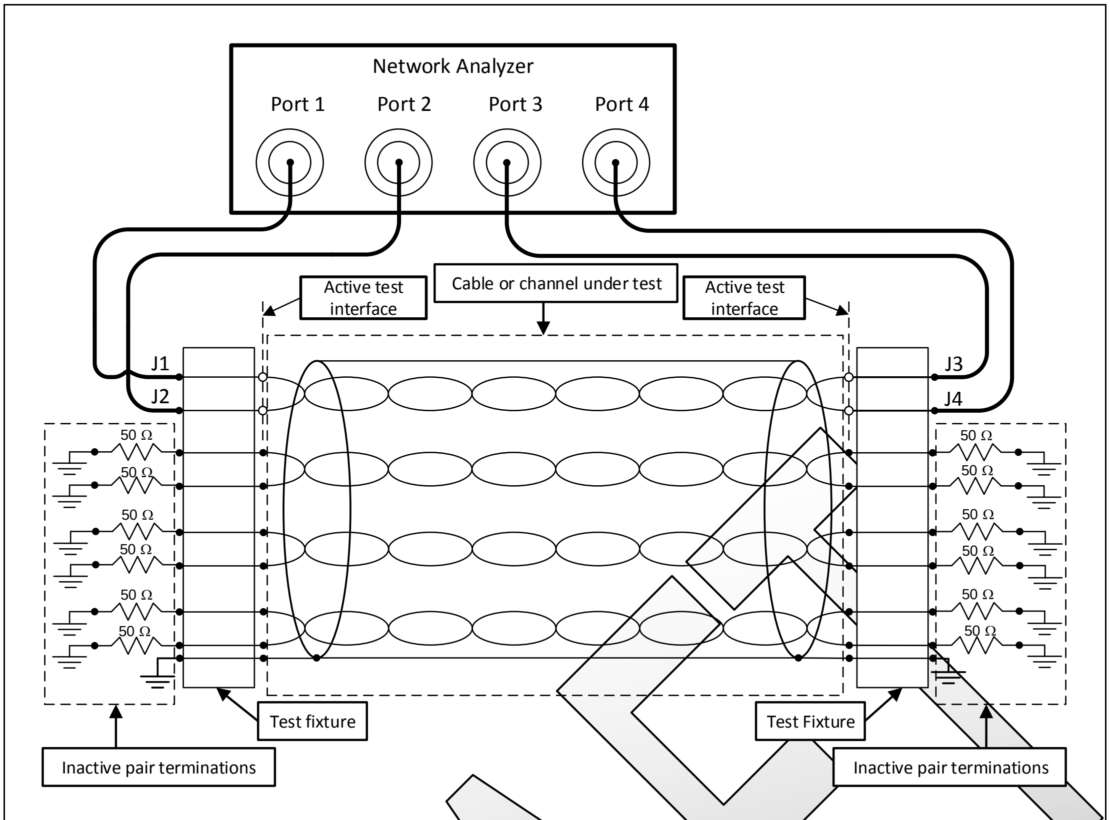


Figure 2 - Laboratory four port test configuration for cable and channel insertion loss, return loss, TCL, TCTL, and propagation delay measurements on a single pair of a four pair DUT.

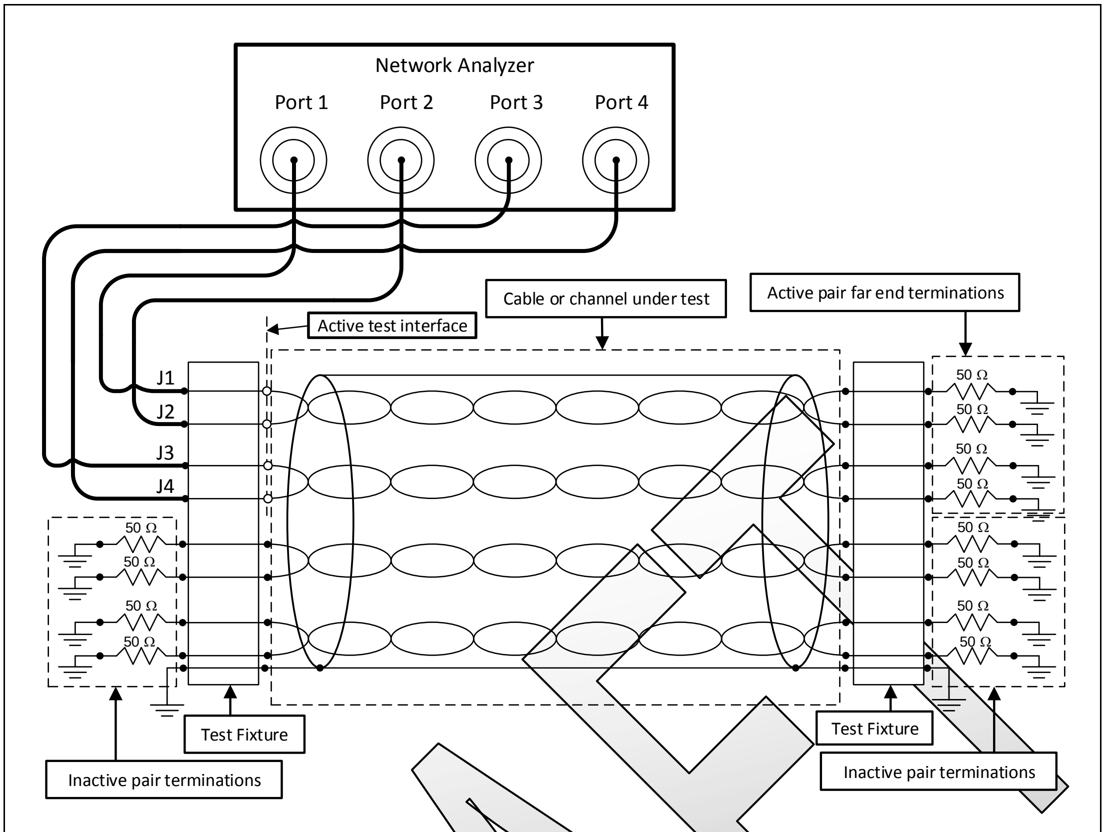


Figure 3 - Laboratory test configuration for NEXT loss between two pairs of a four pair DUT

The configuration of figure 3 may also be used for measurement of return loss and TCL (LCL) of the active pairs under test with the measurement accuracy dependent upon the performance of the far end terminations and the effect those terminations exert on the measurement due to the insertion loss of the DUT.

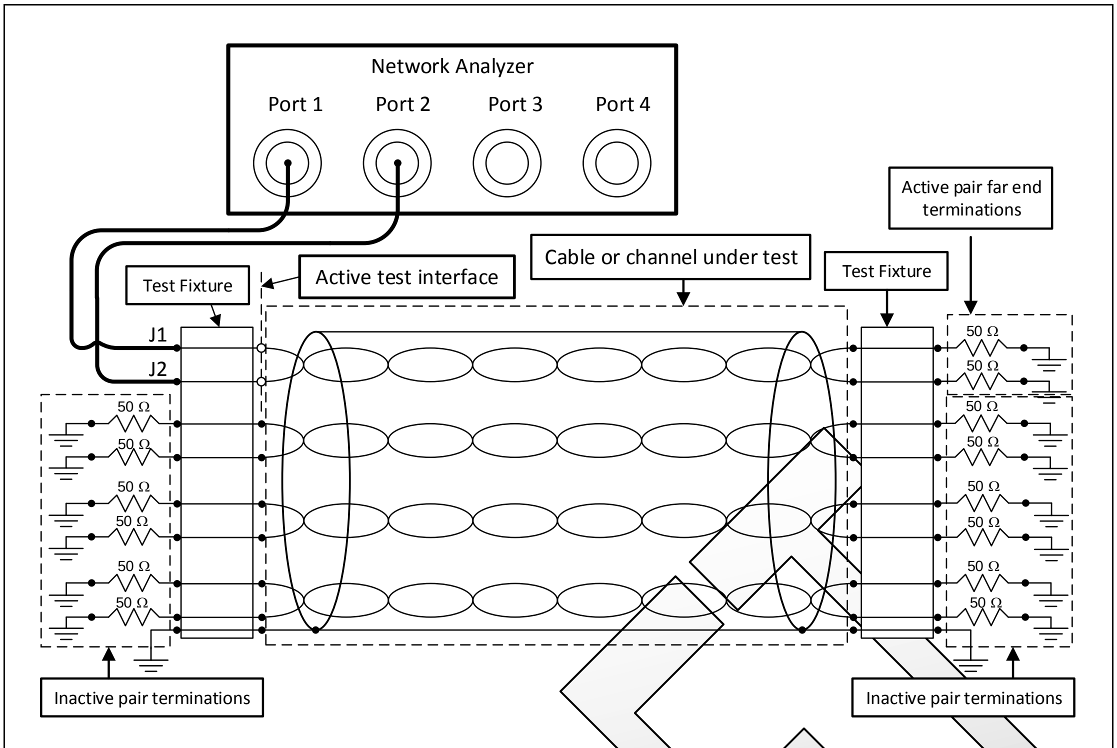


Figure 4 - Laboratory two port test configuration for return loss and TCL (LCL) measurements where the measurement accuracy is dependent upon the performance of the far end terminations.

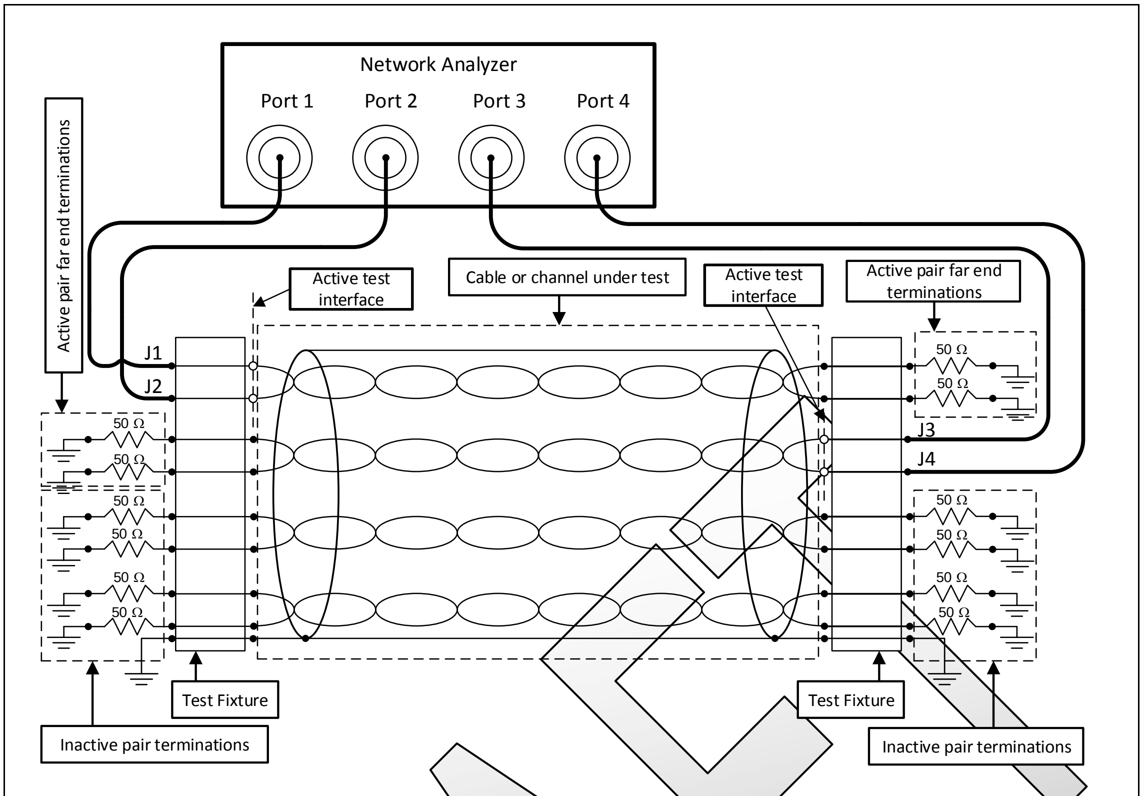


Figure 5 - Laboratory test configuration for FEXT loss between two pairs of a four-pair DUT using a four port network analyzer

The configuration of figure 5 can be used to measure return loss and TCL (LCL) of the active pairs with the measurement accuracy dependent upon the performance of the far end terminations and the effect those terminations exert on the measurement due to the insertion loss of the DUT.
By identifying the three types of terminations possible, active network analyzer terminations, far end passive (resistor) terminations of active ports, and passive terminations of inactive ports, we can structure performance requirements for these passive terminations that yield acceptable measurement accuracy without having to over specify these requirements and enabling the use of network analyzers with fewer active ports than the DUT with automated port switching.

6 Fixtures and setup 6

The test fixtures described in this clause are for making reference measurements of DUT properties. Rather than attempting to define all properties of the test fixtures in terms of their electrical performance, instead the important mechanical dimensions are specified. In addition to maintaining proper impedance of the fixture at the test interface, the fixtures are designed to minimize the length of un-calibrated test leads between the interface and the DUT. Test fixture dimensions are also specified for compatibility, so that comparable reference measurements can be made at different facilities. Other balunless test systems using different layout and dimensions that meet the performance requirements of this standard can be used if equivalent or better accuracy can be demonstrated.

The test system components and test fixtures shall provide isolated signal paths between the ports of the network analyzer and the DUT interface. SMA coaxial connectors and cables are recommended for connection between the test fixture, switching matrices, and the network analyzer. Paired socket connections (figure 10 and Figure 11) in clause 10.1 are preferred for connection to the DUT. Each test fixture consists of eight single-ended connections in an orthogonal arrangement with dimensions as shown in figure 11. The interface dimensions provide a common interface for measurement comparisons. A ground socket is required central to each pair of paired signal sockets. Shielding is required between each pair of sockets to maintain a high level of isolation between pairs. Shielding is also recommended between each signal conductor of a signal pair to the greatest extent possible. Resistor terminations are designated for termination of the far-end of active ports and all inactive ports.

Coaxial attenuators may be used when measuring insertion loss of devices that have very low insertion loss. For this unique measurement configuration, coaxial attenuators are placed in line with the DUT on both ends and calibrated out of the measurement. This has the net effect of absorbing return loss reflections which affect the insertion loss measurement result. The insertion loss of the coaxial attenuators should be 2 dB to 10 dB over the applicable frequency range. See figure 6. The use of coaxial attenuators has the potential to reduce the accuracy of other measurement parameters due to reduced dynamic range and is not recommended.

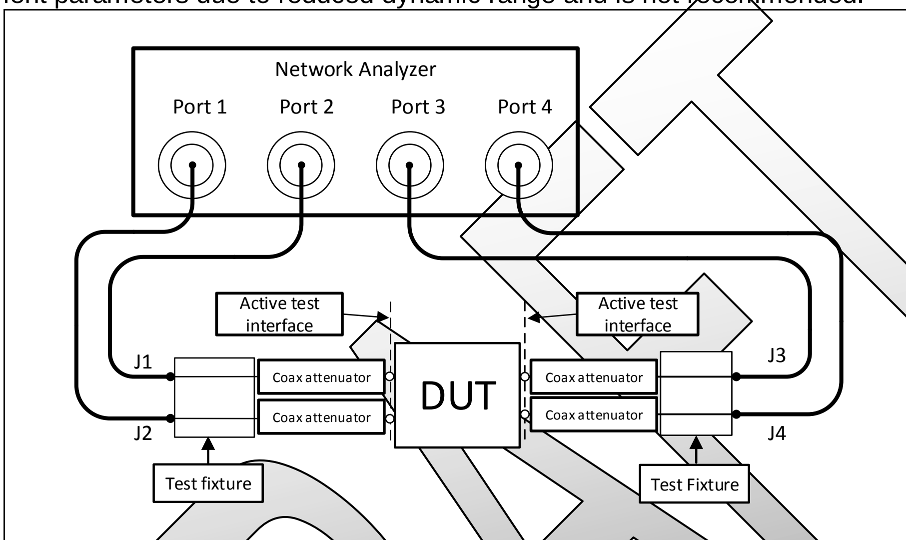


Figure 6 - Partial system diagram for insertion loss measurement of low loss devices.

6.1 Switching and interconnecting coaxial cable requirements

6.1.1 Switching

Switches, if used, shall be of a minimum of a 2x4 configuration. Higher "order" switches, such as 2x8, 2x16 or 4x16 can be beneficial since they enable measurements to be made without disconnecting and moving the DUT. Higher port count switches require a more complex and lengthy calibration procedure. All signal paths shall be configurable as inputs, outputs, or terminations. The inactive ports of the switches shall be terminated with 50 Ω internal resistor terminations.

Table 1 - Switch performance recommendations

Parameter	Frequency (MHz)	Recommended performance
Insertion loss, (dB)	$1 \le f \le 2000$	≤ 2.0 dB
Return loss, (dB)	$1 \le f \le 2000$	≥ 20 dB
Crosstalk (dB)	$1 \le f \le 2000$	≥ 105 dB

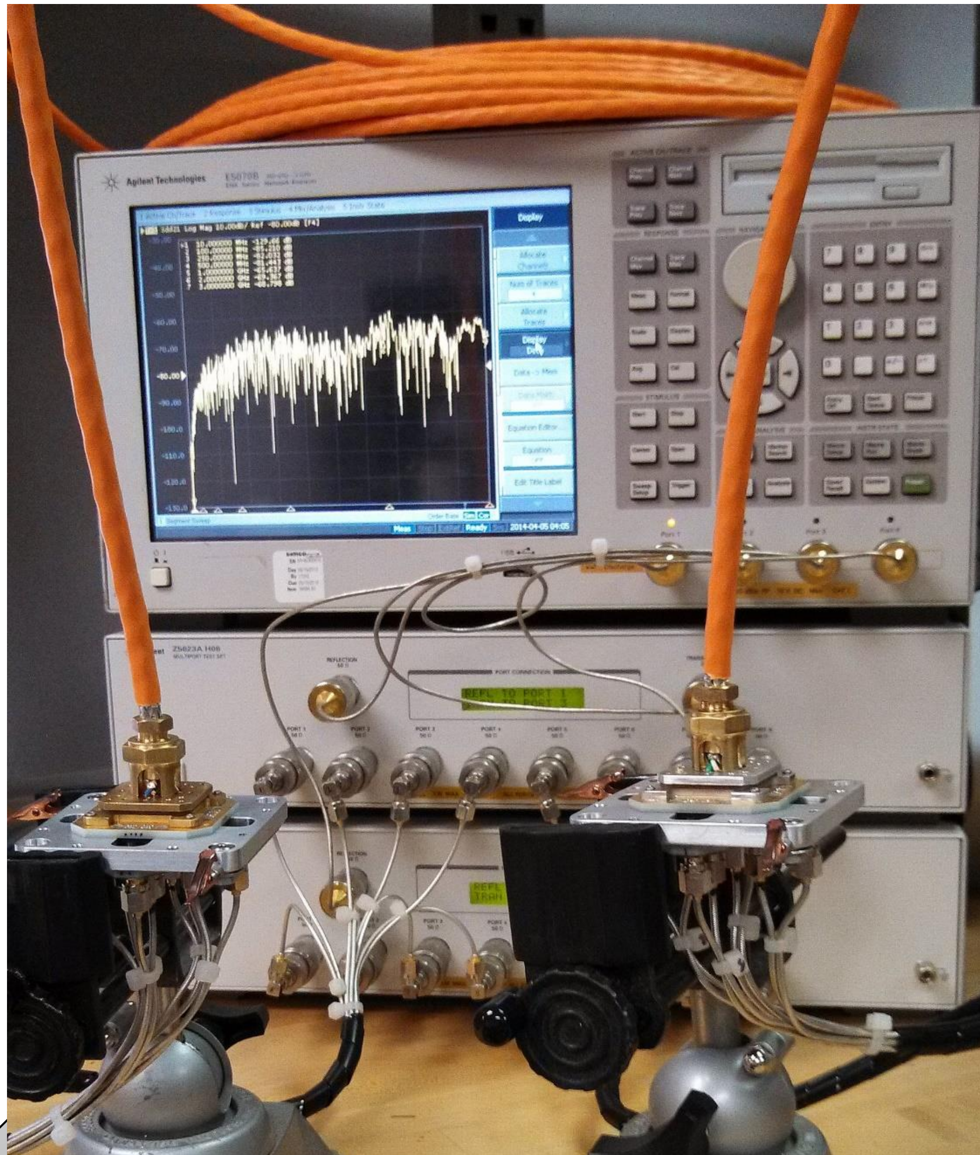


Figure 7 - Example of a four-port test setup with test fixtures and programmable switching

6.1.2 Interconnecting cables

Coaxial cables are used to connect the test fixtures to test equipment. Cables of shielded coaxial construction, 50 Ω impedance, flex life compatible with the intended use and connectors compatible with the network analyzers and test fixtures are recommended. For maximum dynamic range, the total interconnecting cable insertion loss should be less than 1.5 dB per foot at 1 GHz. Cables should have phase stability better than +/- 1 degree at 1 GHz under flexure of +/- 90 degrees from straight at the cable minimum bend radius. Cable return loss should exceed 25 dB at or below 1 GHz.

Interconnecting cables should be of a style that has an exposed shield so that the cable shields can be connected together along their path.

6.2 Test fixture interface performance

Test fixtures shall meet the requirements of table 2 when tested using the appropriate resistor terminations at the pin and socket DUT interface and when the network analyzer has been calibrated using 50 Ω SMA coaxial reference terminations at the SMA input to the test fixture. These requirements apply to each single ended (SE) 50 Ω test port and to each differential mode (DM) 100 Ω test port.

Note: If SE port-to-port NEXT loss and FEXT loss (isolation) is not compliant to table 2, isolation calibration for the SE ports that constitute a pair (or fixture de-embedding, see 0) is required.

Table 2 - Test fixture performance

Parameter	Frequency (MHz)	Requirement	Low frequency plateau[1]
SE port (50 Ω) return loss, (dB)	$1 \le f \le 2000$	$\ge 32 - 20\log(f/100)$ dB,	40 dB
DM port (100 Ω) return loss, (dB)	$1 \le f < 2000$	$\ge 38 - 20\log(f/100)$ dB,	40 dB
CM port (25 Ω) return loss, (dB)	$1 \le f < 2000$	$\ge 28 - 20\log(f/100)$ dB,	35 dB
SE (50 Ω) port-to-port (pair-to-pair) isolation: NEXT loss and FEXT loss	$1 \le f \le 500$ $500 < f \le 2000$	$\ge 94 - 15\log(f/100)$, $\ge 83.5 - 30\log(f/500)$,	105 dB
SE (50 Ω) port-to-port (within a pair) isolation: NEXT loss and FEXT loss	$1 \le f \le 2000$	$\ge 63 - 20\log(f/100)$,	75 dB
DM (100 Ω) port-to-port isolation: NEXT loss and FEXT loss[1]	$1 \le f \le 2000$	$\ge 90 - 20\log(f/100)$,	94 dB
DM (100 Ω) insertion loss	$1 \le f \le 2000$	≤ 1 dB	
TCL, LCL	$1 \le f \le 2000$	$\ge 60 - 20\log(f/100)$,	70 dB
TCTL, LCTL	$1 \le f \le 2000$	$\ge 50 - 20\log(f/100)$,	50 dB
Isolation between test fixtures[1]	$1 \le f \le 2000$	$\ge 94 - 15\log(f/100)$, (TBD) $\ge 83.5 - 20\log(f/500)$, (TBD)	105 (TBD)
[1] Calculations that result in limit values greater than the low frequency plateau shall revert to the requirements specified for the low frequency plateau.			

I[1] The requirement can be met either though separation or shielding applied between fixtures.

6.3 Overall test setup performance before calibration

The overall performance of the test setup including switching and interconnecting cables shall meet the requirements of table 3 when tested using appropriate resistor terminations at the pin and socket DUT interface and when the network analyzer is calibrated using 50 Ω SMA coaxial reference terminations at the output ports network analyzer. These requirements apply to each single ended (SE) 50 Ω test port and to each differential mode (DM) 100 Ω test port.

Table 3 - Overall test setup performance before calibration

Parameter	Frequency (MHz)	Recommendation	Low frequency plateau[1]
SE port (50 Ω) return loss, (dB)	$1 \le f < 2000$	≥ 25 – 20log(f /100) dB, 8 dB min (review requirement) Min 20 dB (TBD)	30 dB
DM port (100 Ω) return loss, (dB)	$1 \le f < 2000$	≥ 28 – 20log(f /100) dB, (review requirement) Min 20 dB (TBD)	30 dB
CM port (25 Ω) return loss, (dB)	$1 \le f \le 2000$	≥ 28 – 20log(f /100) dB, (review requirement) Min 20 dB (TBD)	30 dB
SE (50 Ω) port-to-port (pair-to-pair) isolation: NEXT loss and FEXT loss	$1 \le f \le 2000$	≥ 73 – 20log(f /100), (review requirement)	75 dB
SE (50 Ω) port-to-port (within a pair) isolation: NEXT loss and FEXT loss	$1 \le f \le 2000$	≥ 45 – 20log(f /100),	75 dB
DM (100 Ω) port-to-port isolation: NEXT loss and FEXT loss[1]	$1 \le f \le 2000$	≥ 90 – 20log(f /100),	94 dB
DM (100 Ω) insertion loss	$1 \le f \le 2000$	≤ 12 dB[2]	
TCL, LCL	$1 \le f \le 2000$	≥ 40 – 20log(f /100),	40 dB
TCTL, LCTL	$1 \le f \le 2000$	≥ 40 – 20log(f /100),	40 dB
Isolation between test fixtures[3]	$1 \le f \le 2000$	≥ 94 – 15log(f /100), (TBD) ≥ 83.5 – 20log(f /500), (TBD)	105 (TBD)
1			

[1] Calculations that result in limit values greater than the low frequency plateau shall revert to the requirements specified for the low frequency plateau.

[2]The insertion loss requirements can be relaxed for the insertion loss measurement configuration of Figure 6

[3]The requirement can be met either though separation or shielding applied between fixtures.

7 Port terminations

The system impedance of each active SE port shall be 50 Ω to ground.

Port terminations are of four types.

1. Active terminations within the network analyser. This is a network analyser port connected directly to the DUT (through test fixtures and switching) and has its response fully calibrated.
2. Resistor termination of an active port. This is usually at the far end of the DUT and could be through test fixtures and switching. The performance of the resistor termination is characterized at the DUT interface
3. Resistor termination of inactive ports. These may be at the near end and far end of the DUT, but not directly connected to an active measurement port.
4. Terminations for calibration. Open, short, and load terminations used for calibration.

7.1 Active port network analyzer terminations

The performance of active port network analyzer terminations is specified in TBD

7.2 Active port resistor terminations

The far end terminations of active DUT ports shall comply with the requirements of TBD

7.3 Inactive port resistor terminations

The terminations of inactive ports shall comply with the requirements of TBD. Note that even though the performance of inactive port terminations is not as tightly controlled as the performance of active port resistor terminations, switching may cause these ports to become active port terminations, which are more critical to achieving accurate measurement results.

7.4 Calibration reference loads

The load resistors chosen as a reference for port calibrations shall comply with the requirements of TBD

7.5 Termination resistor selection

The selection of resistors used to construct load terminations is of primary importance to the resulting termination performance. This clause discusses performance metrics for chip resistors at DC and with respect to a broad frequency bandwidth. These chip resistors are typically designated as wideband chip resistors.

Wideband chip resistors of 0603 or smaller size designation shall be selected for minimal impedance variation over the frequency range of interest. Selecting resistors for DC resistance tolerance range must be balanced against performance over a wide frequency range. Two types of chip resistor constructions are typically available. “Wraparound” chip resistor terminals and “flip-chip” resistor terminals. Flip-chip terminals exhibit the most stable wideband response. Flip-chip terminals however are generally more difficult to solder for certain attachment configurations. 0402 chip resistors generally exhibit a more desirable impedance profile relative to frequency than the larger 0603 chip resistors. Where possible it is desirable for the chip resistor to bridge the test fixture or termination terminals directly rather than adding traces or leads to bridge terminals, therefore the optimal size of the chip resistor may be dictated by the geometry of the DUT interface terminals.

Figure 8 shows four examples of chip resistor resistance deviation from nominal impedance with increasing frequency. The 0402 flip chip package size shows the most stable performance for a 50 Ohm value, followed by the 0603 flip chip package size. The 0402 50 Ohm wraparound package begins to deviate from nominal at around 3 GHz, while the 0603 wraparound package begins to deviate from 50 Ohms at around 2 GHz. These graphs reflect examples of typical performance for wideband chip resistors. In this case, all four package constructions would be suitable for measurements to a 2 GHz maximum bandwidth.

7.5.1 Termination resistor impedance tolerance

The DC resistance of the termination resistor shall exhibit a tolerance of less than or equal to +/- 0.1% for active port terminations and less than or equal to +/- 1% for inactive port terminations.

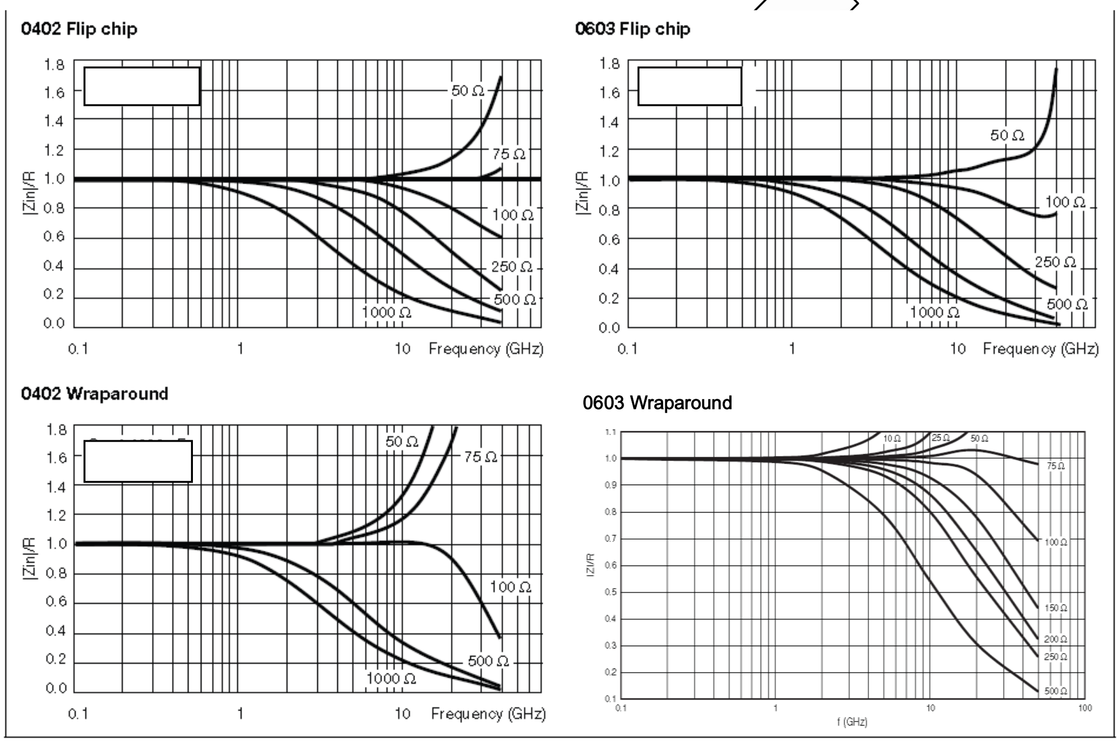


Figure 8 - Example chip resistor performance guide

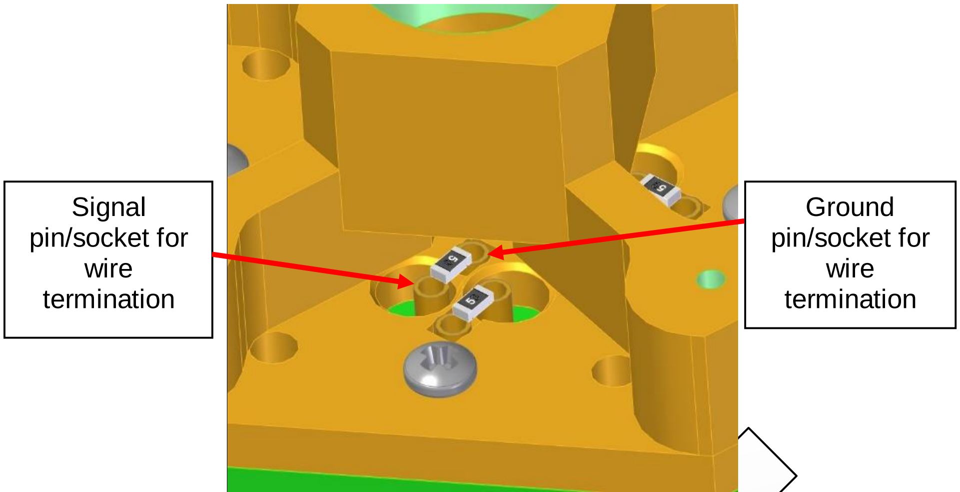


Figure 9 - Example chip resistor terminations using 0603 chip resistors

Figure 9 shows an example of chip resistor terminations applied directly to a socket interface that is intended for cable termination. The chip resistor loads are applied directly across the ends of the interface sockets where the cable conductors would attach. In this case, the terminations are configured to terminate a port for reference calibration.

7.5.2 Load terminations used for calibration

The DC resistance of the termination resistor used for calibration shall exhibit an impedance tolerance of less than or equal to +/- 0.1% when compared to a load reference traceable to international standards using the procedure of clause 7.5.2.1. (TBD)

7.5.2.1 50 Ω reference load measurement procedure

Impedance terminations shall be calibrated against a 50 Ω coaxial load, traceable to an international reference standard. The calibration reference load shall be equal to the nominal impedance of 50 Ω. The reference load(s) for calibration shall be placed in an SMA type connector designed for panel mounting and machined flat on the back side. The chip resistor for verification shall be fixed to the flat side of the connector between the center conductor and ground. One port full calibrations shall utilize the 50 Ω coaxial calibration reference.

7.5.3 Reference loads for calibration

To ensure accurate and traceable measurements, the reference load shall be calibrated against a calibration reference, which shall be a 50 Ω load, traceable to an international reference standard. The reference load terminations for calibration shall comply with the requirements of Table 4.

Table 4 - Calibration termination performance

Parameter	Frequency (MHz)	Requirement
SE (50 Ohm) return loss, (dB)	$1 \le f \le 2000$	40 dB, (TBD)

7.5.4 Calibration kit definitions

When using the calibration references shown in this section, a custom calibration kit definition is required for defining the reference open, short, load and through characteristics compared to ideal open, short, load and through characteristics. Example calibration kit offset coefficients are shown in Table 5.

Table 5 - Example calibration standards definitions

Standard		C0 *10^-15 F	L0 *10^-12 H	C1 *10^-27 F/Hz	L1 *10^-24 H/Hz	C2 *10^-36 F/Hz2	L2 *10^-33 H/Hz2	C3 *10^-45 F/Hz3	L3 *10^-42 H/Hz3	Offset		
Number	Type									Delay, ps	Z 0, Ohms	Loss, G Ohms/s
1	Short									0	50	0
2	Open									0	50	0
3	Load									0	50	0
4	Delay Thru (avg)									192	50	0

7.6 Active port far end termination performance

The performance of impedance matching resistor termination networks are verified by measuring the return loss and isolation of the termination at the calibration plane. The worst case return loss of the load termination and NEXT loss requirements between any two impedance termination networks shall be compliant to the values in table 6.

Table 6 - Active port far end termination performance

Parameter	Frequency (MHz)	Requirement	Low frequency plateau[1]
SE (50 Ohm) return loss, (dB)	$1 \le f \le 100$ $100 < f \le 1000$ $1000 < f \le 2000$	40 (TBD) 40 – 20log(f /100) (TBD) 20 (TBD)	
DM Port-to-port (pair-to-pair) NEXT loss	$1 \le f \le 2000$	90 – 20log(f /100), (TBD)	94 dB (TBD)
SE port-to-port NEXT loss	$1 \le f \le 2000$	3465 – 20log(f /100) dB, (TBD)	90 dB (TBD)

[1] Calculations that result in limit values greater than the low frequency plateau shall revert to the requirements specified for the low frequency plateau.

Note: termination performance bandwidth should be commensurate with the bandwidth of measurement.
Other terminations can be used if equivalent or better accuracy can be demonstrated.
Editor's note: This statement is intended as a placeholder for more detailed explanation of termination requirements based upon DUT insertion loss.

7.7 Inactive port termination performance

The performance of impedance matching resistor termination networks are verified by measuring the return loss and isolation of the termination at the calibration plane. The worst case return loss of the load termination and NEXT loss requirements between any two impedance termination networks shall be compliant to the values in Table 7.

Table 7 - Inactive port far end termination performance

Parameter	Frequency (MHz)	Requirement	Low frequency plateau[1]
SE (50 Ohm) return loss, (dB)	$1 < f \leq 1000$ $1000 < f \leq 2000$	$20 - 20\log(f/100)$ (TBD) 10 (TBD)	
DM Port-to-port NEXT loss	$1 \leq f \leq 2000$	$90 - 20\log(f/100)$, (TBD)	94 (TBD) dB
SE port-to-port NEXT loss	$1 \leq f \leq 2000$	$34 - 20\log(f/100)$ (TBD) dB,	90 (TBD) dB

[1] Calculations that result in limit values greater than the low frequency plateau shall revert to the requirements specified for the low frequency plateau.

Note: termination performance bandwidth should be commensurate with the bandwidth of measurement.

8 Calibration

8.1 General

Calibration may be accomplished through several different methods. Certain aspects of these methods may be unique to each manufacturer's network analyzer. Calibration may be accomplished through use of coaxial reference loads and "de-embedding" test fixture characteristics, or through use of calibration reference loads applied at the pin and socket DUT interface. A full four-port calibration including isolation is required to normalize four 50 Ω ports (two 100 Ω paired ports) of the test fixture. A full four port calibration satisfies the requirements of a full two port calibration of a conventional two-port analyzer using balun transformers and also calibrates common mode and common mode to differential mode signal paths. Calibration procedures are shown using open-short-load and through artifacts for performing a four-port calibration at the pin and socket DUT interface.

Calibration typically consists of normalizing all 50 Ω ports at the DUT interface. A full four-port calibration will fully characterize two sets of paired ports. There are six four-port calibration sets possible to characterize all of the near-end port combinations on one four pair test fixture. If two fixtures are used (for 16 SE ports or 8 differential ports), there are 28 possible four-port calibrations. A switching matrix is ideal for connecting all of the ports to the network analyzer in succession for calibration and measurement. Calibration coefficients obtained during the calibration process for each set of four ports can be stored and later retrieved during the DUT measurement process. It is highly advisable to perform calibrations and measurements under program control.

8.2 Reference loads for calibration

To perform a one, two, or four-port calibration of the test equipment, a short circuit load, an open circuit load and a 50 Ohm reference load are required for each port. Requirements for reference 50 Ohm load terminations for calibration are shown in clause 7.5.3

8.3 Overall test system performance after calibration.

The overall accuracy performance of the test system including switching and interconnecting cables shall meet the requirements of table 3 when tested using appropriate terminations at the DUT interface. These requirements apply to each single ended (SE) 50 Ω test port and to each differential mode (DM) 100 Ω test port after calibration.

Table 8 - Overall test setup performance after calibration (TBD)

Parameter	Requirement	Low frequency plateau[1]
Dynamic Accuracy	+/- 0.2 (TBD) dB	
Dynamic Accuracy FEXT loss	+/- 0.3 (TBD) dB	
Source/load return loss	39 – 15 log(f/100),	43 dB max. 20 dB min
Random noise floor	110 – 15 log(f/100)	110 dB max
Residual NEXT loss	90 – 20 log(f/100)	94 dB Max, 70 dB min
Residual FEXT loss	90 – 20 log(f/100)	94 dB Max, 70 dB min
Residual TCL	54 - 20 log(f/100)	
Residual TCTL	54 - 20 log(f/100)	
Tracking (TBD)	+/- 0.2 (TBD) dB	
Directivity (TBD)	39-15log(f/100), 43 dB max. 20 dB min	
Source match	50 dB	

1 Calculations that result in limit values greater than the low frequency plateau shall revert to the requirements specified for the low frequency plateau.

2The requirement can be met either though separation or shielding applied between fixtures.

9 Procedures for determining test system performance parameters

9.1 General

The following measurements shall be used to determine compliance with the applicable requirements, and shall apply to the entire frequency range specified in these tables. The test equipment parameters shall be verifiable by independent parties.

9.2 Output signal balance (OSB)

Output Signal Balance (OSB) is defined as the ratio of the output common mode voltage to the output differential voltage generated by two SE source ports. The test equipment shall be connected to ground for the measurement as near as possible to the port to be measured. This shall provide a low impedance path to test equipment ground over the specified frequency range. This requirement applies to any two ports that are intended to be configured as a differential pair.

9.3 Residual NEXT loss

Residual NEXT loss is the measured voltage, $V_{m,}$, at the load port due to the source port voltage, V_o, with the test equipment measuring NEXT loss, $Z_l = 50\ \Omega$ +/- 1%. The return loss shall meet the source/load requirements over the specified frequency range. Measured voltage is the voltage determined by the test equipment.

$$\textit{Residual NEXT loss} \geq -20 \log(V_m / V_c) \quad (1)$$

The termination to the test equipment shall be applied at the test interface.

9.4 Dynamic accuracy

Dynamic accuracy is the accuracy of the measured value to an external voltage input as shown in figure 7. The dynamic accuracy is measured on each single ended input port.

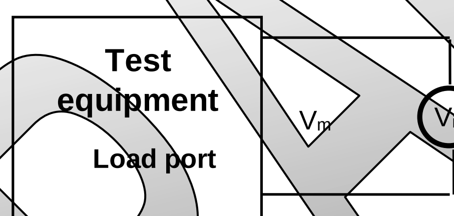


Figure 7 - Block diagram for measuring dynamic accuracy

9.5 Source/load return loss

The source and load return loss shall be measured with a network analyzer calibrated relative to a reference 50 Ω termination resistor with return loss of better than 40 dB over the frequency range of interest.

$$\textit{Return loss} \geq -20 \log(V_{reflected} / V_{incident}) \quad (2)$$

9.6 Random noise floor

The random noise floor is the ratio of the measured voltage V_m when the source port voltage is zero, to the source port voltage V_o under normal measurement conditions; for a possible measurement setup, refer to clause 9.3.

$$\textit{Random Noise Floor} \geq -20\log(V_m / V_o) \qquad (3)$$

A procedure measuring voltage with an external voltmeter at the output of the detector is acceptable if it demonstrates equivalency.

9.7 Residual FEXT loss

The FEXT loss of the test equipment can be determined by measuring the FEXT loss with test fixtures connected back-to-back at the test interface.

Alternately, the residual FEXT loss may be measured by interconnecting the local and remote test interfaces with individually shielded pair cables. In the first measurement configuration the wires are as short as possible and equal length. In the second measurement configuration, the length difference between pairs is selected so that a phase delay of approximately 180° at 100 MHz results. This may also be accomplished by a tip/ring reversal in one of the pairs. The worst case residual FEXT loss of both measurement configurations shall be used, and one half of this amount shall be assigned to the connection at each end.

9.8 Directivity

Directivity is the signal that couples into the measurement channel and adds to the reflected signal that is measured. It is measured by performing a return loss measurement when terminating each pair of the test interface with 100 Ω RF chip resistors that have return loss better than 40 dB relative to a reference calibration resistor from 1 MHz to the upper frequency limit of the category.

$$Directivity_{dB} = -20 \cdot \log\left(10^{\frac{-RL_{load}}{20}}\right) \qquad (4)$$

9.9 Reflection Tracking

Reflection tracking is the response of the transducer used to determine the reflected signal. It is determined from two measurements:

- Measurement of return loss with all ports shorted (the actual reflection coefficient is -1) as a function of frequency,
- Measurement of return loss with all ports open as a function of frequency (the actual reflection coefficient is +1) and
- Measurement of return loss with all ports terminated with 50 Ω reference loads as a function of frequency (the actual reflection coefficient is 0)

The tracking error is given by equation (5).

$$Tr_{dB} = -20 \cdot \log\left(2 \cdot \left| \frac{10^{\frac{-RL_{load}}{20}} - 10^{\frac{-RL_{short}}{20}}}{10^{\frac{-RL_{open}}{20}} - 10^{\frac{-RL_{short}}{20}}} \right| \right) \cdot \left(\left| 10^{\frac{-RL_{open}}{20}} - 10^{\frac{-RL_{load}}{20}} \right| \right) \qquad (5)$$

9.10 Source match

Source match is a measurement of the reflected signal that is not absorbed by the return loss measurement circuitry. It is determined from the measurements of return loss with shorted ports, return loss with open ports and return loss with ports terminated with 50 Ω reference loads. With results of all measurements expressed in positive values of dB, the source match error is given by equation 5.

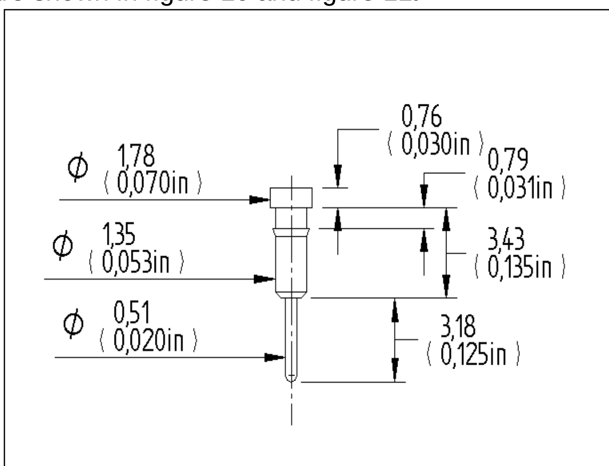
$$Source\_Match_{dB} = -20 \cdot \log\left(\left| \frac{10^{\frac{-RL_{open}}{20}} + 10^{\frac{-RL_{short}}{20}} - 10^{\frac{-RL_{load}}{20}}}{10^{\frac{-RL_{open}}{20}} - 10^{\frac{-RL_{short}}{20}}} \right| \right) \qquad (6)$$

10 Test fixture Interface description

A standardized test interface facilitates comparison between different test systems. A standardized test interface allows calibration artifacts and DUTs to be exchanged between systems without altering the physical construction of the devices which may affect their performance. The test interface is designed to minimize the effects of the connection point on the measurement parameters of the DUT. The test fixture interface described in this document is designed to be optimized for connection to cables with four sets of paired conductors with a minimum conductor size of 26 AWG and a maximum conductor size of 22 AWG.

10.1 Fixture dimensions

The test setup uses pin and socket connectors for interface to the DUT. The dimensions and technical specifications of the connectors and the dimensions of the preferred paired interfaces are shown in figure 10 and figure 11.



Example socket description:

Material=Brass alloy
Contact: 4 finger contact
Contact material: BeCu
Contact mating pin diameter: 0,38 mm – 0,63 mm (0.015 in – 0.025 in)
Shell plating: 10 µin gold over nickel
Contact plating: 30 µin gold over nickel
Mounting hole: 1,45 mm (0.057 in) +/- 0,076 mm (0.003 in), press fit

Figure 10 - Example pin and socket interface dimension

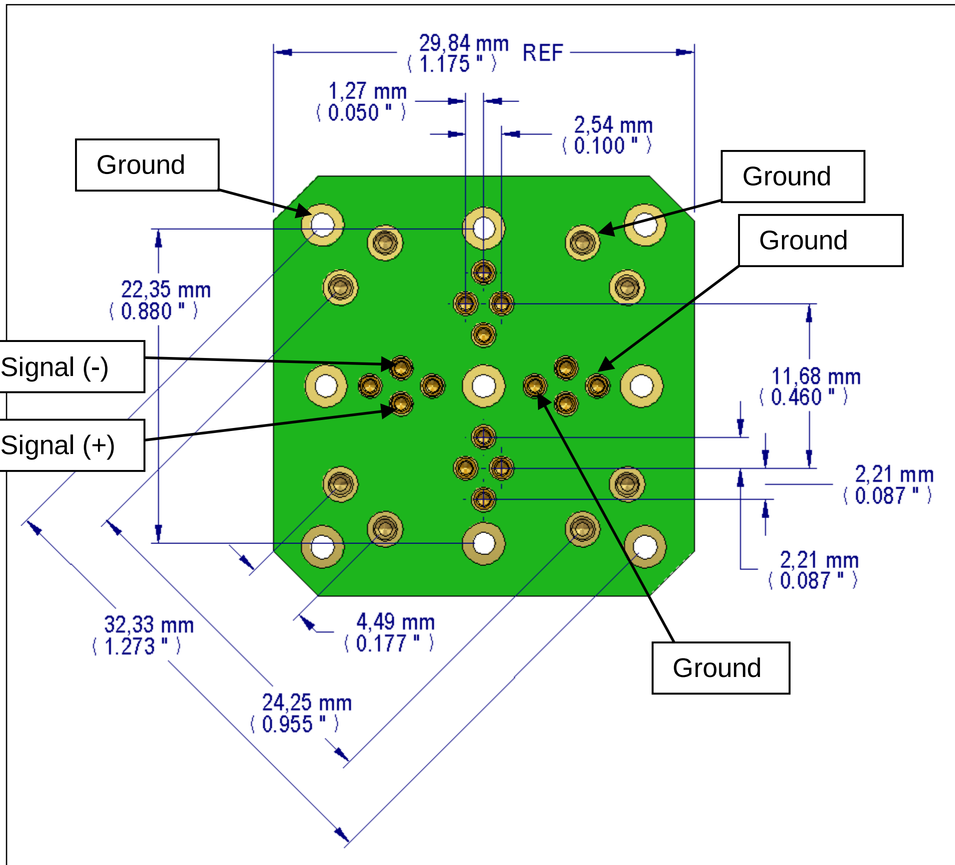


Figure 11 - DUT interface dimensions

The example test fixture shown in figure 12 is configured to provide 8 single-ended ports or four paired ports for interface to a four-pair DUT.

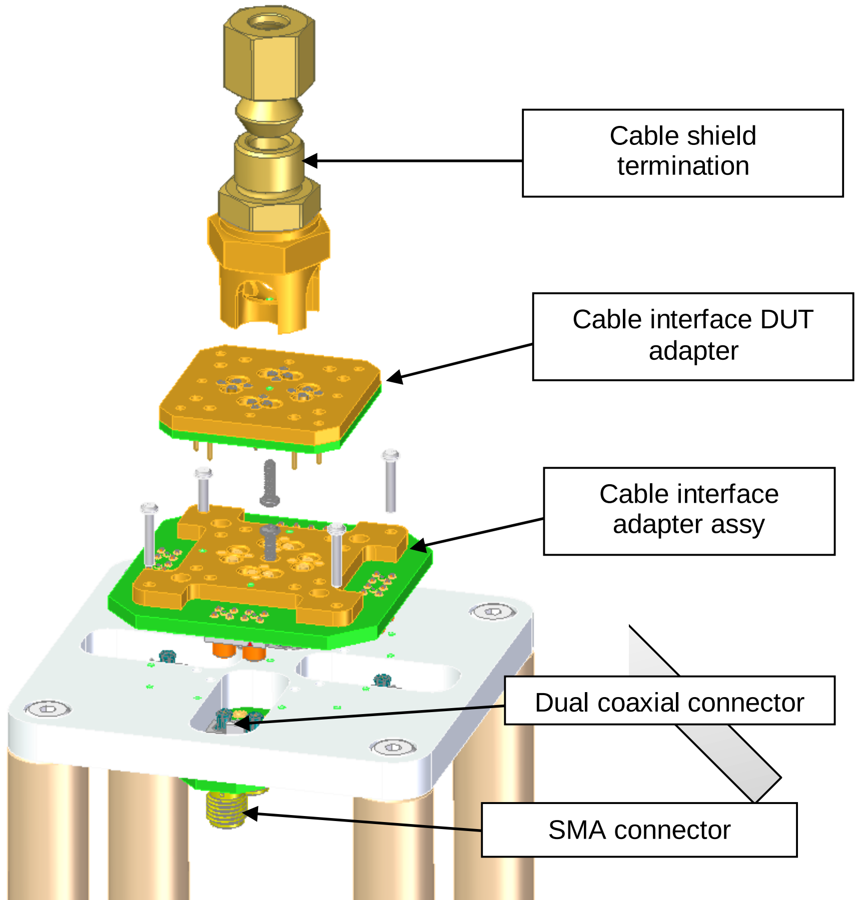


Figure 12 - Example test fixture exploded assembly

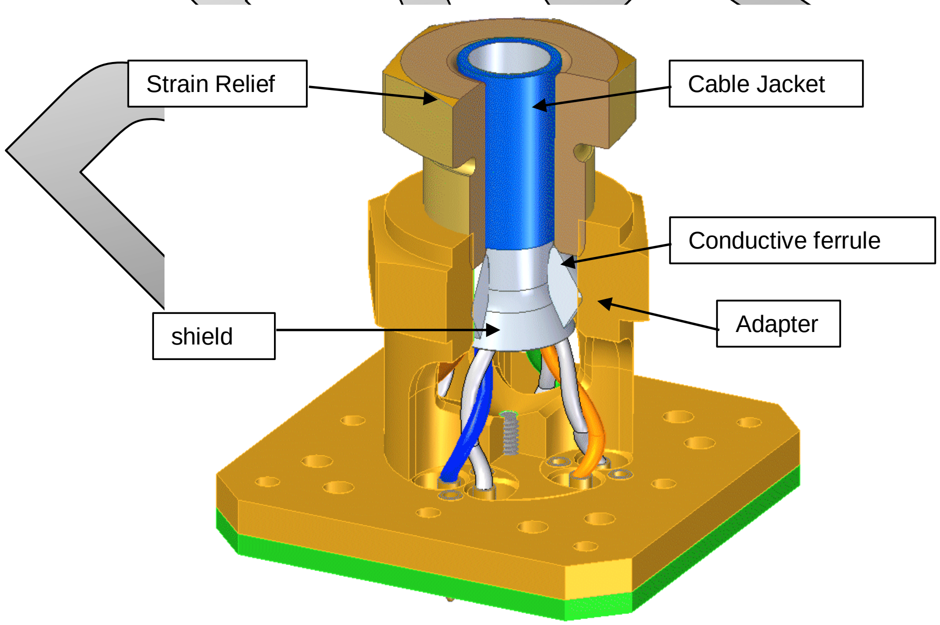


Figure 13 - Example test fixture assembly

Figure 12 and Figure 13 show a test fixture for interface to a shielded cable including shielding between connecting sockets and a device for termination of the cable shield elements. The fixture design ensures the shortest practical length for the unstrapped portion of the cable conductors and strain relief so that the wire connections are not disturbed during testing.

The interface adapter allows for the interchange of adapters to others specific to connector testing as well.

Annex A (informative)- Derivation of mixed mode parameters from four port S parameter measurements

The theory of how to derive mixed mode parameters from 4-port measurements of S-parameters is outlined below.[1]

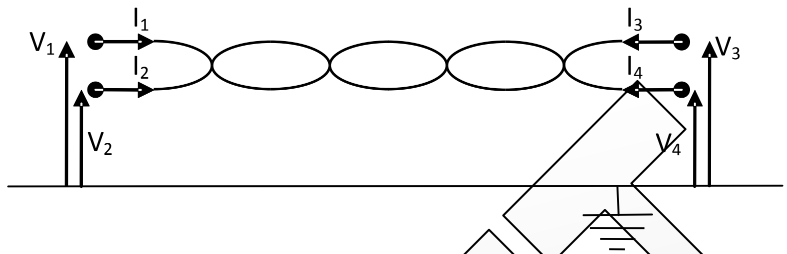


Figure A.1 - Voltage and current on balanced DUT with respect to a ground plane

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \tag{A1}$$

The modal domain impedance matrix is calculated by using the conversion matrices ***P*** and ***Q***

$$Z^m = P_e^{-1} Z Q_e \tag{A2}$$

Where, $P_e^{-1} = \begin{bmatrix} P^{-1} & 0 \\ 0 & P^{-1} \end{bmatrix}$ $Q_e = \begin{bmatrix} Q & 0 \\ 0 & Q \end{bmatrix}$ (A3)

For a single pair, the matrices have the following values:

$$P = \begin{bmatrix} \frac{1}{2} & 1 \\ -\frac{1}{2} & 1 \end{bmatrix}, \qquad \mathrm{Q} = \begin{bmatrix} 1 & \frac{1}{2} \\ -1 & \frac{1}{2} \end{bmatrix} Q = \begin{bmatrix} 1 & \frac{1}{2} \\ -1 & \frac{1}{2} \end{bmatrix} \tag{A4}$$

[1] Modal decomposition [non-balun] measurement technique: Error analysis and application to UTP and STP characterization to 500 MHz. Koichi Yanagawa and John Cross. Proc. 44th Int. Wire and Cable Symp. (IWCS), IWCS 1995, pp. 126-133.

These conversion matrices operate as transformers, in other words, we can replace the BALUN transformers with these conversion matrices.

$$\begin{bmatrix} \mathrm{V}_1 \\ \mathrm{V}_2 \\ \mathrm{V}_3 \\ \mathrm{V}_4 \end{bmatrix} = \mathrm{P}_\mathrm{e} \begin{bmatrix} \mathrm{V}_{\mathrm{D1}} \\ \mathrm{V}_{\mathrm{C1}} \\ \mathrm{V}_{\mathrm{D2}} \\ \mathrm{V}_{\mathrm{C2}} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = P_e \begin{bmatrix} V_{D1} \\ V_{C1} \\ V_{D2} \\ V_{C2} \end{bmatrix}, \qquad \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = Q_e \begin{bmatrix} I_{D1} \\ I_{C1} \\ I_{D2} \\ I_{C2} \end{bmatrix} \tag{A5}$$

Substituting equation 5 into equation 1 yields equation 6.

$$\begin{bmatrix} V_{D1} \\ V_{C1} \\ V_{D2} \\ V_{C2} \end{bmatrix} = \begin{bmatrix} Z_{11}^m & Z_{12}^m & Z_{13}^m & Z_{14}^m \\ Z_{21}^m & Z_{22}^m & Z_{23}^m & Z_{24}^m \\ Z_{31}^m & Z_{32}^m & Z_{33}^m & Z_{34}^m \\ Z_{41}^m & Z_{42}^m & Z_{43}^m & Z_{44}^m \end{bmatrix} \begin{bmatrix} I_{D1} \\ I_{C1} \\ I_{D2} \\ I_{C2} \end{bmatrix} \tag{A6}$$

These matrices are equivalent to a set of ideal mathematical transformers connected at each end of a cable pair.

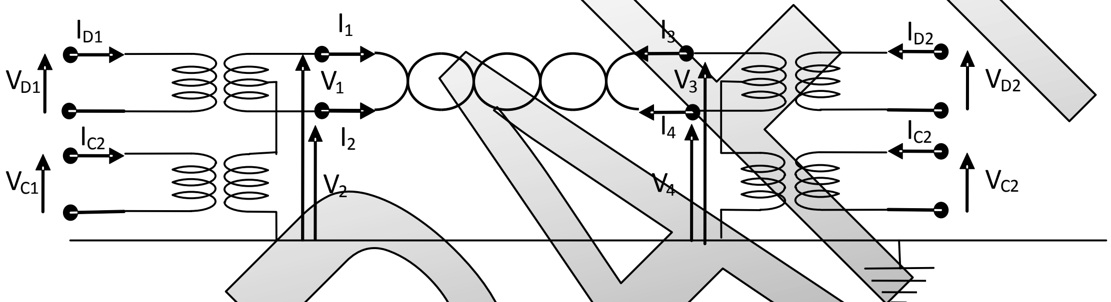


Figure A.2 - Voltage and current conversion by two mathematical transformers

The relationship between the impedance matrix and the S-parameter matrix of a 2n-port circuit can be represented by equation A7.

$$Z = R^{\frac{1}{2}} \cdot \left[E + S\right] \cdot \left[E - S\right]^{-1} \cdot R^{\frac{1}{2}} \tag{A7}$$

Where E is a 2n x 2n unit matrix and $R^{\frac{1}{2}}$ is a diagonal matrix:

$$R^{\frac{1}{2}} = \begin{bmatrix} \sqrt{r_1} & 0 & \cdots & 0 \\ 0 & \sqrt{r_2} & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \cdots & 0 & \sqrt{r_{2n}} \end{bmatrix} \tag{A8}$$

Where $\boldsymbol{r_x}$ is the impedance of the measurement port, typically 50 Ω

$$R^{\frac{1}{2}} = \begin{bmatrix} \sqrt{50} & 0 & \cdots & 0 \\ 0 & \sqrt{50} & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \cdots & 0 & \sqrt{50} \end{bmatrix} \qquad \text{(A9)}$$

Since most of the parameters of interest are S parameters in the modal domain, the modal domain Z-parameters can be converted into S-parameters using the equation 10.

$$S^{m} = R_m^{-\frac{1}{2}} \cdot \left[Z^{m} - R_m\right] \cdot \left[Z^{m} + R_m\right]^{-1} \cdot R_m^{\frac{1}{2}} \qquad \text{(A10)}$$

Where $\boldsymbol{R_m}$ is a matrix of termination resistors in the modal domain, typically 100 Ohms balanced mode and 25 Ohms common mode.

$$R_m^{\frac{1}{2}} = \begin{bmatrix} \sqrt{r_{m1}} & 0 & \cdots & 0 \\ 0 & \sqrt{r_{m2}} & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \cdots & 0 & \sqrt{r_{m2n}} \end{bmatrix} \qquad \text{(A11)}$$

Thus we can convert the S-parameters measured by a conventional unbalanced network analyzer into S-parameters in the modal domain, which contain both balanced and unbalanced mode S-parameters as in equation 12.

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \Rightarrow \begin{bmatrix} S_{DD11} & S_{DC11} & S_{DD12} & S_{DC12} \\ S_{CD11} & S_{CC11} & S_{CD12} & S_{CC12} \\ S_{DD21} & S_{DC21} & S_{DD22} & S_{DC22} \\ S_{CD21} & S_{CC21} & S_{CD22} & S_{CC22} \end{bmatrix} \qquad \text{(A12)}$$

Annex B (informative)- Impedance transformation calculations

It may be necessary to express the measurement results in terms of a different set of reference common mode impedances as opposed to the impedances used during measurement[2]. In this case, a transformation is employed to convert the measured S parameters to their corresponding resultant S parameters in terms of the new impedances.

This impedance transformation theory and method is fully described in ANSI/TIA-1183 2012, Annex B.

Annex C (informative) Cabling standards and termination impedances for differential cabling systems

There are at least three differential cable types in common usage, which have different practical common mode characteristic impedances. They are:

1. Unshielded twisted pair (UTP)
2. Shielded twisted pairs. (Where each pair is shielded)
3. Two coaxial cables operated in differential mode.

The first type is unshielded twisted pair (UTP) cable. By definition, the common mode impedance is undefined, because the existence of a ground conductor is not specified. From a practical standpoint, however, a twisted pair usually is part of a cable with other twisted pairs in close proximity. In this case, the other pairs form a low impedance path to ground. The common mode characteristic impedance of such a configuration is dependent on the proximity of the adjacent conductors to the pair under test, and will vary depending on the cable construction. The common mode characteristic impedance of a multi-pair UTP cable can be found through measurement or through simulation of the particular cable construction. Screened multi-pair cables (F/UTP, SF/UTP) which have only an overall shield, are considered similar to UTP cables in terms of the common mode characteristic impedance, in that the proximity of the shield member to the pair is dependent on the cable design, and therefore the common mode characteristic impedance is best determined by measurement or simulation.

The second type of cable construction is the screened twisted pair (U/FTP, S/FTP). The pair may not be twisted in some constructions. There is a foil, or braid, or both surrounding each pair of conductors. In this case, the common mode characteristic impedance is well controlled and defined by the presence of the shield member. For constructions with 100Ω differential impedance, the common mode characteristic impedance has been found empirically to have a nominal value of 33Ω. For multi-pair cables, there may also be an overall foil and/or braid shield. This does not affect the common mode characteristic impedance of a pair.

A third type of cable construction is of two paired coaxial conductors. A single coax of 50 Ω impedance, when paired with another 50 Ω coax, exhibits 100 Ω differential impedance and 25 Ω common mode impedance. This is easily determined through simple calculation. The common mode characteristic impedance of this cable type is well defined and stable. These constructions are typically used for very high frequency data transmission.

The common mode termination reference impedances have been defined in standards for measurement purposes. As an example, see clause 3.2.2.2.1 of ISO/IEC 61156-1 (2007) where it states:

> The differential mode impedance of multiple pair cables is a well-known design parameter. However, the common mode impedance depends largely upon the design of the cable and is influenced primarily by the insulation thickness, the dielectric constant of the insulation, the proximity and number of neighboring pairs and finally by the presence of shields. Thus the common mode impedance of nominally 100 Ω cables can vary within the range of 25 to 75 Ω for STP and UTP cables, respectively (see Figure C.1). The baluns used for measuring are matching generally the input impedance of the S-parameter test set to the differential mode impedance of the cable under test (CUT). It is, however, impractical to measure first for each cable the common mode impedance to match it then to the corresponding common mode impedance terminations used on the balun. Therefore, the terminations at the

common mode port are made throughout in 50 Ω (50 Ω for 100Ω, 60 Ω for 120 Ω and 75 Ω for 150 Ω nominal impedance cables, respectively), to match the common mode impedance of the balun and the pair under test (cable under test, e.g. CUT). For cables with a nominal impedance of 100Ω, the 50 Ω termination is presented by the input impedance of the network analyzer. Due to inevitable impedance mismatches, a variation of the unbalance attenuation due to the reflected signal is expected. Thus a return loss of 10 dB yields an uncertainty of about ± 1 dB

The text points out the limitations inherent in some standards in the specification of the reference common mode termination impedances for measurements. For the purposes of this standard it is important to recognize that the common mode termination impedances have an effect on the measurement results of differential mode, cross-modal, and common mode measurements.

The reference termination common mode impedance for measurement of balanced twisted pair cabling has also been defined in clause B.6.2 of ANSI/TIA-568-C.2 as 50 ohms

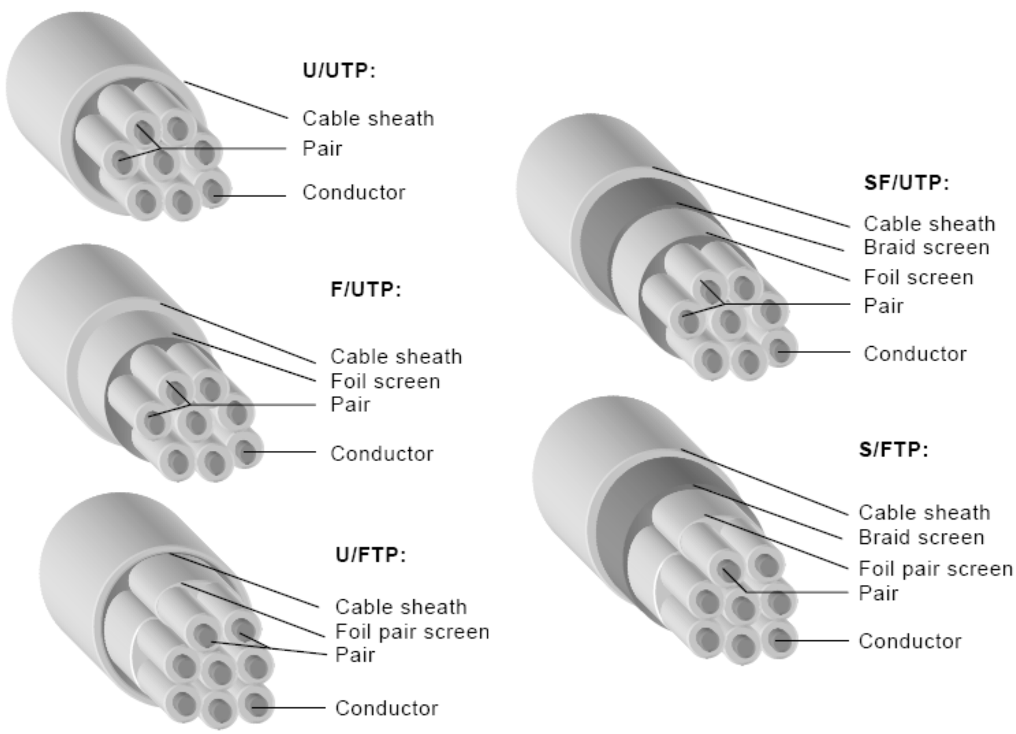


Figure C.1 - Example cable types

Annex D (informative) Port identification and nomenclature

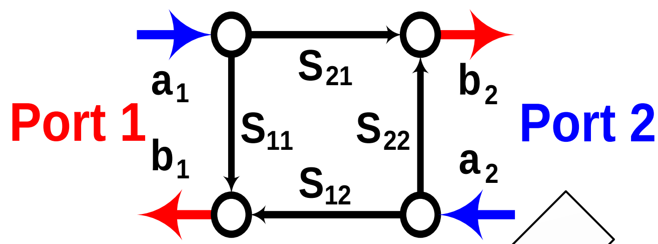


Figure D.1 - Example S-parameter notation for two ports

Figure D.1 represents a signal flow diagram for a two port network. The parameter notation represents the signal power flow into and out of each port.

Port nomenclature is referenced to the standard notation for 100 Ω differential ports or 50 Ω single-ended ports with respect to the DUT, as in Figure D.2. Only two ports of the DUT are defined, even though the DUT may have multiple ports.

Two differential ports can fully characterize the response of only a single pair of conductors. Typically the cabling systems utilize at least two or more pairs for transmission. A four pair system can be fully characterized by the measurement of all responses at 8 ports, see Figure D.3.

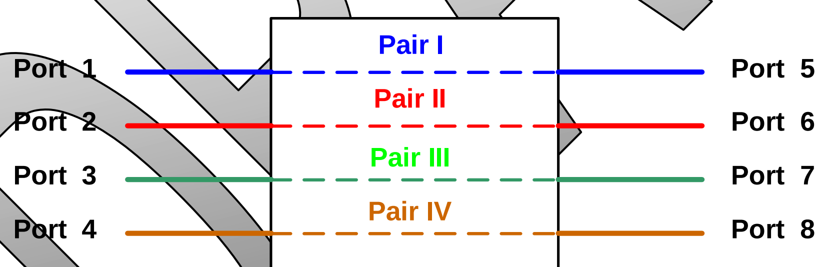


Figure D.2 - Four pair DUT port numbering

Table D.1 - Horizontal 100 Ω twisted pair cable color codes

Pair Identification	Color Code	Abbreviation	conductor numbers Input	Output
Pair 1	White-Blue (NOTE 1) Blue (NOTE 2)	(W-BL) (BL)	1 2	9 10
Pair 2	White-Orange (NOTE 1) Orange (NOTE 2)	(W-O) (O)	3 4	11 12
Pair 3	White-Green (NOTE 1) Green (NOTE 2)	(W-G) (G)	5 6	13 14
Pair 4	White-Brown (NOTE 1) Brown (NOTE 2)	(W-BR) (BR)	7 8	15 16

NOTES:

1 The wire insulation is white, and a colored marking is added for identification. For cables with tightly twisted-pairs, the mate conductor may serve as the marking for the white conductor.

2 A white marking is optional.

3 This table does not represent pin-pair mappings in a connector (eg T568A or T568B as defined in figures D.4, D.5 and table D.3).

Depending on which ports are measured, the S parameter responses have further designations as shown in Table D.2 for a four port network. Redundant port stimulus and response designations are not shown. The 8 port numbering scheme follows the convention where ports 1 and 2 describe a single pair. The notation is then expanded to include all 8 ports as shown in Table D.2. This port numbering scheme can be extended to any number of pairs, or reduced to only one pair while maintaining the port numbers.

Mapping 16 wire devices to 16 port mixed-mode ports is easily visualized through the use of balun transformers in the circuit diagram. The differential mode port 1 is Port1d. The common mode port 1 is Port1c. These mappings are shown in schematic form in Figure D.3.

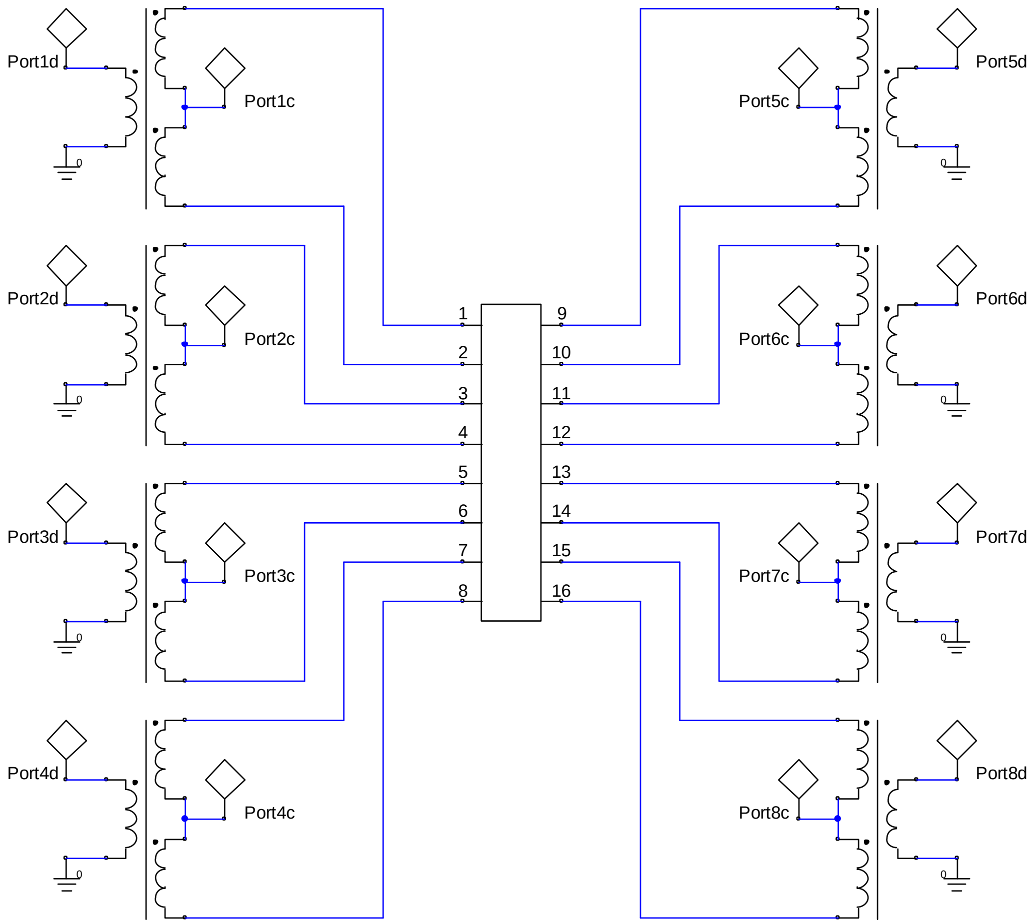


Figure D.3 - Mapping 16 port network to mixed mode network

Table D.2 - Stimulus and response designations for ports 1 and 2

		Differential-mode stimulus		**Common-mode stimulus**	
		Port 1	**Port 2**	**Port 1**	**Port 2**
Differential-mode response	**Port 1**	S_{DD11}	S_{DD12}	S_{DC11}	S_{DC12}
	Port 2	S_{DD21}	S_{DD22}	S_{DC21}	S_{DC22}
Common-mode response	**Port 1**	S_{CD11}	S_{CD12}	S_{CC11}	S_{CC12}
	Port 2	S_{CD21}	S_{CD22}	S_{CC21}	S_{CC22}

Where:

S_{DD} Is defined as the ratio of the differential mode response to the differential mode stimulus.
S_{DC} Is defined as the ratio of the differential mode response to the common mode stimulus.
S_{CD} Is defined as the ratio of the common mode response to the differential mode stimulus.
S_{CC} Is defined as the ratio of the common mode response to the common mode stimulus.

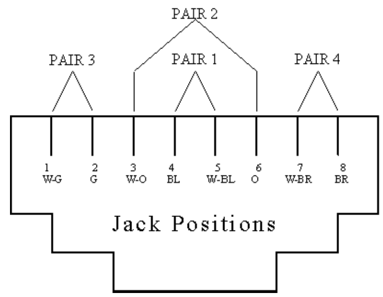


Figure D.4 - T568A pin/pair mapping

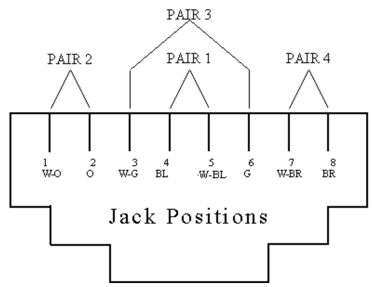


Figure D.5 - T568B pin/pair mapping

Modular jack pin designations are included for reference.

Table D.3 - Modular connector conductor mappings (ref)

		Modular jack (ref)		16P	
Conductor Identification	Color Code	T568A	T568B	In	Out
Pair 1	White-Blue	5	5	1	9
	Blue	4	4	2	10
Pair 2	White-Orange	3	1	3	11
	Orange	6	2	4	12
Pair 3	White-Green	1	3	5	13
	Green	2	6	6	14
Pair 4	White-Brown	7	7	7	15
	Brown	8	8	8	16

Table D.4 Port nomenclature

	Port 1		Port 2		Port 3		Port 4		Port 5		Port 6		Port 7		Port 8	
Port 1	Sdd11	RLdd11	Sdd12	NEXTdd12	Sdd13	NEXTdd13	Sdd14	NEXTdd14	Sdd15	ILdd15	Sdd16	FEXTdd16	Sdd17	FEXTdd17	Sdd18	FEXTdd18
Port 2	Sdd21	NEXTdd21	Sdd22	RLdd22	Sdd23	NEXTdd23	Sdd24	NEXTdd24	Sdd25	FEXTdd25	Sdd26	ILdd26	Sdd27	FEXTdd27	Sdd28	FEXTdd28
Port 3	Sdd31	NEXTdd31	Sdd32	NEXTdd32	Sdd33	RLdd33	Sdd34	NEXTdd34	Sdd35	FEXTdd35	Sdd36	FEXTdd36	Sdd37	ILdd37	Sdd38	FEXTdd38
Port 4	Sdd41	NEXTdd41	Sdd42	NEXTdd42	Sdd43	NEXTdd43	Sdd44	RLdd44	Sdd45	FEXTdd45	Sdd46	FEXTdd46	Sdd47	FEXTdd47	Sdd48	ILdd48
Port 5	Sdd51	ILdd51	Sdd52	FEXTdd52	Sdd53	FEXTdd53	Sdd54	FEXTdd54	Sdd55	RLdd55	Sdd56	NEXTdd56	Sdd57	NEXTdd57	Sdd58	NEXTdd58
Port 6	Sdd61	FEXTdd61	Sdd62	ILdd62	Sdd63	FEXTdd63	Sdd64	FEXTdd64	Sdd65	NEXTdd65	Sdd66	RLdd66	Sdd67	NEXTdd67	Sdd68	NEXTdd68
Port 7	Sdd71	FEXTdd71	Sdd72	FEXTdd72	Sdd73	ILdd73	Sdd74	FEXTdd74	Sdd75	NEXTdd75	Sdd76	NEXTdd76	Sdd77	RLdd77	Sdd78	NEXTdd78
Port 8	Sdd81	FEXTdd81	Sdd82	FEXTdd82	Sdd83	FEXTdd83	Sdd84	ILdd84	Sdd85	NEXTdd85	Sdd86	NEXTdd86	Sdd87	NEXTdd87	Sdd88	RLdd88
Port 1	Sdc11	LCLdc11	Sdc12	NEXTdc12	Sdc13	NEXTdc13	Sdc14	NEXTdc14	Sdc15	LCTLdc15	Sdc16	FEXTdc16	Sdc17	FEXTdc17	Sdc18	FEXTdc18
Port 2	Sdc21	NEXTdc21	Sdc22	LCLdc22	Sdc23	NEXTdc23	Sdc24	NEXTdc24	Sdc25	FEXTdc25	Sdc26	LCTLdc26	Sdc27	FEXTdc27	Sdc28	FEXTdc28
Port 3	Sdc31	NEXTdc31	Sdc32	NEXTdc32	Sdc33	LCLdc33	Sdc34	NEXTdc34	Sdc35	FEXTdc35	Sdc36	FEXTdc36	Sdc37	LCTLdc37	Sdc38	FEXTdc38
Port 4	Sdc41	NEXTdc41	Sdc42	NEXTdc42	Sdc43	NEXTdc43	Sdc44	LCLdc44	Sdc45	FEXTdc45	Sdc46	FEXTdc46	Sdc47	FEXTdc47	Sdc48	LCTLdc48
Port 5	Sdc51	LCTLdc51	Sdc52	FEXTdc52	Sdc53	FEXTdc53	Sdc54	FEXTdc54	Sdc55	LCLdc55	Sdc56	NEXTdc56	Sdc57	NEXTdc57	Sdc58	NEXTdc58
Port 6	Sdc61	FEXTdc61	Sdc62	LCTLdc62	Sdc63	FEXTdc63	Sdc64	FEXTdc64	Sdc65	NEXTdc65	Sdc66	LCLdc66	Sdc67	NEXTdc67	Sdc68	NEXTdc68
Port 7	Sdc71	FEXTdc71	Sdc72	FEXTdc72	Sdc73	LCTLdc73	Sdc74	FEXTdc74	Sdc75	NEXTdc75	Sdc76	NEXTdc76	Sdc77	LCLdc77	Sdc78	NEXTdc78
Port 8	Sdc81	FEXTdc81	Sdc82	FEXTdc82	Sdc83	FEXTdc83	Sdc84	LCTLdc84	Sdc85	NEXTdc85	Sdc86	NEXTdc86	Sdc87	NEXTdc87	Sdc88	LCLdc88
Port 1	Scd11	TCLcd11	Scd12	NEXTcd12	Scd13	NEXTcd13	Scd14	NEXTcd14	Scd15	TCTLcd15	Scd16	FEXTcd16	Scd17	FEXTcd17	Scd18	FEXTcd18
Port 2	Scd21	NEXTcd21	Scd22	TCLcd22	Scd23	NEXTcd23	Scd24	NEXTcd24	Scd25	FEXTcd25	Scd26	TCTLcd26	Scd27	FEXTcd27	Scd28	FEXTcd28
Port 3	Scd31	NEXTcd31	Scd32	NEXTcd32	Scd33	TCLcd33	Scd34	NEXTcd34	Scd35	FEXTcd35	Scd36	FEXTcd36	Scd37	TCTLcd37	Scd38	FEXTcd38
Port 4	Scd41	NEXTcd41	Scd42	NEXTcd42	Scd43	NEXTcd43	Scd44	TCLcd44	Scd45	FEXTcd45	Scd46	FEXTcd46	Scd47	FEXTcd47	Scd48	TCTLcd48
Port 5	Scd51	TCTLcd51	Scd52	FEXTcd52	Scd53	FEXTcd53	Scd54	FEXTcd54	Scd55	TCLcd55	Scd56	NEXTcd56	Scd57	NEXTcd57	Scd58	NEXTcd58
Port 6	Scd61	FEXTcd61	Scd62	TCTLcd62	Scd63	FEXTcd63	Scd64	FEXTcd64	Scd65	NEXTcd65	Scd66	TCLcd66	Scd67	NEXTcd67	Scd68	NEXTcd68
Port 7	Scd71	FEXTcd71	Scd72	FEXTcd72	Scd73	TCTLcd73	Scd74	FEXTcd74	Scd75	NEXTcd75	Scd76	NEXTcd76	Scd77	TCLcd77	Scd78	NEXTcd78
Port 8	Scd81	FEXTcd81	Scd82	FEXTcd82	Scd83	FEXTcd83	Scd84	TCTLcd84	Scd85	NEXTcd85	Scd86	NEXTcd86	Scd87	NEXTcd87	Scd88	TCLcd88
Port 1	Scc11	RLcc11	Scc12	NEXTcc12	Scc13	NEXTcc13	Scc14	NEXTcc14	Scc15	ILcc15	Scc16	FEXTcc16	Scc17	FEXTcc17	Scc18	FEXTcc18
Port 2	Scc21	NEXTcc21	Scc22	RLcc22	Scc23	NEXTcc23	Scc24	NEXTcc24	Scc25	FEXTcc25	Scc26	ILcc26	Scc27	FEXTcc27	Scc28	FEXTcc28
Port 3	Scc31	NEXTcc31	Scc32	NEXTcc32	Scc33	RLcc33	Scc34	NEXTcc34	Scc35	FEXTcc35	Scc36	FEXTcc36	Scc37	ILcc37	Scc38	FEXTcc38
Port 4	Scc41	NEXTcc41	Scc42	NEXTcc42	Scc43	NEXTcc43	Scc44	RLcc44	Scc45	FEXTcc45	Scc46	FEXTcc46	Scc47	FEXTcc47	Scc48	ILcc48
Port 5	Scc51	ILcc51	Scc52	FEXTcc52	Scc53	FEXTcc53	Scc54	FEXTcc54	Scc55	RLcc55	Scc56	NEXTcc56	Scc57	NEXTcc57	Scc58	NEXTcc58
Port 6	Scc61	FEXTcc61	Scc62	ILcc62	Scc63	FEXTcc63	Scc64	FEXTcc64	Scc65	NEXTcc65	Scc66	RLcc66	Scc67	NEXTcc67	Scc68	NEXTcc68
Port 7	Scc71	FEXTcc71	Scc72	FEXTcc72	Scc73	ILcc73	Scc74	FEXTcc74	Scc75	NEXTcc75	Scc76	NEXTcc76	Scc77	RLcc77	Scc78	NEXTcc78
Port 8	Scc81	FEXTcc81	Scc82	FEXTcc82	Scc83	FEXTcc83	Scc84	ILcc84	Scc85	NEXTcc85	Scc86	NEXTcc86	Scc87	NEXTcc87	Scc88	RLcc88

Annex E (informative) De-embedding balunless 16 port test fixtures.

This annex presents an alternative calibration method which eliminates the utilization of specialized calibration artifacts. This alternative method requires four major operations: calibrating at ends of test cables, pre-characterizing balunless test fixtures, determining de-embedding matrices from the pre-characterization, and cascading de-embedding matrices to an unprocessed measurement. These operations are further described in this annex.

The de-embedding technique can be applied by considering the measurement fixture at each port as an independent 4-port S-parameter matrix, however it is recommended to consider the interactions between measurement ports and treat the fixtures at each end of the DUT as a 16-port fixture.

E.1 Four port fixture method. General calibration approach

This method requires a characterization of balunless test fixtures before making an unprocessed measurement. The method assumes that the inter-pair couplings in test fixtures are sufficiently smaller than the inter-pair couplings found in the DUT. When this assumption is made, one can characterize a single differential path in test fixtures as a 4-port S-parameter matrix. The 4-port S-parameters of all differential paths in both forward and reverse test fixtures are directly measured. These matrices are labeled as *FWD1*, *FWD2*, *FWD3*, *FWD4*, *REV1*, *REV2*, *REV3*, and *REV4* in Figure E.3.

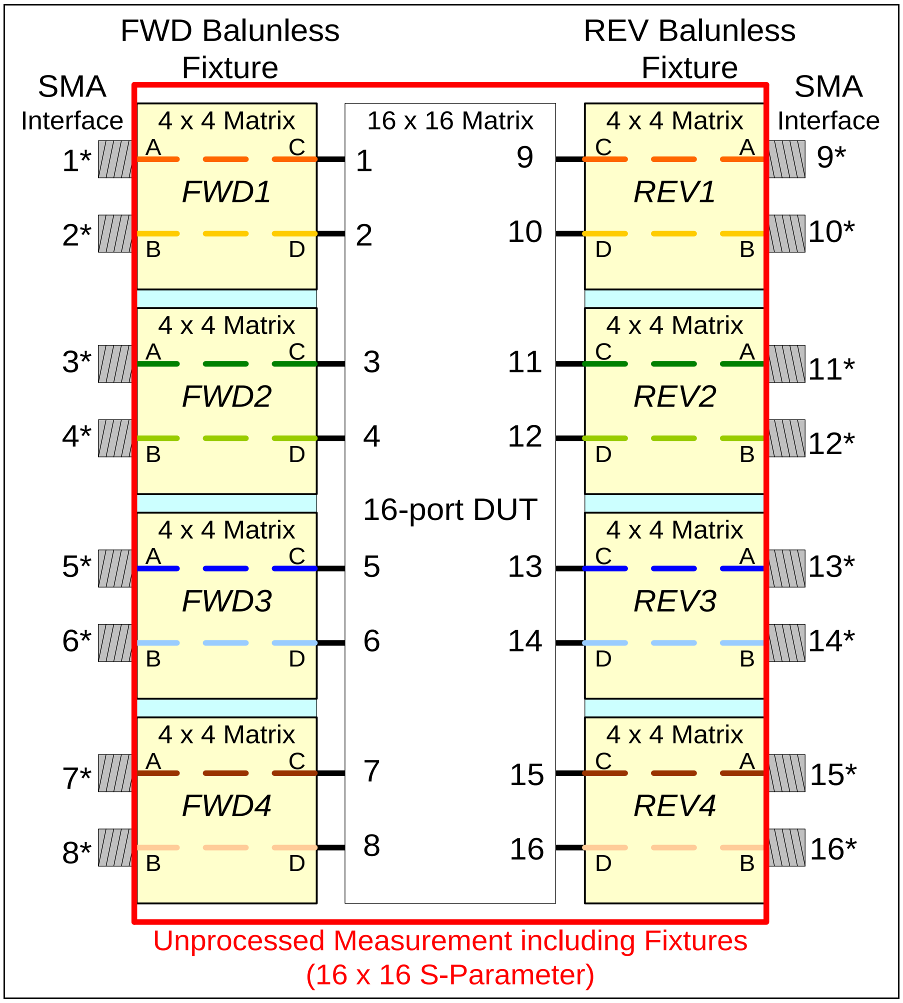


Figure E.1 - Unprocessed measurement includes test fixtures and DUT

It should be noted that in Figure E.1 the reverse fixtures are flipped to face the opposite direction compared to the forward fixtures. This occurs when physically identical fixtures to be used at either end of the DUT.

Once the forward matrices, *FWD1* through *FWD4* (*FWDx*), and reverse matrices, *REV1* through *REV4* (*REVx*), are pre-characterized by direct measurement, the matrices are then converted to de-embedding matrices and are used to negate the effect of the test fixtures.

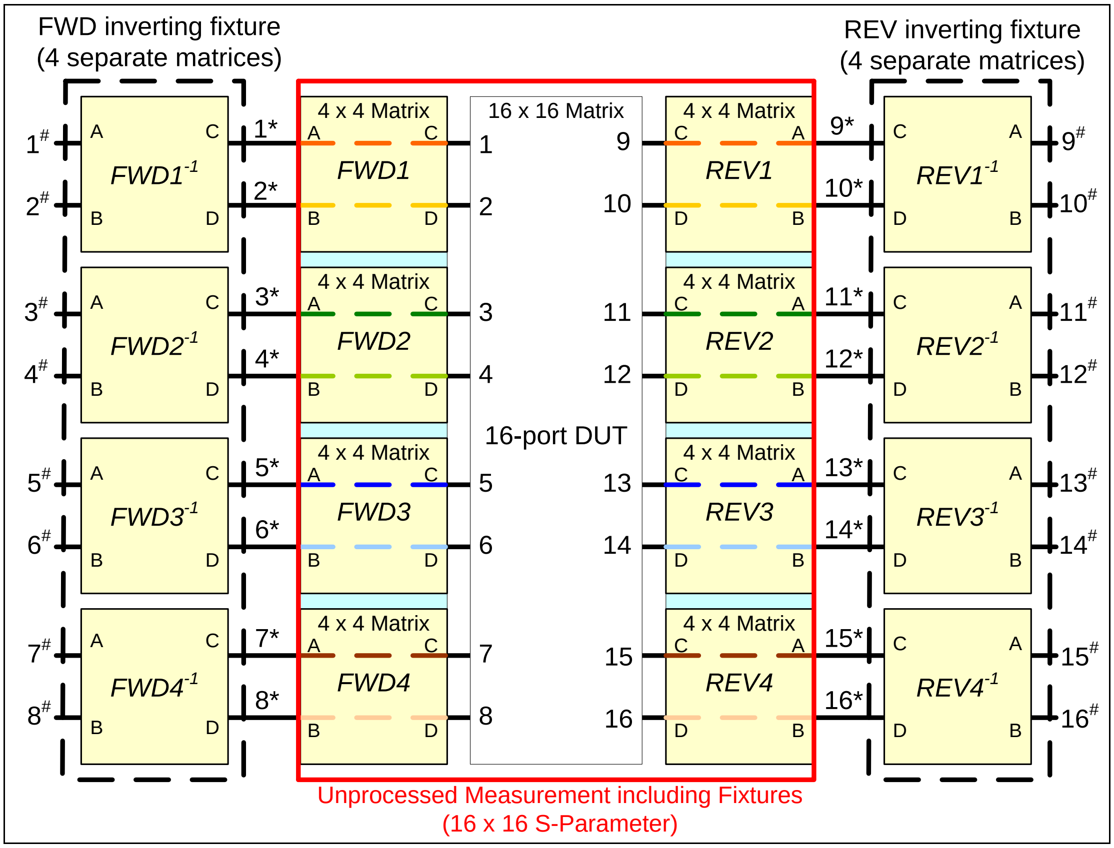


Figure E.2 - De-embedding matrices cascaded to unprocessed 16-port matrix

E.1.1 Four port fixture method. Pre-characterization of probing devices

The eight separate 4-port S-parameters are measured for each of the two test fixtures: four in the forward fixture and four in the reverse fixture. The measurement requires calibrated probing devices to interface with ports C and D, which are pin-socket ports, of *FWDx* and REVx.

The probing device is directly characterized to provide a 2-port matrix for the probing devices according to Clause E.3.

Additional measurements for the probing device are included for crosstalk according to Clause E.3.

Measurements taken using the probing device will then follow a 4-port de-embedding process to remove the probing fixture from the DUT,

The probing devices must be well-shielded to ensure high isolation during the measurement because the one-port calibration method will not suffice if the probing devices have poor isolation. An example of a pair of probing devices is shown in Figure E.3, or alternatively a second fixture can be used as a probe.

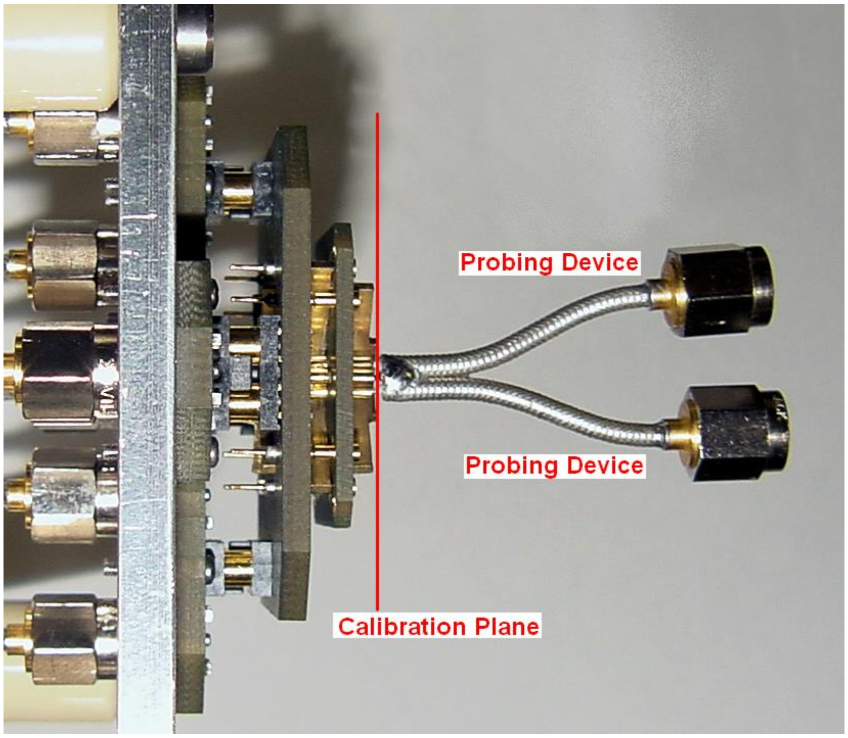


Figure E.3 - An example of probing devices (rigid SMA cable is modified)

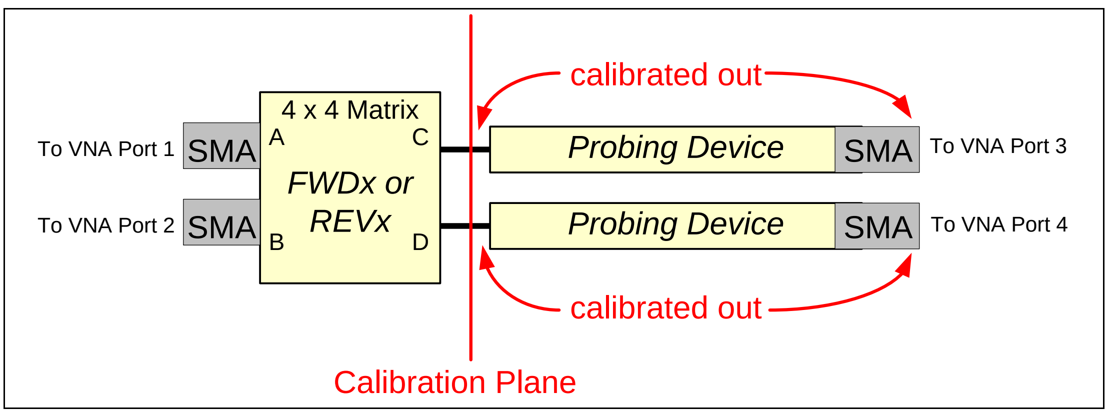


Figure E.4 - Using probing devices to interface ports C and D to measure FWDx and REVx

E.1.2 Four port fixture method. Determination of fixture matrices

The 4-port fixture matrices *FWDx* and *REVx* are determined by measurements using the methodology in clause E.4. The matrix for the forward 4-port fixture is given by equation (E1).

$$FWDx = \begin{bmatrix} S_{FWDx_{AA}} & S_{FWDx_{AB}} & S_{FWDx_{AC}} & S_{FWDx_{AD}} \\ S_{FWDx_{BA}} & S_{FWDx_{BB}} & S_{FWDx_{BC}} & S_{FWDx_{BD}} \\ S_{FWDx_{CA}} & S_{FWDx_{CB}} & S_{FWDx_{CC}} & S_{FWDx_{CD}} \\ S_{FWDx_{DA}} & S_{FWDx_{DB}} & S_{FWDx_{DC}} & S_{FWDx_{DD}} \end{bmatrix} \qquad \text{(E1)}$$

In the case of the reverse 4-port fixture, when the orientation of use is 180 degrees rotated compared to the orientation in which the fixture was characterized, the matrix for reverse 4-port fixture is given by Equation (E2)

$$REVx = \begin{bmatrix} S_{REVx_{CC}} & S_{REVx_{CD}} & S_{REVx_{CA}} & S_{REVx_{CB}} \\ S_{REVx_{DC}} & S_{REVx_{DD}} & S_{REVx_{DA}} & S_{REVx_{DB}} \\ S_{REVx_{AC}} & S_{REVx_{AD}} & S_{REVx_{AA}} & S_{REVx_{AB}} \\ S_{REVx_{BC}} & S_{REVx_{BD}} & S_{REVx_{BA}} & S_{REVx_{BB}} \end{bmatrix} \qquad \text{(E2)}$$

This provides a total of eight 4-port matrices, FWD_1, FWD_2, FWD_3, FWD_4, REV_1, REV_2, REV_3 and REV_4,

It may be possible to apply these 4-port matrices directly to the measurement data with the network analyzer software.

E.1.3 Four port fixture method. Cascading de-embedding matrices

Once the 4-port fixtures are calculated using equation E1 and E2, the unprocessed measurement in Figure E.1 can be cascaded with the de-embedding matrices (see Figure E.2). The most straight-forward method of cascading de-embedding matrices is outlined in the following steps, illustrated in Figure E.2.

1. Create a single 16-port S-parameter matrix from FWD_1, FWD_2, FWD_3, FWD_4 using the single ended port numbering provided in Figure E.1. *This provides a 16-port S matrix for the forward fixture.*

S_{FWD} =

$$\left(\begin{array}{cccccccccccccccc}
S_{FWD1_{AA}} & S_{FWD1_{AB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD1_{AC}} & S_{FWD1_{AD}} & 0 & 0 & 0 & 0 & 0 & 0 \\
S_{FWD1_{BA}} & S_{FWD1_{BB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD1_{BC}} & S_{FWD1_{BD}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & S_{FWD2_{AA}} & S_{FWD1_{AB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD2_{AC}} & S_{FWD2_{AD}} & 0 & 0 & 0 & 0 \\
0 & 0 & S_{FWD2_{BA}} & S_{FWD2_{BB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD2_{BC}} & S_{FWD2_{BD}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & S_{FWD3_{AA}} & S_{FWD3_{AB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD3_{AC}} & S_{FWD3_{AD}} & 0 & 0 \\
0 & 0 & 0 & 0 & S_{FWD3_{BA}} & S_{FWD3_{BB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD3_{BC}} & S_{FWD3_{BD}} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & S_{FWD4_{AA}} & S_{FWD4_{AB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD4_{AC}} & S_{FWD4_{AD}} \\
0 & 0 & 0 & 0 & 0 & 0 & S_{FWD4_{BA}} & S_{FWD4_{BB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD4_{BC}} & S_{FWD4_{BD}} \\
S_{FWD1_{CA}} & S_{FWD1_{CB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD1_{CC}} & S_{FWD1_{CD}} & 0 & 0 & 0 & 0 & 0 & 0 \\
S_{FWD1_{DA}} & S_{FWD1_{DB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD1_{DC}} & S_{FWD1_{DD}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & S_{FWD2_{CA}} & S_{FWD2_{CB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD2_{CC}} & S_{FWD2_{CD}} & 0 & 0 & 0 & 0 \\
0 & 0 & S_{FWD2_{DA}} & S_{FWD2_{DB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD2_{DC}} & S_{FWD2_{DD}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & S_{FWD3_{CA}} & S_{FWD3_{CB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD3_{CC}} & S_{FWD3_{CD}} & 0 & 0 \\
0 & 0 & 0 & 0 & S_{FWD3_{DA}} & S_{FWD3_{DB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD3_{DC}} & S_{FWD3_{DD}} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & S_{FWD4_{CA}} & S_{FWD4_{CB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD4_{CC}} & S_{FWD4_{CD}} \\
0 & 0 & 0 & 0 & 0 & 0 & S_{FWD4_{DA}} & S_{FWD4_{DB}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{FWD4_{DC}} & S_{FWD4_{DD}}
\end{array}\right) \text{(E3)}$$

Note: The zeros in matrix equation E3 arise due to the assumption of negligible coupling between four port fixture matrices. This may result in a measurement error if the coupling between four port fixtures is not negligible. This could be accounted for using the 16-port de-embedding technique.

2. Convert the 16 by 16 matrix from step (1) into a T-parameter matrix using the methodology provide in clause E.6.2 (Call this matrix T_{Fwd})
3. Calculate the inverse of T_{Fwd} to give T_{Fwd}^{-1}.
4. Create a single 16-port S-parameter matrix of unprocessed measurement
5. Convert the 16 by 16 matrix from step 4 into a T-parameter matrix (Call this matrix $T_{Fwd+DUT+Rev}$)
6. Create a single 16-port S-parameter matrix from REV_1, REV_2, REV_3, REV_4 using the single ended port numbering provided in Figure E.1. *This provides a 16-port S matrix for the Reverse fixture.*

In the case of the reverse fixture, when the orientation of use is 180 degrees rotated compared to the orientation in which the fixture was characterized, the matrix for reverse 16-port fixture is given by:

S_{REV}=

$$\begin{pmatrix}
S_{REV1_{CC}} & S_{REV1_{CD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV1_{CA}} & S_{REV1_{CB}} & 0 & 0 & 0 & 0 & 0 & 0 \\
S_{REV1_{DC}} & S_{REV1_{DD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV1_{DA}} & S_{REV1_{DB}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & S_{REV2_{CC}} & S_{REV2_{CD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV2_{CA}} & S_{REV2_{CB}} & 0 & 0 & 0 & 0 \\
0 & 0 & S_{REV2_{DC}} & S_{REV2_{DD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV2_{DA}} & S_{REV2_{DB}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & S_{REV3_{CC}} & S_{REV3_{CD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV3_{CA}} & S_{REV3_{CB}} & 0 & 0 \\
0 & 0 & 0 & 0 & S_{REV3_{DC}} & S_{REV3_{DD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV3_{DA}} & S_{REV3_{DB}} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & S_{REV4_{CC}} & S_{REV4_{CD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV4_{CA}} & S_{REV4_{CB}} \\
0 & 0 & 0 & 0 & 0 & 0 & S_{REV4_{DC}} & S_{REV4_{DD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV4_{DA}} & S_{REV4_{DB}} \\
S_{REV1_{AC}} & S_{REV1_{AD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV1_{AA}} & S_{REV1_{AB}} & 0 & 0 & 0 & 0 & 0 & 0 \\
S_{REV1_{BC}} & S_{REV1_{BD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV1_{BA}} & S_{REV1_{BB}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & S_{REV2_{AC}} & S_{REV2_{AD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV2_{AA}} & S_{REV2_{AB}} & 0 & 0 & 0 & 0 \\
0 & 0 & S_{REV2_{BC}} & S_{REV2_{BD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV2_{BA}} & S_{REV2_{BB}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & S_{REV3_{AC}} & S_{REV3_{AD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV3_{AA}} & S_{REV3_{AB}} & 0 & 0 \\
0 & 0 & 0 & 0 & S_{REV3_{BC}} & S_{REV3_{BD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV3_{BA}} & S_{REV3_{BB}} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & S_{REV4_{AC}} & S_{REV4_{AD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV4_{AA}} & S_{REV4_{AB}} \\
0 & 0 & 0 & 0 & 0 & 0 & S_{REV4_{BC}} & S_{REV4_{BD}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{REV4_{BA}} & S_{REV4_{BB}}
\end{pmatrix} \quad \text{(E4)}$$

7. Convert the 16 by 16 matrix from step (6) into a T-parameter matrix using the methodology provide in Clause E.6.2 (Call this matrix T_{Rev})
8. Calculate the inverse of T_{Rev} to give T_{Rev}^{-1}.
9. Multiply matrices T_{Fwd}^{-1}, $T_{Fwd+DUT+Rev}$, and T_{Rev}^{-1} in order to give:

$$T_{DUT} = T_{FWD}{}^{-1} \cdot T_{Fwd+DUT+Rev} \cdot T_{Rev}{}^{-1} \quad \text{(E5)}$$

10. Convert the 16 by 16 matrix T_{DUT} from step (9) into an S-parameter matrix using the methodology in Clause E.6.3 to give the 16x 16 Single ended S-matrix for the DUT.

E.2 Sixteen port fixture method. General calibration approach

Further accuracy can be achieved by characterizing the 16-port measurement fixture for those S-parameters that describe coupling in between the constituent 4-port fixtures. This method includes the inter-pair couplings in test fixtures and removes them from the results measured for the unprocessed measurement as described in Figure E.1.

E.2.1 Sixteen port fixture method. Determining fixture matrices

The 4 - port fixture matrices are characterized in the same manner as in clause E.1.2.
The additional NEXT and FEXT couplings of the 16-port forward and reverse fixtures are characterized according to the methodology of clause E.5.

E.2.2 Sixteen port fixture method. Cascading de-embedding matrices

Once the 16-port fixtures are characterized the unprocessed measurement in Figure E.1 can be cascaded with the de-embedding matrices (see Figure E.2). This step extracts the characteristics of the DUT from the effect of the test fixture. The methodology is provided by Clause E.1.3, however the matrices shown in equations E6 and E7 should be used for S_{FWD} and S_{REV}

The matrix element numbering designates elements by row and column pairs. Rows 1 through 16 and columns 1 through 16 are defined. Thus S_{11} designates the matrix element for row one column 1, S_{214} designates the element for row two column 14, and S_{1616} designates the element for row 16 column 16.

$$S_{FWD} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} & S_{17} & S_{18} & S_{19} & S_{110} & S_{111} & S_{112} & S_{113} & S_{114} & S_{115} & S_{116} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} & S_{27} & S_{28} & S_{29} & S_{210} & S_{211} & S_{212} & S_{213} & S_{214} & S_{215} & S_{216} \\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} & S_{37} & S_{38} & S_{39} & S_{310} & S_{311} & S_{312} & S_{313} & S_{314} & S_{315} & S_{316} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} & S_{47} & S_{48} & S_{49} & S_{410} & S_{411} & S_{412} & S_{413} & S_{414} & S_{415} & S_{416} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} & S_{57} & S_{58} & S_{59} & S_{510} & S_{511} & S_{512} & S_{513} & S_{514} & S_{515} & S_{516} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} & S_{67} & S_{68} & S_{69} & S_{610} & S_{611} & S_{612} & S_{613} & S_{614} & S_{615} & S_{616} \\ S_{71} & S_{72} & S_{73} & S_{74} & S_{75} & S_{76} & S_{77} & S_{78} & S_{79} & S_{710} & S_{711} & S_{712} & S_{713} & S_{714} & S_{715} & S_{716} \\ S_{81} & S_{82} & S_{83} & S_{84} & S_{85} & S_{86} & S_{87} & S_{88} & S_{89} & S_{810} & S_{811} & S_{812} & S_{813} & S_{814} & S_{815} & S_{816} \\ S_{91} & S_{92} & S_{93} & S_{94} & S_{95} & S_{96} & S_{97} & S_{98} & S_{99} & S_{910} & S_{911} & S_{912} & S_{913} & S_{914} & S_{915} & S_{916} \\ S_{101} & S_{102} & S_{103} & S_{104} & S_{105} & S_{106} & S_{107} & S_{108} & S_{109} & S_{1010} & S_{1011} & S_{1012} & S_{1013} & S_{1014} & S_{1015} & S_{1016} \\ S_{111} & S_{112} & S_{113} & S_{114} & S_{115} & S_{116} & S_{117} & S_{118} & S_{119} & S_{1110} & S_{1111} & S_{1112} & S_{1113} & S_{1114} & S_{1115} & S_{1116} \\ S_{121} & S_{122} & S_{123} & S_{124} & S_{125} & S_{126} & S_{127} & S_{128} & S_{129} & S_{1210} & S_{1211} & S_{1212} & S_{1213} & S_{1214} & S_{1215} & S_{1216} \\ S_{131} & S_{132} & S_{133} & S_{134} & S_{135} & S_{136} & S_{137} & S_{138} & S_{139} & S_{1310} & S_{1311} & S_{1312} & S_{1313} & S_{1314} & S_{1315} & S_{1316} \\ S_{141} & S_{142} & S_{143} & S_{144} & S_{145} & S_{146} & S_{147} & S_{148} & S_{149} & S_{1410} & S_{1411} & S_{1412} & S_{1413} & S_{1414} & S_{1415} & S_{1416} \\ S_{151} & S_{152} & S_{153} & S_{154} & S_{155} & S_{156} & S_{157} & S_{158} & S_{159} & S_{1510} & S_{1511} & S_{1512} & S_{1513} & S_{1514} & S_{1515} & S_{1516} \\ S_{161} & S_{162} & S_{163} & S_{164} & S_{165} & S_{166} & S_{167} & S_{168} & S_{169} & S_{1610} & S_{1611} & S_{1612} & S_{1613} & S_{1614} & S_{1615} & S_{1616} \end{pmatrix} \tag{E6}$$

$$S_{REV} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} & S_{17} & S_{18} & S_{19} & S_{110} & S_{111} & S_{112} & S_{113} & S_{114} & S_{115} & S_{116} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} & S_{27} & S_{28} & S_{29} & S_{210} & S_{211} & S_{212} & S_{213} & S_{214} & S_{215} & S_{216} \\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} & S_{37} & S_{38} & S_{39} & S_{310} & S_{311} & S_{312} & S_{313} & S_{314} & S_{315} & S_{316} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} & S_{47} & S_{48} & S_{49} & S_{410} & S_{411} & S_{412} & S_{413} & S_{414} & S_{415} & S_{416} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} & S_{57} & S_{58} & S_{59} & S_{510} & S_{511} & S_{512} & S_{513} & S_{514} & S_{515} & S_{516} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} & S_{67} & S_{68} & S_{69} & S_{610} & S_{611} & S_{612} & S_{613} & S_{614} & S_{615} & S_{616} \\ S_{71} & S_{72} & S_{73} & S_{74} & S_{75} & S_{76} & S_{77} & S_{78} & S_{79} & S_{710} & S_{711} & S_{712} & S_{713} & S_{714} & S_{715} & S_{716} \\ S_{81} & S_{82} & S_{83} & S_{84} & S_{85} & S_{86} & S_{87} & S_{88} & S_{89} & S_{810} & S_{811} & S_{812} & S_{813} & S_{814} & S_{815} & S_{816} \\ S_{91} & S_{92} & S_{93} & S_{94} & S_{95} & S_{96} & S_{97} & S_{98} & S_{99} & S_{910} & S_{911} & S_{912} & S_{913} & S_{914} & S_{915} & S_{916} \\ S_{101} & S_{102} & S_{103} & S_{104} & S_{105} & S_{106} & S_{107} & S_{108} & S_{109} & S_{1010} & S_{1011} & S_{1012} & S_{1013} & S_{1014} & S_{1015} & S_{1016} \\ S_{111} & S_{112} & S_{113} & S_{114} & S_{115} & S_{116} & S_{117} & S_{118} & S_{119} & S_{1110} & S_{1111} & S_{1112} & S_{1113} & S_{1114} & S_{1115} & S_{1116} \\ S_{121} & S_{122} & S_{123} & S_{124} & S_{125} & S_{126} & S_{127} & S_{128} & S_{129} & S_{1210} & S_{1211} & S_{1212} & S_{1213} & S_{1214} & S_{1215} & S_{1216} \\ S_{131} & S_{132} & S_{133} & S_{134} & S_{135} & S_{136} & S_{137} & S_{138} & S_{139} & S_{1310} & S_{1311} & S_{1312} & S_{1313} & S_{1314} & S_{1315} & S_{1316} \\ S_{141} & S_{142} & S_{143} & S_{144} & S_{145} & S_{146} & S_{147} & S_{148} & S_{149} & S_{1410} & S_{1411} & S_{1412} & S_{1413} & S_{1414} & S_{1415} & S_{1416} \\ S_{151} & S_{152} & S_{153} & S_{154} & S_{155} & S_{156} & S_{157} & S_{158} & S_{159} & S_{1510} & S_{1511} & S_{1512} & S_{1513} & S_{1514} & S_{1515} & S_{1516} \\ S_{161} & S_{162} & S_{163} & S_{164} & S_{165} & S_{166} & S_{167} & S_{168} & S_{169} & S_{1610} & S_{1611} & S_{1612} & S_{1613} & S_{1614} & S_{1615} & S_{1616} \end{pmatrix} \tag{E7}$$

E.3 Characterizing the probing fixture

In order to characterize the IL and FEXT transmission S-parameters of the test fixture, this method utilizes a “probe” fixture to interface to the port C and port D of the test fixture as shown in Figure E.5

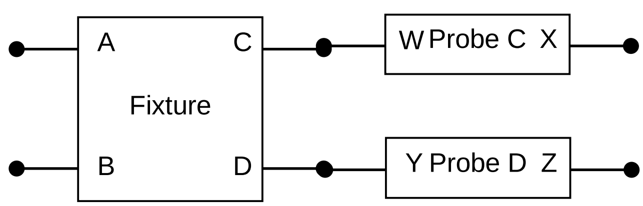


Figure E.5 - Diagram of 4-port measuring fixture and 2-port probing fixture

In order to characterize the probe, the VNA is calibrated using a 1 port procedure at the end of the test cables.
The probe is then attached to the test cables (ports X and Z according to Figure E.5), and the far end of the probe (ports W and Y according to Figure E.5) is terminated and measured with an open circuit, a short to ground, and then a 50Ω load to ground. These measurements are then processed (as complex numbers) according to equations E8, E9 and E10 to derive the 2 port S-matrix based on single ended measurements. These equations can be found in TIA 568C.2 Annex C.

It should be noted that the following calculations should be based on unwrapped phase information, this eliminates the 2·π jumps in phase when plotted against frequency that would otherwise result in choosing the 'wrong' root for some frequencies in equations E8, E9, and E10. Look at each delta between angles as frequency increases. If the delta is greater than π, add or subtract 2·π from subsequent angles, depending on the sign of the delta. If delta is positive, subtract 2·π, and if negative, add 2·π. The result of this should be a smoothly monotonic angle when plotted against frequencies, with no big discontinuities.

$$S_{XX} = \Gamma_{Load} \quad \text{(E8)}$$

$$S_{WW} = \frac{(\Gamma_{Open} + \Gamma_{Short}) - 2\Gamma_{Load}}{(\Gamma_{Open} - \Gamma_{Short})} \quad \text{(E9)}$$

$$S_{WX} = \sqrt{\frac{2(\Gamma_{Load} - \Gamma_{Short})(\Gamma_{Open} - \Gamma_{Load})}{(\Gamma_{Open} - \Gamma_{Short})}} \quad \text{(E10)}$$

It is assumed that that S21 and S12 are reciprocal, therefore:

$$S_{XW} = \sqrt{\frac{2(\Gamma_{Load} - \Gamma_{Short})(\Gamma_{Open} - \Gamma_{Load})}{(\Gamma_{Open} - \Gamma_{Short})}} \quad \text{(E11)}$$

Using the measurements above we can then calculate the 2-port matrices for the two probes:

$$S_{ProbeC} = \begin{pmatrix} S_{WW} & S_{WX} \\ S_{XW} & S_{XX} \end{pmatrix} \quad \text{(E12)}$$

$$S_{ProbeD} = \begin{pmatrix} S_{YY} & S_{YZ} \\ S_{ZY} & S_{ZZ} \end{pmatrix} \quad \text{(E13)}$$

These probe matrices can then be used to de-embed from the results achieved as required when using the probe to measure 2-port transmission parameters of the fixture.

In order to use these probes to characterize the far end NEXT of a 4-port test fixture it is also necessary to combine Probes C and D in to a single 4-port probe

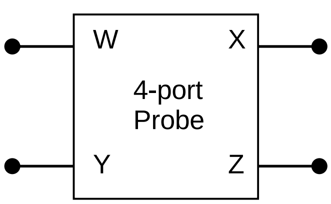


Figure E.6 - Diagram of four port probing fixture

$$S_{Probe4port} = \begin{pmatrix} S_{WW} & 0 & S_{WX} & 0 \\ 0 & S_{YY} & 0 & S_{YZ} \\ S_{XW} & 0 & S_{XX} & S_{XZ} \\ 0 & S_{ZY} & S_{ZX} & S_{ZZ} \end{pmatrix} \quad \text{(E14)}$$

Note: the zero terms in the above equation are not assumed to be zero in actuality. A compromise is assumed to ease the physical measurement of the probing device. Including accurate accounting of the zero terms would improve the characterization of the probing device.

Editor's note: This is an item of discussion.

The terms S_{XZ} and S_{ZX} can be directly measure on the 4-port probe when terminating ports W and Y with 50Ω to ground terminations.

E.4 Characterizing a 4-port fixture

The following procedure can be used to characterize the S-matrix terms for any 4- port device. The example used in the rest of this clauses is that of the FWD1 fixture according to Figure E.1. The process must be repeated for all 8 balanced ports of a pair of fixtures. Although it is possible to shortcut this process by using the 4-port matrix calculated for a given port to directly measure the 4-port matrices for all other balanced ports, it is recommended that each balanced port (and SE port) is characterized by direct measurements where possible.

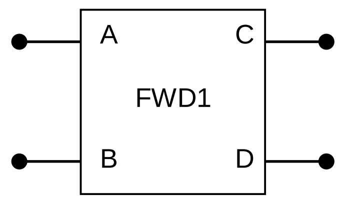


Figure E.7 - Notation of 4-port measurement fixture FWD1

$$S_{Fixture=} = \begin{pmatrix} S_{AA} & S_{AB} & S_{AC} & S_{AD} \\ S_{BA} & S_{BB} & S_{BC} & S_{BD} \\ S_{CA} & S_{CB} & S_{CC} & S_{CD} \\ S_{DA} & S_{DB} & S_{DC} & S_{DD} \end{pmatrix} \quad \text{(E15)}$$

E.4.1 Determination of S_{AA}, S_{BB}, S_{AB} and S_{BA},

A minimum of a 2-port calibration should be applied to the ends of the test cables. The test cables should be connected to ports A and B of the fixture and 50Ω to ground terminations applied to ports C and D at the calibration plane according to Figure E.8.

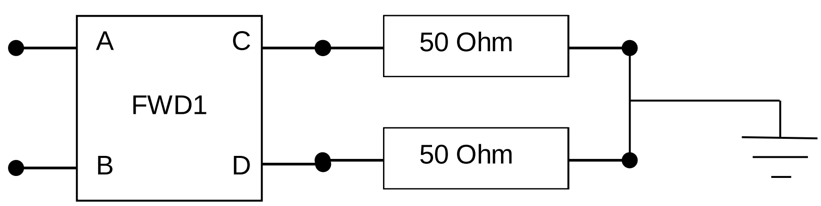


Figure E.8 - First Setup for Characterization of a 4-Port Measurement Fixture

Directly characterize S_{AA}, S_{BB} , S_{AB} and S_{BA} of the fixture.

E.4.2 Determination of SCC SAC and SCA

A minimum of a 1-port calibration should be applied to the ends of the test cables. The test cable should be connected to port A, port B of the fixture should be terminated by 50Ω to ground and 50Ω to ground terminations applied to ports D at the calibration plane according to Figure E.9. Measurements of S_{AA} should be performed when using an open circuit and short circuit to ground terminations at port C.

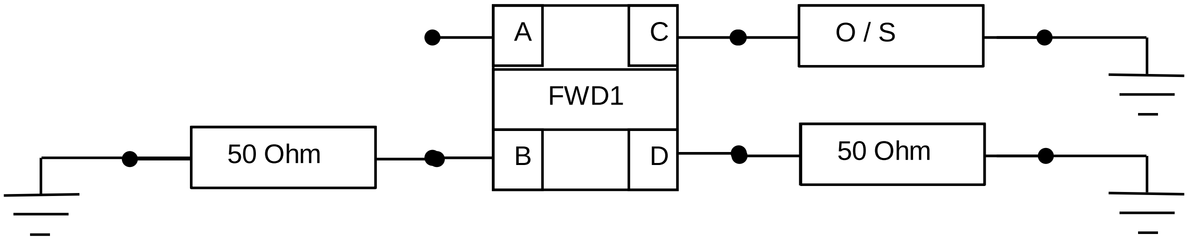


Figure E.9 - Second setup for characterization of a 4-port measurement fixture

The results for open, short and load from Clause E.4.1 of S_{AA} are processed according to the equations in Clause E.3 to provide S_{CC}, S_{AC} ,S_{CA} the fixture.

E.4.3 Determination of SDD SBD and SDB

A minimum of a 1-port calibration should be applied to the ends of the test cables.
The test cable should be connected to port B. Port A of the fixture should be terminated by 50Ω to ground and 50Ω to ground terminations applied to port C at the calibration plane according to Figure E.10. Measurements of S_{BB} should be performed when using an open circuit and short circuit to ground terminations at port D.

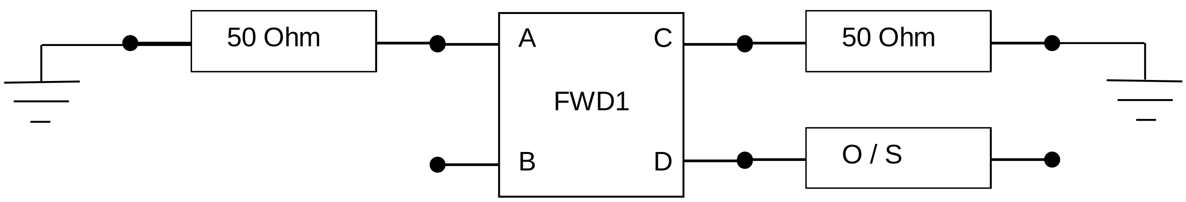


Figure E.10 - Third setup for characterization of a 4-port measurement fixture

The results for open, short and load from Clause E.4.1 of S_{BB} are processed according to the equations in clause E.3 to provide S_{DD}, S_{BD} ,S_{DB} the fixture.

E.4.4 Determination of SDA, SAD, SBC, SCB, SCD and SDC

A minimum of a 4-port calibration should be applied to the ends of the test cables. The 4-port probing fixture should be connected to the 4-port measurement fixture according to Figure E.11, and a complete 4-port result should be measured.

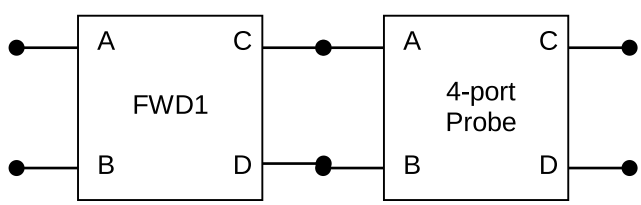


Figure E.11 - Fourth setup for characterization of a 4-port measurement fixture

The 4-port S-matrix for the probing device should then be de-embedded from the result to provide the FEXT terms S_{DA}, S_{AD}, S_{BC} and S_{CB}, and the far end NEXT terms S_{DC} and S_{CD} for the measurement fixture.

E.5 Characterizing a 16-port fixture

In addition to the instructions provided in Clause E.4, the additional NEXT and FEXT couplings of the 16-port fixture can be characterized.

The instructions in Clause E.4 provide the following terms of the S-Matrix of the fixture:

$$S_{Fixtue} = \begin{pmatrix}
S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} & S_{17} & S_{18} & S_{19} & S_{110} & S_{111} & S_{112} & S_{113} & S_{114} & S_{115} & S_{116} \\
S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} & S_{27} & S_{28} & S_{29} & S_{210} & S_{211} & S_{212} & S_{213} & S_{214} & S_{215} & S_{216} \\
S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} & S_{37} & S_{38} & S_{39} & S_{310} & S_{311} & S_{312} & S_{313} & S_{314} & S_{315} & S_{316} \\
S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} & S_{47} & S_{48} & S_{49} & S_{410} & S_{411} & S_{412} & S_{413} & S_{414} & S_{415} & S_{416} \\
S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} & S_{57} & S_{58} & S_{59} & S_{510} & S_{511} & S_{512} & S_{513} & S_{514} & S_{515} & S_{516} \\
S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} & S_{67} & S_{68} & S_{69} & S_{610} & S_{611} & S_{612} & S_{613} & S_{614} & S_{615} & S_{616} \\
S_{71} & S_{72} & S_{73} & S_{74} & S_{75} & S_{76} & S_{77} & S_{78} & S_{79} & S_{710} & S_{711} & S_{712} & S_{713} & S_{714} & S_{715} & S_{716} \\
S_{81} & S_{82} & S_{83} & S_{84} & S_{85} & S_{86} & S_{87} & S_{88} & S_{89} & S_{810} & S_{811} & S_{812} & S_{813} & S_{814} & S_{815} & S_{816} \\
S_{91} & S_{92} & S_{93} & S_{94} & S_{95} & S_{96} & S_{97} & S_{98} & S_{99} & S_{910} & S_{911} & S_{912} & S_{913} & S_{914} & S_{915} & S_{916} \\
S_{101} & S_{102} & S_{103} & S_{104} & S_{105} & S_{106} & S_{107} & S_{108} & S_{109} & S_{1010} & S_{1011} & S_{1012} & S_{1013} & S_{1014} & S_{1015} & S_{1016} \\
S_{111} & S_{112} & S_{113} & S_{114} & S_{115} & S_{116} & S_{117} & S_{118} & S_{119} & S_{1110} & S_{1111} & S_{1112} & S_{1113} & S_{1114} & S_{1115} & S_{1116} \\
S_{121} & S_{122} & S_{123} & S_{124} & S_{125} & S_{126} & S_{127} & S_{128} & S_{129} & S_{1210} & S_{1211} & S_{1212} & S_{1213} & S_{1214} & S_{1215} & S_{1216} \\
S_{131} & S_{132} & S_{133} & S_{134} & S_{135} & S_{136} & S_{137} & S_{138} & S_{139} & S_{1310} & S_{1311} & S_{1312} & S_{1313} & S_{1314} & S_{1315} & S_{1316} \\
S_{141} & S_{142} & S_{143} & S_{144} & S_{145} & S_{146} & S_{147} & S_{148} & S_{149} & S_{1410} & S_{1411} & S_{1412} & S_{1413} & S_{1414} & S_{1415} & S_{1416} \\
S_{151} & S_{152} & S_{153} & S_{154} & S_{155} & S_{156} & S_{157} & S_{158} & S_{159} & S_{1510} & S_{1511} & S_{1512} & S_{1513} & S_{1514} & S_{1515} & S_{1516} \\
S_{161} & S_{162} & S_{163} & S_{164} & S_{165} & S_{166} & S_{167} & S_{168} & S_{169} & S_{1610} & S_{1611} & S_{1612} & S_{1613} & S_{1614} & S_{1615} & S_{1616}
\end{pmatrix} \quad \text{(E16)}$$

E.5.1 Additional FEXT coupling elements of the 16 port fixture matrix

Using the instructions in Clause E.4.4 (e.g. by connecting ports 1 and 11 of the fixture to the VNA and terminating all other ports with 50Ω to ground), it is possible to populate all of the additional FEXT terms of the fixture matrix.

In this manner the fixture matrix can be populated with the additional highlighted terms in equation E17:

$$S_{Fixture} = \begin{pmatrix}
S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} & S_{17} & S_{18} & S_{19} & S_{110} & S_{111} & S_{112} & S_{113} & S_{114} & S_{115} & S_{116} \\
S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} & S_{27} & S_{28} & S_{29} & S_{210} & S_{211} & S_{212} & S_{213} & S_{214} & S_{215} & S_{216} \\
S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} & S_{37} & S_{38} & S_{39} & S_{310} & S_{311} & S_{312} & S_{313} & S_{314} & S_{315} & S_{316} \\
S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} & S_{47} & S_{48} & S_{49} & S_{410} & S_{411} & S_{412} & S_{413} & S_{414} & S_{415} & S_{416} \\
S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} & S_{57} & S_{58} & S_{59} & S_{510} & S_{511} & S_{512} & S_{513} & S_{514} & S_{515} & S_{516} \\
S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} & S_{67} & S_{68} & S_{69} & S_{610} & S_{611} & S_{612} & S_{613} & S_{614} & S_{615} & S_{616} \\
S_{71} & S_{72} & S_{73} & S_{74} & S_{75} & S_{76} & S_{77} & S_{78} & S_{79} & S_{710} & S_{711} & S_{712} & S_{713} & S_{714} & S_{715} & S_{716} \\
S_{81} & S_{82} & S_{83} & S_{84} & S_{85} & S_{86} & S_{87} & S_{88} & S_{89} & S_{810} & S_{811} & S_{812} & S_{813} & S_{814} & S_{815} & S_{816} \\
S_{91} & S_{92} & S_{93} & S_{94} & S_{95} & S_{96} & S_{97} & S_{98} & S_{99} & S_{910} & S_{911} & S_{912} & S_{913} & S_{914} & S_{915} & S_{916} \\
S_{101} & S_{102} & S_{103} & S_{104} & S_{105} & S_{106} & S_{107} & S_{108} & S_{109} & S_{1010} & S_{1011} & S_{1012} & S_{1013} & S_{1014} & S_{1015} & S_{1016} \\
S_{111} & S_{112} & S_{113} & S_{114} & S_{115} & S_{116} & S_{117} & S_{118} & S_{119} & S_{1110} & S_{1111} & S_{1112} & S_{1113} & S_{1114} & S_{1115} & S_{1116} \\
S_{121} & S_{122} & S_{123} & S_{124} & S_{125} & S_{126} & S_{127} & S_{128} & S_{129} & S_{1210} & S_{1211} & S_{1212} & S_{1213} & S_{1214} & S_{1215} & S_{1216} \\
S_{131} & S_{132} & S_{133} & S_{134} & S_{135} & S_{136} & S_{137} & S_{138} & S_{139} & S_{1310} & S_{1311} & S_{1312} & S_{1313} & S_{1314} & S_{1315} & S_{1316} \\
S_{141} & S_{142} & S_{143} & S_{144} & S_{145} & S_{146} & S_{147} & S_{148} & S_{149} & S_{1410} & S_{1411} & S_{1412} & S_{1413} & S_{1414} & S_{1415} & S_{1416} \\
S_{151} & S_{152} & S_{153} & S_{154} & S_{155} & S_{156} & S_{157} & S_{158} & S_{159} & S_{1510} & S_{1511} & S_{1512} & S_{1513} & S_{1514} & S_{1515} & S_{1516} \\
S_{161} & S_{162} & S_{163} & S_{164} & S_{165} & S_{166} & S_{167} & S_{168} & S_{169} & S_{1610} & S_{1611} & S_{1612} & S_{1613} & S_{1614} & S_{1615} & S_{1616}
\end{pmatrix} \quad \text{(E17)}$$

E.5.2 Additional NEXT coupling elements of the 16 port matrix

By terminating Port 9, 10, 11, 12, 13, 14, 15 and 16 of the fixture with 50Ω to ground, and connecting ports 1, 2, 3, 4, 5, 6, 7 and 8 of the fixture to the VNA, direct measurements of near end coupling S-parameters can further populate the fixture matrix.

In this manner the fixture matrix can be populated with the highlighted terms in equation E18:

$$S_{Fixture} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} & S_{17} & S_{18} & S_{19} & S_{110} & S_{111} & S_{112} & S_{113} & S_{114} & S_{115} & S_{116} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} & S_{27} & S_{28} & S_{29} & S_{210} & S_{211} & S_{212} & S_{213} & S_{214} & S_{215} & S_{216} \\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} & S_{37} & S_{38} & S_{39} & S_{310} & S_{311} & S_{312} & S_{313} & S_{314} & S_{315} & S_{316} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} & S_{47} & S_{48} & S_{49} & S_{410} & S_{411} & S_{412} & S_{413} & S_{414} & S_{415} & S_{416} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} & S_{57} & S_{58} & S_{59} & S_{510} & S_{511} & S_{512} & S_{513} & S_{514} & S_{515} & S_{516} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} & S_{67} & S_{68} & S_{69} & S_{610} & S_{611} & S_{612} & S_{613} & S_{614} & S_{615} & S_{616} \\ S_{71} & S_{72} & S_{73} & S_{74} & S_{75} & S_{76} & S_{77} & S_{78} & S_{79} & S_{710} & S_{711} & S_{712} & S_{713} & S_{714} & S_{715} & S_{716} \\ S_{81} & S_{82} & S_{83} & S_{84} & S_{85} & S_{86} & S_{87} & S_{88} & S_{89} & S_{810} & S_{811} & S_{812} & S_{813} & S_{814} & S_{815} & S_{816} \\ S_{91} & S_{92} & S_{93} & S_{94} & S_{95} & S_{96} & S_{97} & S_{98} & S_{99} & S_{910} & S_{911} & S_{912} & S_{913} & S_{914} & S_{915} & S_{916} \\ S_{101} & S_{102} & S_{103} & S_{104} & S_{105} & S_{106} & S_{107} & S_{108} & S_{109} & S_{1010} & S_{1011} & S_{1012} & S_{1013} & S_{1014} & S_{1015} & S_{1016} \\ S_{111} & S_{112} & S_{113} & S_{114} & S_{115} & S_{116} & S_{117} & S_{118} & S_{119} & S_{1110} & S_{1111} & S_{1112} & S_{1113} & S_{1114} & S_{1115} & S_{1116} \\ S_{121} & S_{122} & S_{123} & S_{124} & S_{125} & S_{126} & S_{127} & S_{128} & S_{129} & S_{1210} & S_{1211} & S_{1212} & S_{1213} & S_{1214} & S_{1215} & S_{1216} \\ S_{131} & S_{132} & S_{133} & S_{134} & S_{135} & S_{136} & S_{137} & S_{138} & S_{139} & S_{1310} & S_{1311} & S_{1312} & S_{1313} & S_{1314} & S_{1315} & S_{1316} \\ S_{141} & S_{142} & S_{143} & S_{144} & S_{145} & S_{146} & S_{147} & S_{148} & S_{149} & S_{1410} & S_{1411} & S_{1412} & S_{1413} & S_{1414} & S_{1415} & S_{1416} \\ S_{151} & S_{152} & S_{153} & S_{154} & S_{155} & S_{156} & S_{157} & S_{158} & S_{159} & S_{1510} & S_{1511} & S_{1512} & S_{1513} & S_{1514} & S_{1515} & S_{1516} \\ S_{161} & S_{162} & S_{163} & S_{164} & S_{165} & S_{166} & S_{167} & S_{168} & S_{169} & S_{1610} & S_{1611} & S_{1612} & S_{1613} & S_{1614} & S_{1615} & S_{1616} \end{pmatrix} \tag{E18}$$

E.5.3 Additional reciprocal NEXT coupling elements of the 16-port matrix

The probes shown in Figure E.3, either as a 2-port probe or a 4-port probe, do not allow for connections that would allow measurement of the remaining terms of the 16-port matrix.

However, if using alternative probes or fixtures that do allow connection a direct measurement of NEXT should be used to populate the final terms of the matrix.

If by the nature of this fixturing it is not possible to take a direct measurement, a de-embedded probe may be used to qualify these NEXT terms.

If no measurement is possible the reciprocal relationships of near to far end NEXT are provided in Table E.1.

Table E.1 Reciprocal relationships in a 16 port matrix

$S_{911} = S_{13}$	$S_{912} = S_{14}$	$S_{913} = S_{15}$	$S_{914} = S_{16}$	$S_{915} = S_{17}$	$S_{916} = S_{18}$
$S_{1011} = S_{23}$	$S_{1012} = S_{24}$	$S_{1013} = S_{25}$	$S_{1014} = S_{26}$	$S_{1015} = S_{27}$	$S_{1016} = S_{28}$
$S_{119} = S_{31}$	$S_{1110} = S_{32}$	$S_{1113} = S_{35}$	$S_{1114} = S_{36}$	$S_{1115} = S_{37}$	$S_{1116} = S_{38}$
$S_{129} = S_{41}$	$S_{1210} = S_{42}$	$S_{1213} = S_{45}$	$S_{1214} = S_{46}$	$S_{1215} = S_{47}$	$S_{1216} = S_{48}$
$S_{139} = S_{51}$	$S_{1310} = S_{52}$	$S_{1311} = S_{53}$	$S_{1312} = S_{54}$	$S_{1315} = S_{57}$	$S_{1316} = S_{58}$
$S_{149} = S_{61}$	$S_{1410} = S_{62}$	$S_{1411} = S_{63}$	$S_{1412} = S_{64}$	$S_{1415} = S_{67}$	$S_{1416} = S_{68}$
$S_{159} = S_{71}$	$S_{1510} = S_{72}$	$S_{1511} = S_{73}$	$S_{1512} = S_{74}$	$S_{1513} = S_{75}$	$S_{1514} = S_{76}$
$S_{169} = S_{81}$	$S_{1610} = S_{82}$	$S_{1611} = S_{83}$	$S_{1612} = S_{84}$	$S_{1613} = S_{85}$	$S_{1614} = S_{86}$

E.6 RF simulation software consideration.

The simplest way of cascading de-embedding matrices is to use an RF simulation software application. The software eliminates the need for creating and converting matrices manually. An example of cascading using RF modeling software is illustrated in Figure E.12 and Figure E.13. Figure E.12 de-embeds the fixtures, and Figure E.13 applies ideal baluns for modal decomposition.

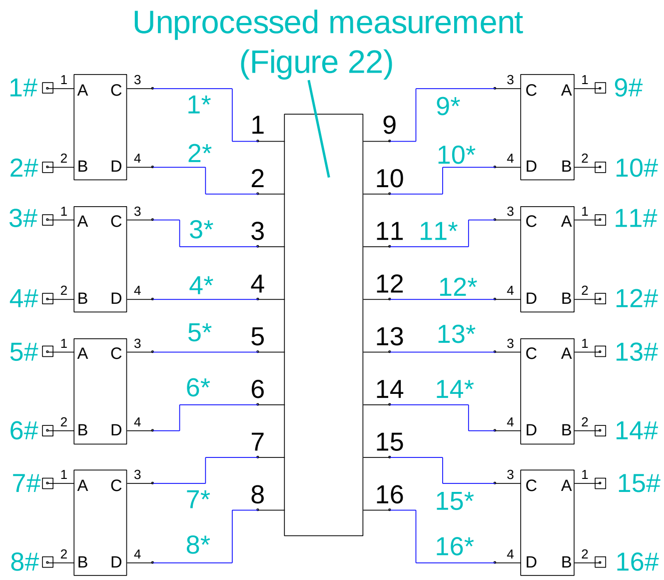


Figure E.12 - Cascading using RF simulation application (comparable to Figure E.2)

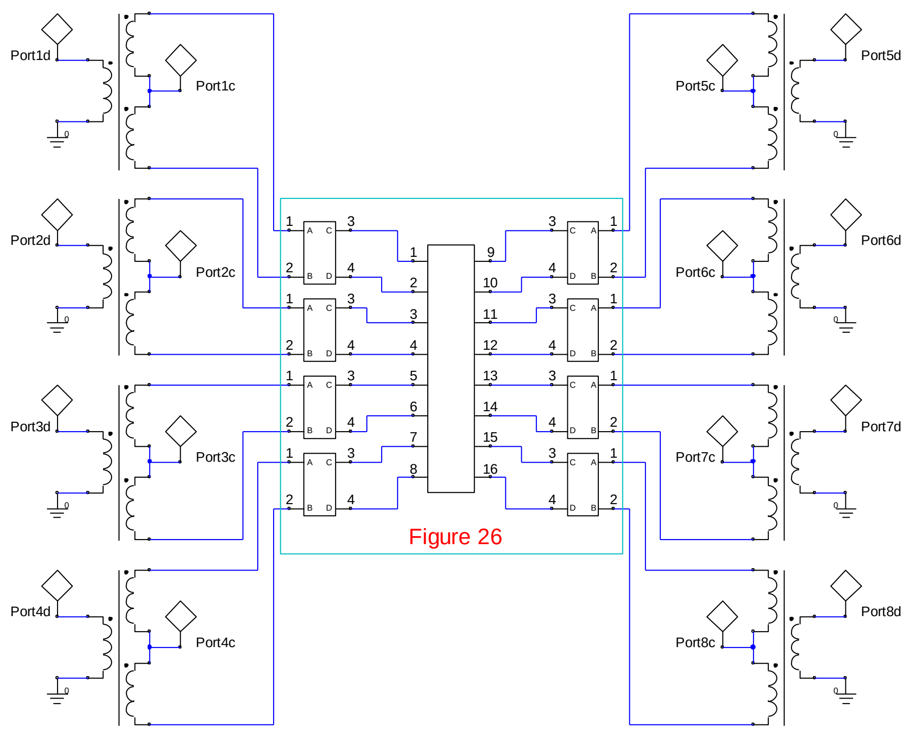


Figure E.13 - Adding ideal baluns to extract mixed mode parameters

E.6.1 **Port mapping of fixtures in a back-to-back configuration.**

When the fixtures shown in Figure E.14, are used, four measurement fixtures are arranged in a fixed position relative to each other. Note that when two fixtures are placed back-to-back, such as for a through calibration, pair 2n would connect to pair 4f, and pair 4n would connect to pair 2f.

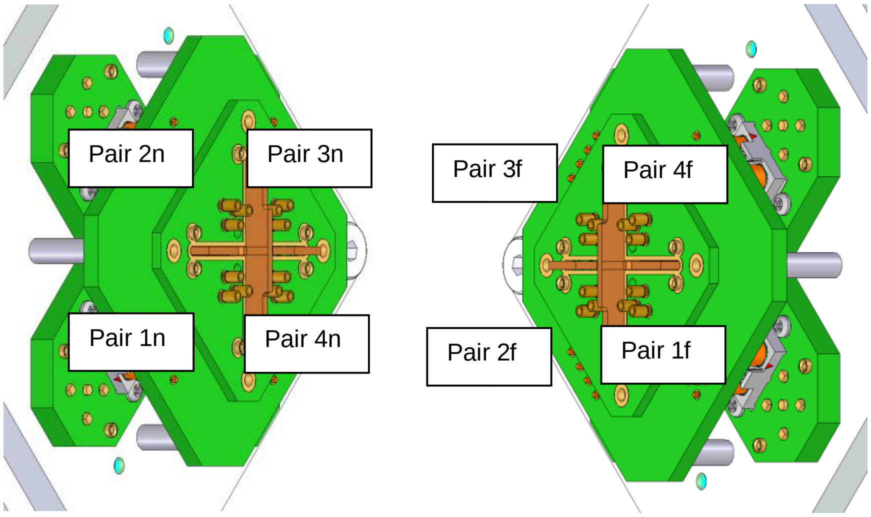


Figure E.14 - Port numbering of near and far end test fixtures

When a given fixture is to be used as a reverse fixture, it can be characterized in the opposite direction to the methodology used in clauses E.4 and E.5, however it can be more convenient to rearrange the matrix previously characterized for using the given fixture as a forward fixture.

Examples of the conversion of a characterization of a forward fixture to be used as a reverse fixture the following conversations are shown below. It should be noted that the conversion below “swaps” the fixtures REV 2 and REV4 to avoid the need to “cross pairs” between the near and far end fixture.

Table E-2 Test fixture port re-mapping for back-to-back through calibrations

When using a given 1183-1 Fixture as a forward fixture (4- Port Version)	When using a given 1183-1 Fixture as a reverse fixture (4- Port Version)
$S_{FWD1} = \begin{pmatrix} S_{FWD1_{AA}} & S_{FWD1_{AB}} & S_{FWD1_{AC}} & S_{FWD1_{AD}} \\ S_{FWD1_{BA}} & S_{FWD1_{BB}} & S_{FWD1_{BC}} & S_{FWD1_{BD}} \\ S_{FWD1_{CA}} & S_{FWD1_{CB}} & S_{FWD1_{CC}} & S_{FWD1_{CD}} \\ S_{FWD1_{DA}} & S_{FWD1_{DB}} & S_{FWD1_{DC}} & S_{FWD1_{DD}} \end{pmatrix}$	$S_{REV1} = \begin{pmatrix} S_{FWD1_{CC}} & S_{FWD1_{CD}} & S_{FWD1_{CA}} & S_{FWD1_{CB}} \\ S_{FWD1_{DC}} & S_{FWD1_{DD}} & S_{FWD1_{DA}} & S_{FWD1_{DB}} \\ S_{FWD1_{AC}} & S_{FWD1_{AD}} & S_{FWD1_{AA}} & S_{FWD1_{AB}} \\ S_{FWD1_{BC}} & S_{FWD1_{BD}} & S_{FWD1_{BA}} & S_{FWD1_{BB}} \end{pmatrix}$
$S_{FWD2} = \begin{pmatrix} S_{FWD2_{AA}} & S_{FWD2_{AB}} & S_{FWD2_{AC}} & S_{FWD2_{AD}} \\ S_{FWD2_{BA}} & S_{FWD2_{BB}} & S_{FWD2_{BC}} & S_{FWD2_{BD}} \\ S_{FWD2_{CA}} & S_{FWD2_{CB}} & S_{FWD2_{CC}} & S_{FWD2_{CD}} \\ S_{FWD2_{DA}} & S_{FWD2_{DB}} & S_{FWD2_{DC}} & S_{FWD2_{DD}} \end{pmatrix}$	$S_{REV4} = \begin{pmatrix} S_{FWD4_{CC}} & S_{FWD4_{CD}} & S_{FWD4_{CA}} & S_{FWD4_{CB}} \\ S_{FWD4_{DC}} & S_{FWD4_{DD}} & S_{FWD4_{DA}} & S_{FWD4_{DB}} \\ S_{FWD4_{AC}} & S_{FWD4_{AD}} & S_{FWD4_{AA}} & S_{FWD4_{AB}} \\ S_{FWD4_{BC}} & S_{FWD4_{BD}} & S_{FWD4_{BA}} & S_{FWD4_{BB}} \end{pmatrix}$
$S_{FWD3} = \begin{pmatrix} S_{FWD3_{AA}} & S_{FWD3_{AB}} & S_{FWD3_{AC}} & S_{FWD3_{AD}} \\ S_{FWD3_{BA}} & S_{FWD3_{BB}} & S_{FWD3_{BC}} & S_{FWD3_{BD}} \\ S_{FWD3_{CA}} & S_{FWD3_{CB}} & S_{FWD3_{CC}} & S_{FWD3_{CD}} \\ S_{FWD3_{DA}} & S_{FWD3_{DB}} & S_{FWD3_{DC}} & S_{FWD3_{DD}} \end{pmatrix}$	$S_{REV3} = \begin{pmatrix} S_{FWD3_{CC}} & S_{FWD3_{CD}} & S_{FWD3_{CA}} & S_{FWD3_{CB}} \\ S_{FWD3_{DC}} & S_{FWD3_{DD}} & S_{FWD3_{DA}} & S_{FWD3_{DB}} \\ S_{FWD3_{AC}} & S_{FWD3_{AD}} & S_{FWD3_{AA}} & S_{FWD3_{AB}} \\ S_{FWD3_{BC}} & S_{FWD3_{BD}} & S_{FWD3_{BA}} & S_{FWD3_{BB}} \end{pmatrix}$

$S_{FWD4} = \begin{pmatrix} S_{FWD4_{AA}} & S_{FWD4_{AB}} & S_{FWD4_{AC}} & S_{FWD4_{AD}} \\ S_{FWD4_{BA}} & S_{FWD4_{BB}} & S_{FWD4_{BC}} & S_{FWD4_{BD}} \\ S_{FWD4_{CA}} & S_{FWD4_{CB}} & S_{FWD4_{CC}} & S_{FWD4_{CD}} \\ S_{FWD4_{DA}} & S_{FWD4_{DB}} & S_{FWD4_{DC}} & S_{FWD4_{DD}} \end{pmatrix}$	$S_{REV2} = \begin{pmatrix} S_{FWD2_{CC}} & S_{FWD2_{CD}} & S_{FWD2_{CA}} & S_{FWD2_{CB}} \\ S_{FWD2_{DC}} & S_{FWD2_{DD}} & S_{FWD2_{DA}} & S_{FWD2_{DB}} \\ S_{FWD2_{AC}} & S_{FWD2_{AD}} & S_{FWD2_{AA}} & S_{FWD2_{AB}} \\ S_{FWD2_{BC}} & S_{FWD2_{BD}} & S_{FWD2_{BA}} & S_{FWD2_{BB}} \end{pmatrix}$

When using a fixture which has four balanced measurement ports in a fixed arrangement, the forward fixture can be rearranged to a reverse fixture using the 16 port rearrangement shown below. It should be noted that the conversion below “swaps” the fixtures REV 2 and REV4 to avoid the need to “cross pairs” between the near and far end fixture.

$$S_{FWD} = \begin{pmatrix}
S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} & S_{17} & S_{18} & S_{19} & S_{110} & S_{111} & S_{112} & S_{113} & S_{114} & S_{115} & S_{116} \\
S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} & S_{27} & S_{28} & S_{29} & S_{210} & S_{211} & S_{212} & S_{213} & S_{214} & S_{215} & S_{216} \\
S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} & S_{37} & S_{38} & S_{39} & S_{310} & S_{311} & S_{312} & S_{313} & S_{314} & S_{315} & S_{316} \\
S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} & S_{47} & S_{48} & S_{49} & S_{410} & S_{411} & S_{412} & S_{413} & S_{414} & S_{415} & S_{416} \\
S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} & S_{57} & S_{58} & S_{59} & S_{510} & S_{511} & S_{512} & S_{513} & S_{514} & S_{515} & S_{516} \\
S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} & S_{67} & S_{68} & S_{69} & S_{610} & S_{611} & S_{612} & S_{613} & S_{614} & S_{615} & S_{616} \\
S_{71} & S_{72} & S_{73} & S_{74} & S_{75} & S_{76} & S_{77} & S_{78} & S_{79} & S_{710} & S_{711} & S_{712} & S_{713} & S_{714} & S_{715} & S_{716} \\
S_{81} & S_{82} & S_{83} & S_{84} & S_{85} & S_{86} & S_{87} & S_{88} & S_{89} & S_{810} & S_{811} & S_{812} & S_{813} & S_{814} & S_{815} & S_{816} \\
S_{91} & S_{92} & S_{93} & S_{94} & S_{95} & S_{96} & S_{97} & S_{98} & S_{99} & S_{910} & S_{911} & S_{912} & S_{913} & S_{914} & S_{915} & S_{916} \\
S_{101} & S_{102} & S_{103} & S_{104} & S_{105} & S_{106} & S_{107} & S_{108} & S_{109} & S_{1010} & S_{1011} & S_{1012} & S_{1013} & S_{1014} & S_{1015} & S_{1016} \\
S_{111} & S_{112} & S_{113} & S_{114} & S_{115} & S_{116} & S_{117} & S_{118} & S_{119} & S_{1110} & S_{1111} & S_{1112} & S_{1113} & S_{1114} & S_{1115} & S_{1116} \\
S_{121} & S_{122} & S_{123} & S_{124} & S_{125} & S_{126} & S_{127} & S_{128} & S_{129} & S_{1210} & S_{1211} & S_{1212} & S_{1213} & S_{1214} & S_{1215} & S_{1216} \\
S_{131} & S_{132} & S_{133} & S_{134} & S_{135} & S_{136} & S_{137} & S_{138} & S_{139} & S_{1310} & S_{1311} & S_{1312} & S_{1313} & S_{1314} & S_{1315} & S_{1316} \\
S_{141} & S_{142} & S_{143} & S_{144} & S_{145} & S_{146} & S_{147} & S_{148} & S_{149} & S_{1410} & S_{1411} & S_{1412} & S_{1413} & S_{1414} & S_{1415} & S_{1416} \\
S_{151} & S_{152} & S_{153} & S_{154} & S_{155} & S_{156} & S_{157} & S_{158} & S_{159} & S_{1510} & S_{1511} & S_{1512} & S_{1513} & S_{1514} & S_{1515} & S_{1516} \\
S_{161} & S_{162} & S_{163} & S_{164} & S_{165} & S_{166} & S_{167} & S_{168} & S_{169} & S_{1610} & S_{1611} & S_{1612} & S_{1613} & S_{1614} & S_{1615} & S_{1616}
\end{pmatrix} \qquad \text{(E19)}$$

$$S_{REV} = \begin{pmatrix}
S_{99} & S_{910} & S_{915} & S_{916} & S_{913} & S_{914} & S_{911} & S_{912} & S_{91} & S_{92} & S_{97} & S_{98} & S_{95} & S_{96} & S_{93} & S_{94} \\
S_{109} & S_{1010} & S_{1015} & S_{1016} & S_{1013} & S_{1014} & S_{1011} & S_{1012} & S_{101} & S_{102} & S_{107} & S_{108} & S_{105} & S_{106} & S_{103} & S_{104} \\
S_{159} & S_{1510} & S_{1515} & S_{1516} & S_{1513} & S_{1514} & S_{1511} & S_{1512} & S_{151} & S_{152} & S_{157} & S_{158} & S_{155} & S_{156} & S_{153} & S_{154} \\
S_{169} & S_{1610} & S_{1615} & S_{1616} & S_{1613} & S_{1614} & S_{1611} & S_{1612} & S_{161} & S_{162} & S_{167} & S_{168} & S_{165} & S_{166} & S_{163} & S_{164} \\
S_{139} & S_{1310} & S_{1315} & S_{1316} & S_{1313} & S_{1314} & S_{1311} & S_{1312} & S_{131} & S_{132} & S_{137} & S_{138} & S_{135} & S_{136} & S_{133} & S_{134} \\
S_{149} & S_{1410} & S_{1415} & S_{1416} & S_{1413} & S_{1414} & S_{1411} & S_{1412} & S_{141} & S_{142} & S_{147} & S_{148} & S_{145} & S_{146} & S_{143} & S_{144} \\
S_{119} & S_{1110} & S_{1115} & S_{1116} & S_{1113} & S_{1114} & S_{1111} & S_{1112} & S_{111} & S_{112} & S_{117} & S_{118} & S_{115} & S_{116} & S_{113} & S_{114} \\
S_{129} & S_{1210} & S_{1215} & S_{1216} & S_{1213} & S_{1214} & S_{1211} & S_{1212} & S_{121} & S_{122} & S_{127} & S_{128} & S_{125} & S_{126} & S_{123} & S_{124} \\
S_{19} & S_{110} & S_{115} & S_{116} & S_{113} & S_{114} & S_{111} & S_{112} & S_{11} & S_{12} & S_{17} & S_{18} & S_{15} & S_{16} & S_{13} & S_{14} \\
S_{29} & S_{210} & S_{215} & S_{216} & S_{213} & S_{214} & S_{211} & S_{212} & S_{21} & S_{22} & S_{27} & S_{28} & S_{25} & S_{26} & S_{23} & S_{24} \\
S_{79} & S_{710} & S_{715} & S_{716} & S_{713} & S_{714} & S_{711} & S_{712} & S_{71} & S_{72} & S_{77} & S_{78} & S_{75} & S_{76} & S_{73} & S_{74} \\
S_{89} & S_{810} & S_{815} & S_{816} & S_{813} & S_{814} & S_{811} & S_{812} & S_{81} & S_{82} & S_{87} & S_{88} & S_{85} & S_{86} & S_{83} & S_{84} \\
S_{59} & S_{510} & S_{515} & S_{516} & S_{513} & S_{514} & S_{511} & S_{512} & S_{51} & S_{52} & S_{57} & S_{58} & S_{55} & S_{56} & S_{53} & S_{54} \\
S_{69} & S_{610} & S_{615} & S_{616} & S_{613} & S_{614} & S_{611} & S_{612} & S_{61} & S_{62} & S_{67} & S_{68} & S_{65} & S_{66} & S_{63} & S_{64} \\
S_{39} & S_{310} & S_{315} & S_{316} & S_{313} & S_{314} & S_{311} & S_{312} & S_{31} & S_{32} & S_{37} & S_{38} & S_{35} & S_{36} & S_{33} & S_{34} \\
S_{49} & S_{410} & S_{415} & S_{416} & S_{413} & S_{414} & S_{411} & S_{412} & S_{41} & S_{42} & S_{47} & S_{48} & S_{45} & S_{46} & S_{43} & S_{44}
\end{pmatrix} \qquad \text{(E20)}$$

E.6.2 Performing 16 Port S to T transformations

The following conversion can be used to transform 16 Port Fixture matrices from S to T matrices:

$$S_{Fixtue} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} & S_{17} & S_{18} & S_{19} & S_{110} & S_{111} & S_{112} & S_{113} & S_{114} & S_{115} & S_{116} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} & S_{27} & S_{28} & S_{29} & S_{210} & S_{211} & S_{212} & S_{213} & S_{214} & S_{215} & S_{216} \\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} & S_{37} & S_{38} & S_{39} & S_{310} & S_{311} & S_{312} & S_{313} & S_{314} & S_{315} & S_{316} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} & S_{47} & S_{48} & S_{49} & S_{410} & S_{411} & S_{412} & S_{413} & S_{414} & S_{415} & S_{416} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} & S_{57} & S_{58} & S_{59} & S_{510} & S_{511} & S_{512} & S_{513} & S_{514} & S_{515} & S_{516} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} & S_{67} & S_{68} & S_{69} & S_{610} & S_{611} & S_{612} & S_{613} & S_{614} & S_{615} & S_{616} \\ S_{71} & S_{72} & S_{73} & S_{74} & S_{75} & S_{76} & S_{77} & S_{78} & S_{79} & S_{710} & S_{711} & S_{712} & S_{713} & S_{714} & S_{715} & S_{716} \\ S_{81} & S_{82} & S_{83} & S_{84} & S_{85} & S_{86} & S_{87} & S_{88} & S_{89} & S_{810} & S_{811} & S_{812} & S_{813} & S_{814} & S_{815} & S_{816} \\ S_{91} & S_{92} & S_{93} & S_{94} & S_{95} & S_{96} & S_{97} & S_{98} & S_{99} & S_{910} & S_{911} & S_{912} & S_{913} & S_{914} & S_{915} & S_{916} \\ S_{101} & S_{102} & S_{103} & S_{104} & S_{105} & S_{106} & S_{107} & S_{108} & S_{109} & S_{1010} & S_{1011} & S_{1012} & S_{1013} & S_{1014} & S_{1015} & S_{1016} \\ S_{111} & S_{112} & S_{113} & S_{114} & S_{115} & S_{116} & S_{117} & S_{118} & S_{119} & S_{1110} & S_{1111} & S_{1112} & S_{1113} & S_{1114} & S_{1115} & S_{1116} \\ S_{121} & S_{122} & S_{123} & S_{124} & S_{125} & S_{126} & S_{127} & S_{128} & S_{129} & S_{1210} & S_{1211} & S_{1212} & S_{1213} & S_{1214} & S_{1215} & S_{1216} \\ S_{131} & S_{132} & S_{133} & S_{134} & S_{135} & S_{136} & S_{137} & S_{138} & S_{139} & S_{1310} & S_{1311} & S_{1312} & S_{1313} & S_{1314} & S_{1315} & S_{1316} \\ S_{141} & S_{142} & S_{143} & S_{144} & S_{145} & S_{146} & S_{147} & S_{148} & S_{149} & S_{1410} & S_{1411} & S_{1412} & S_{1413} & S_{1414} & S_{1415} & S_{1416} \\ S_{151} & S_{152} & S_{153} & S_{154} & S_{155} & S_{156} & S_{157} & S_{158} & S_{159} & S_{1510} & S_{1511} & S_{1512} & S_{1513} & S_{1514} & S_{1515} & S_{1516} \\ S_{161} & S_{162} & S_{163} & S_{164} & S_{165} & S_{166} & S_{167} & S_{168} & S_{169} & S_{1610} & S_{1611} & S_{1612} & S_{1613} & S_{1614} & S_{1615} & S_{1616} \end{pmatrix} \quad \text{(E21)}$$

$$a = \begin{pmatrix} 0 & S_{19} & 0 & S_{110} & 0 & S_{111} & 0 & S_{112} & 0 & S_{113} & 0 & S_{114} & 0 & S_{115} & 0 & S_{116} \\ 0 & S_{29} & 0 & S_{210} & 0 & S_{211} & 0 & S_{212} & 0 & S_{213} & 0 & S_{214} & 0 & S_{215} & 0 & S_{216} \\ 0 & S_{39} & 0 & S_{310} & 0 & S_{311} & 0 & S_{312} & 0 & S_{313} & 0 & S_{314} & 0 & S_{315} & 0 & S_{316} \\ 0 & S_{49} & 0 & S_{410} & 0 & S_{411} & 0 & S_{412} & 0 & S_{413} & 0 & S_{414} & 0 & S_{415} & 0 & S_{416} \\ 0 & S_{59} & 0 & S_{510} & 0 & S_{511} & 0 & S_{512} & 0 & S_{513} & 0 & S_{514} & 0 & S_{515} & 0 & S_{516} \\ 0 & S_{69} & 0 & S_{610} & 0 & S_{611} & 0 & S_{612} & 0 & S_{613} & 0 & S_{614} & 0 & S_{615} & 0 & S_{616} \\ 0 & S_{79} & 0 & S_{710} & 0 & S_{711} & 0 & S_{712} & 0 & S_{713} & 0 & S_{714} & 0 & S_{715} & 0 & S_{716} \\ 0 & S_{89} & 0 & S_{810} & 0 & S_{811} & 0 & S_{812} & 0 & S_{813} & 0 & S_{814} & 0 & S_{815} & 0 & S_{816} \\ -1 & S_{99} & 0 & S_{910} & 0 & S_{911} & 0 & S_{912} & 0 & S_{913} & 0 & S_{914} & 0 & S_{915} & 0 & S_{916} \\ 0 & S_{109} & -1 & S_{1010} & 0 & S_{1011} & 0 & S_{1012} & 0 & S_{1013} & 0 & S_{1014} & 0 & S_{1015} & 0 & S_{1016} \\ 0 & S_{119} & 0 & S_{1110} & -1 & S_{1111} & 0 & S_{1112} & 0 & S_{1113} & 0 & S_{1114} & 0 & S_{1115} & 0 & S_{1116} \\ 0 & S_{129} & 0 & S_{1210} & 0 & S_{1211} & -1 & S_{1212} & 0 & S_{1213} & 0 & S_{1214} & 0 & S_{1215} & 0 & S_{1216} \\ 0 & S_{139} & 0 & S_{1310} & 0 & S_{1311} & 0 & S_{1312} & -1 & S_{1313} & 0 & S_{1314} & 0 & S_{1315} & 0 & S_{1316} \\ 0 & S_{149} & 0 & S_{1410} & 0 & S_{1411} & 0 & S_{1412} & 0 & S_{1413} & -1 & S_{1414} & 0 & S_{1415} & 0 & S_{1416} \\ 0 & S_{159} & 0 & S_{1510} & 0 & S_{1511} & 0 & S_{1512} & 0 & S_{1513} & 0 & S_{1514} & -1 & S_{1515} & 0 & S_{1516} \\ 0 & S_{169} & 0 & S_{1610} & 0 & S_{1611} & 0 & S_{1612} & 0 & S_{1613} & 0 & S_{1614} & 0 & S_{1615} & -1 & S_{1616} \end{pmatrix} \quad \text{(E22)}$$

$$b = \begin{pmatrix} -S_{11} & 1 & -S_{12} & 0 & -S_{13} & 0 & -S_{14} & 0 & -S_{15} & 0 & -S_{16} & 0 & -S_{17} & 0 & -S_{18} & 0 \\ -S_{21} & 0 & -S_{22} & 1 & -S_{23} & 0 & -S_{24} & 0 & -S_{25} & 0 & -S_{26} & 0 & -S_{27} & 0 & -S_{28} & 0 \\ -S_{31} & 0 & -S_{32} & 0 & -S_{33} & 1 & -S_{34} & 0 & -S_{35} & 0 & -S_{36} & 0 & -S_{37} & 0 & -S_{38} & 0 \\ -S_{41} & 0 & -S_{42} & 0 & -S_{43} & 0 & -S_{44} & 1 & -S_{45} & 0 & -S_{46} & 0 & -S_{47} & 0 & -S_{48} & 0 \\ -S_{51} & 0 & -S_{52} & 0 & -S_{53} & 0 & -S_{54} & 0 & -S_{55} & 1 & -S_{56} & 0 & -S_{57} & 0 & -S_{58} & 0 \\ -S_{61} & 0 & -S_{62} & 0 & -S_{63} & 0 & -S_{64} & 0 & -S_{65} & 0 & -S_{66} & 1 & -S_{67} & 0 & -S_{68} & 0 \\ -S_{71} & 0 & -S_{72} & 0 & -S_{73} & 0 & -S_{74} & 0 & -S_{75} & 0 & -S_{76} & 0 & -S_{77} & 1 & -S_{78} & 0 \\ -S_{81} & 0 & -S_{82} & 0 & -S_{83} & 0 & -S_{84} & 0 & -S_{85} & 0 & -S_{86} & 0 & -S_{87} & 0 & -S_{88} & 1 \\ -S_{91} & 0 & -S_{92} & 0 & -S_{93} & 0 & -S_{94} & 0 & -S_{95} & 0 & -S_{96} & 0 & -S_{97} & 0 & -S_{98} & 0 \\ -S_{101} & 0 & -S_{102} & 0 & -S_{103} & 0 & -S_{104} & 0 & -S_{105} & 0 & -S_{106} & 0 & -S_{107} & 0 & -S_{108} & 0 \\ -S_{111} & 0 & -S_{112} & 0 & -S_{113} & 0 & -S_{114} & 0 & -S_{115} & 0 & -S_{116} & 0 & -S_{117} & 0 & -S_{118} & 0 \\ -S_{121} & 0 & -S_{122} & 0 & -S_{123} & 0 & -S_{124} & 0 & -S_{125} & 0 & -S_{126} & 0 & -S_{127} & 0 & -S_{128} & 0 \\ -S_{131} & 0 & -S_{132} & 0 & -S_{133} & 0 & -S_{134} & 0 & -S_{135} & 0 & -S_{136} & 0 & -S_{137} & 0 & -S_{138} & 0 \\ -S_{141} & 0 & -S_{142} & 0 & -S_{143} & 0 & -S_{144} & 0 & -S_{145} & 0 & -S_{146} & 0 & -S_{147} & 0 & -S_{148} & 0 \\ -S_{151} & 0 & -S_{152} & 0 & -S_{153} & 0 & -S_{154} & 0 & -S_{155} & 0 & -S_{156} & 0 & -S_{157} & 0 & -S_{158} & 0 \\ -S_{151} & 0 & -S_{152} & 0 & -S_{153} & 0 & -S_{154} & 0 & -S_{155} & 0 & -S_{156} & 0 & -S_{157} & 0 & -S_{158} & 0 \end{pmatrix} \quad \text{(E23)}$$

$$T\_Fixture = Inv(b) \cdot a \quad \text{(E24)}$$

E.6.3 Performing 16 Port T to S transformations

The following conversion can be used to transform 16-port fixture matrices from T to S matrices:

$$T_{Fixtue} = \begin{pmatrix}
T_{11} & T_{12} & T_{13} & T_{14} & T_{15} & T_{16} & T_{17} & T_{18} & T_{19} & T_{110} & T_{111} & T_{112} & T_{113} & T_{114} & T_{115} & T_{116} \\
T_{21} & T_{22} & T_{23} & T_{24} & T_{25} & T_{26} & T_{27} & T_{28} & T_{29} & T_{210} & T_{211} & T_{212} & T_{213} & T_{214} & T_{215} & T_{216} \\
T_{31} & T_{32} & T_{33} & T_{34} & T_{35} & T_{36} & T_{37} & T_{38} & T_{39} & T_{310} & T_{311} & T_{312} & T_{313} & T_{314} & T_{315} & T_{316} \\
T_{41} & T_{42} & T_{43} & T_{44} & T_{45} & T_{46} & T_{47} & T_{48} & T_{49} & T_{410} & T_{411} & T_{412} & T_{413} & T_{414} & T_{415} & T_{416} \\
T_{51} & T_{52} & T_{53} & T_{54} & T_{55} & T_{56} & T_{57} & T_{58} & T_{59} & T_{510} & T_{511} & T_{512} & T_{513} & T_{514} & T_{515} & T_{516} \\
T_{61} & T_{62} & T_{63} & T_{64} & T_{65} & T_{66} & T_{67} & T_{68} & T_{69} & T_{610} & T_{611} & T_{612} & T_{613} & T_{614} & T_{615} & T_{616} \\
T_{71} & T_{72} & T_{73} & T_{74} & T_{75} & T_{76} & T_{77} & T_{78} & T_{79} & T_{710} & T_{711} & T_{712} & T_{713} & T_{714} & T_{715} & T_{716} \\
T_{81} & T_{82} & T_{83} & T_{84} & T_{85} & T_{86} & T_{87} & T_{88} & T_{89} & T_{810} & T_{811} & T_{812} & T_{813} & T_{814} & T_{815} & T_{816} \\
T_{91} & T_{92} & T_{93} & T_{94} & T_{95} & T_{T96} & T_{97} & T_{98} & T_{99} & T_{910} & T_{911} & T_{912} & T_{913} & T_{914} & T_{915} & T_{916} \\
T_{101} & T_{102} & T_{103} & T_{104} & T_{105} & T_{106} & T_{107} & T_{108} & T_{109} & T_{1010} & T_{1011} & T_{1012} & T_{1013} & T_{1014} & T_{1015} & T_{1016} \\
T_{111} & T_{112} & T_{113} & T_{114} & T_{115} & T_{116} & T_{117} & T_{118} & T_{119} & T_{1110} & T_{1111} & T_{1112} & T_{1113} & T_{1114} & T_{1115} & T_{1116} \\
T_{121} & T_{122} & T_{123} & T_{124} & T_{125} & T_{126} & T_{127} & T_{128} & T_{129} & T_{1210} & T_{1211} & T_{1212} & T_{1213} & T_{1214} & T_{1215} & T_{1216} \\
T_{131} & T_{132} & T_{133} & T_{134} & T_{135} & T_{136} & T_{137} & T_{138} & T_{139} & T_{1310} & T_{1311} & T_{1312} & T_{1313} & T_{1314} & T_{1315} & T_{1316} \\
T_{141} & T_{142} & T_{143} & T_{144} & T_{145} & T_{146} & T_{147} & T_{148} & T_{149} & T_{1410} & T_{1411} & T_{1412} & T_{1413} & T_{1414} & T_{1415} & T_{1416} \\
T_{151} & T_{152} & T_{153} & T_{154} & T_{155} & T_{156} & T_{157} & T_{158} & T_{159} & T_{1510} & T_{1511} & T_{1512} & T_{1513} & T_{1514} & T_{1515} & T_{1516} \\
T_{161} & T_{162} & T_{163} & T_{164} & T_{165} & T_{166} & T_{167} & T_{168} & T_{169} & T_{1610} & T_{1611} & T_{1612} & T_{1613} & T_{1614} & T_{1615} & T_{1616}
\end{pmatrix} \quad \text{(E25)}$$

$$a = \begin{pmatrix}
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{12} & T_{14} & T_{16} & T_{18} & T_{110} & T_{112} & T_{114} & T_{116} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{22} & T_{24} & T_{26} & T_{28} & T_{210} & T_{212} & T_{214} & T_{216} \\
0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & T_{32} & T_{34} & T_{36} & T_{38} & T_{310} & T_{312} & T_{314} & T_{316} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{42} & T_{44} & T_{46} & T_{48} & T_{410} & T_{412} & T_{414} & T_{416} \\
0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & T_{52} & T_{54} & T_{56} & T_{58} & T_{510} & T_{512} & T_{514} & T_{516} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{62} & T_{64} & T_{66} & T_{68} & T_{610} & T_{612} & T_{614} & T_{616} \\
0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & T_{72} & T_{74} & T_{76} & T_{78} & T_{710} & T_{712} & T_{714} & T_{716} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{82} & T_{84} & T_{86} & T_{88} & T_{810} & T_{812} & T_{814} & T_{816} \\
0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & T_{92} & T_{94} & T_{96} & T_{98} & T_{910} & T_{912} & T_{914} & T_{916} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{102} & T_{104} & T_{106} & T_{108} & T_{1010} & T_{1012} & T_{1014} & T_{1016} \\
0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & T_{112} & T_{114} & T_{116} & T_{118} & T_{1110} & T_{1112} & T_{1114} & T_{1116} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{122} & T_{124} & T_{126} & T_{128} & T_{1210} & T_{1212} & T_{1214} & T_{1216} \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & T_{132} & T_{134} & T_{136} & T_{138} & T_{1310} & T_{1312} & T_{1314} & T_{1316} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{142} & T_{144} & T_{146} & T_{148} & T_{1410} & T_{1412} & T_{1414} & T_{1416} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & T_{152} & T_{154} & T_{156} & T_{158} & T_{1510} & T_{1512} & T_{1514} & T_{1516} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{162} & T_{164} & T_{166} & T_{168} & T_{1610} & T_{1612} & T_{1614} & T_{1616}
\end{pmatrix} \quad \text{(E26)}$$

$$b = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -T_{11} & -T_{13} & -T_{15} & -T_{17} & -T_{19} & -T_{111} & -T_{113} & -T_{115} \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -T_{21} & -T_{23} & -T_{25} & -T_{27} & -T_{29} & -T_{211} & -T_{213} & -T_{215} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -T_{31} & -T_{33} & -T_{35} & -T_{37} & -T_{39} & -T_{311} & -T_{313} & -T_{315} \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -T_{41} & -T_{43} & -T_{45} & -T_{47} & -T_{49} & -T_{411} & -T_{413} & -T_{415} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -T_{51} & -T_{53} & -T_{55} & -T_{57} & -T_{59} & -T_{511} & -T_{513} & -T_{515} \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -T_{61} & -T_{63} & -T_{65} & -T_{67} & -T_{69} & -T_{611} & -T_{613} & -T_{615} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -T_{71} & -T_{73} & -T_{75} & -T_{77} & -T_{79} & -T_{711} & -T_{713} & -T_{715} \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -T_{81} & -T_{83} & -T_{85} & -T_{87} & -T_{89} & -T_{811} & -T_{813} & -T_{815} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -T_{91} & -T_{93} & -T_{95} & -T_{97} & -T_{99} & -T_{911} & -T_{913} & -T_{915} \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -T_{101} & -T_{103} & -T_{105} & -T_{107} & -T_{109} & -T_{1011} & -T_{1013} & -T_{1015} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -T_{111} & -T_{113} & -T_{115} & -T_{117} & -T_{119} & -T_{1111} & -T_{1113} & -T_{1115} \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -T_{121} & -T_{123} & -T_{125} & -T_{127} & -T_{129} & -T_{1211} & -T_{1213} & -T_{1215} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -T_{131} & -T_{133} & -T_{135} & -T_{137} & -T_{139} & -T_{1311} & -T_{1313} & -T_{1315} \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -T_{141} & -T_{143} & -T_{145} & -T_{147} & -T_{149} & -T_{1411} & -T_{1413} & -T_{1415} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -T_{151} & -T_{153} & -T_{155} & -T_{157} & -T_{159} & -T_{1511} & -T_{1513} & -T_{1515} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -T_{161} & -T_{163} & -T_{165} & -T_{167} & -T_{169} & -T_{1611} & -T_{1613} & -T_{1615}
\end{pmatrix} \quad \text{(E27)}$$

$$S\_Fixture = Inv(b) \cdot a \quad \text{(E28)}$$

E.7 Balun conversion

One may further process the resulting S-parameters to decompose the cross-modal parameters. The following list of steps will apply ideal baluns to the resulting S-parameters.

A generic definition of an ideal lossless mathematical balun that converts to 100Ω differential mode and a variable common mode impedance is given by:

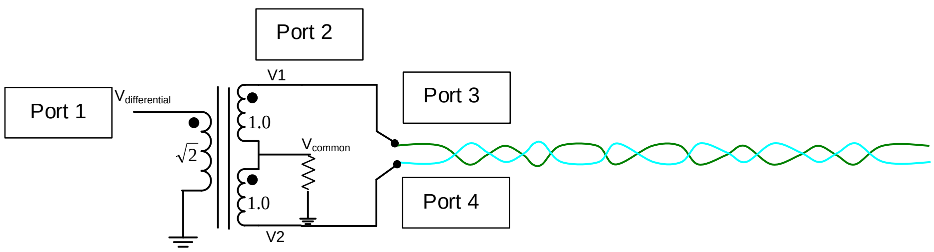


Figure E.15 - Balun schematic

$$S - Parameters = \begin{bmatrix} 0 & 0 & \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \\ 0 & \Gamma & CMTP & CMTP \\ \frac{1}{\sqrt{2}} & CMTP & TPRL & TPRL \\ \frac{-1}{\sqrt{2}} & CMTP & TPRL & TPRL \end{bmatrix} \quad \text{(E29)}$$

Note: the fixed elements are a result of converting to 100 Ohms differential impedance

$$\Gamma = \frac{\mathcal{Z}_{load} - \mathcal{Z}_{ref}}{\mathcal{Z}_{load} + \mathcal{Z}_{ref}} \quad \text{(E30)}$$

Where: $\mathcal{Z}_{load}$ = the actual common mode load of 25 Ω (two 50 Ω lines in parallel)

and $\mathcal{Z}_{ref}$ = the reference impedance of the port (e.g. 50 Ω)

From Γ, CMTP and then TPRL can be computed from the sum-to-1 rule, the square of each element in a row or column summed together equals 1.

$$\Gamma^2 + 2 * CMTP^2 = 1 \quad \text{(E31)}$$

Thus:

$$CMTP = \sqrt{\frac{1-\Gamma^2}{2}} \quad \text{(E32)}$$

Note: choose the positive root

Likewise:

$$\left(\frac{1}{\sqrt{2}}\right)^2 + CMTP^2 + 2 * TPRL^2 = 1 \quad \text{(E33)}$$

Thus:

$$TPRL = \sqrt{\frac{1-\frac{1}{2}-CMTP^2}{2}} \quad \text{(E34)}$$

Note: TPRL has to opposite sign as Γ

Converting the single end measurements to mixed mode measurements with a reference impedance of 100Ω Differential mode and 50Ω Common mode, the 4 port balun equation is given by:

$$4\text{ Port } Balun\ Matrix\ Fwd\ (100\ Differntial\ 50\ Common) = S_{BAL} = \begin{pmatrix} (0) & (0) & \left(\frac{1}{\sqrt{2}}\right) & \left(\frac{-1}{\sqrt{2}}\right) \\ (0) & \left(\frac{-1}{3}\right) & \left(\frac{2}{3}\right) & \left(\frac{2}{3}\right) \\ \left(\frac{1}{\sqrt{2}}\right) & \left(\frac{2}{3}\right) & \left(\frac{1}{6}\right) & \left(\frac{1}{6}\right) \\ \left(\frac{-1}{\sqrt{2}}\right) & \left(\frac{2}{3}\right) & \left(\frac{1}{6}\right) & \left(\frac{1}{6}\right) \end{pmatrix} \qquad \text{(E35)}$$

Arranging the 4 port balun equation in a 16 port manner gives:

$$16\ Port\ Balun\ Matrix\ Fwd\ = \begin{pmatrix}
S_{BAL_{11}} & S_{BAL_{12}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{13}} & S_{BAL_{14}} & 0 & 0 & 0 & 0 & 0 & 0 \\
S_{BAL_{21}} & S_{BAL_{22}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{23}} & S_{BAL_{24}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & S_{BAL_{11}} & S_{BAL_{12}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{13}} & S_{BAL_{14}} & 0 & 0 & 0 & 0 \\
0 & 0 & S_{BAL_{21}} & S_{BAL_{22}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{23}} & S_{BAL_{24}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & S_{BAL_{11}} & S_{BAL_{12}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{13}} & S_{BAL_{14}} & 0 & 0 \\
0 & 0 & 0 & 0 & S_{BAL_{21}} & S_{BAL_{22}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{23}} & S_{BAL_{24}} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{11}} & S_{BAL_{12}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{13}} & S_{BAL_{14}} \\
0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{21}} & S_{BAL_{22}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{23}} & S_{BAL_{24}} \\
S_{BAL_{31}} & S_{BAL_{32}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{33}} & S_{BAL_{34}} & 0 & 0 & 0 & 0 & 0 & 0 \\
S_{BAL_{41}} & S_{BAL_{42}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{43}} & S_{BAL_{44}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & S_{BAL_{31}} & S_{BAL_{32}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{33}} & S_{BAL_{34}} & 0 & 0 & 0 & 0 \\
0 & 0 & S_{BAL_{41}} & S_{BAL_{42}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{43}} & S_{BAL_{44}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & S_{BAL_{31}} & S_{BAL_{32}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{33}} & S_{BAL_{34}} & 0 & 0 \\
0 & 0 & 0 & 0 & S_{BAL_{41}} & S_{BAL_{42}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{43}} & S_{BAL_{44}} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{31}} & S_{BAL_{32}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{33}} & S_{BAL_{34}} \\
0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{41}} & S_{BAL_{42}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{43}} & S_{BAL_{44}}
\end{pmatrix} \qquad \text{(E36)}$$

$$16\ Port\ Balun\ Matrix\ Rev\ = \begin{pmatrix}
S_{BAL_{33}} & S_{BAL_{34}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{31}} & S_{BAL_{32}} & 0 & 0 & 0 & 0 & 0 & 0 \\
S_{BAL_{43}} & S_{BAL_{44}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{41}} & S_{BAL_{42}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & S_{BAL_{33}} & S_{BAL_{34}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{31}} & S_{BAL_{32}} & 0 & 0 & 0 & 0 \\
0 & 0 & S_{BAL_{43}} & S_{BAL_{44}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{41}} & S_{BAL_{42}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & S_{BAL_{33}} & S_{BAL_{34}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{31}} & S_{BAL_{32}} & 0 & 0 \\
0 & 0 & 0 & 0 & S_{BAL_{43}} & S_{BAL_{44}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{41}} & S_{BAL_{42}} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{33}} & S_{BAL_{34}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{31}} & S_{BAL_{32}} \\
0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{43}} & S_{BAL_{44}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{41}} & S_{BAL_{42}} \\
S_{BAL_{13}} & S_{BAL_{14}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{11}} & S_{BAL_{12}} & 0 & 0 & 0 & 0 & 0 & 0 \\
S_{BAL_{23}} & S_{BAL_{24}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{21}} & S_{BAL_{22}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & S_{BAL_{13}} & S_{BAL_{14}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{11}} & S_{BAL_{12}} & 0 & 0 & 0 & 0 \\
0 & 0 & S_{BAL_{23}} & S_{BAL_{24}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{21}} & S_{BAL_{22}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & S_{BAL_{13}} & S_{BAL_{14}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{11}} & S_{BAL_{12}} & 0 & 0 \\
0 & 0 & 0 & 0 & S_{BAL_{23}} & S_{BAL_{24}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{21}} & S_{BAL_{22}} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{13}} & S_{BAL_{14}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{11}} & S_{BAL_{12}} \\
0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{23}} & S_{BAL_{24}} & 0 & 0 & 0 & 0 & 0 & 0 & S_{BAL_{21}} & S_{BAL_{22}}
\end{pmatrix} \qquad \text{(E34)}$$

1. Create a single 16-port S-Parameter matrix of 4 baluns for the forward side
2. Convert the 16 by 16 matrix from step (1)into a T-Parameter matrix (Call this matrix M)
3. Create a single 16-port S-Parameter matrix of 4 baluns for the reverse side
4. Convert the 16 by 16 matrix from step (3) into a T-Parameter matrix (Call this matrix N)
5. Multiply matrices M, T_{DUT}, and N in order
6. Convert the 16 by 16 matrix from step 5 into an S-Parameter matrix

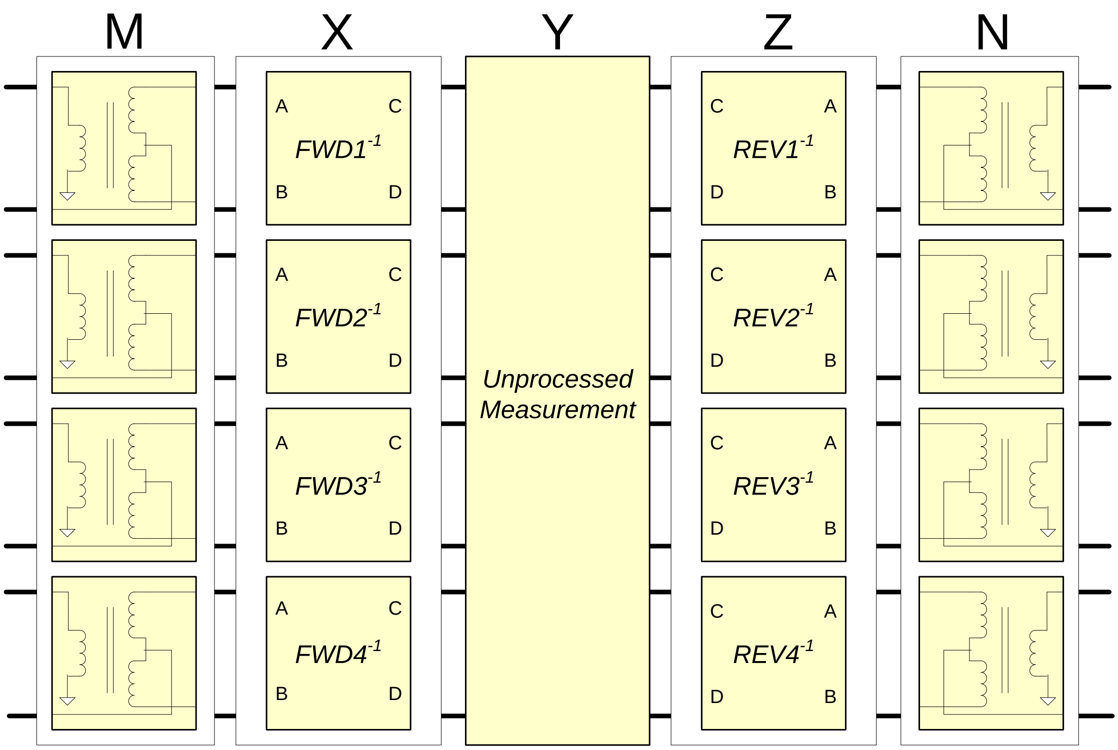


Figure E.16 - Illustration for cascading de-embedding matrices and ideal baluns

When using the mathematics described in clause E.7, the S16P output file would take the format describes in Table E.3.

Table E.3 Balun conversion S16P port identification

Port #	Description
1	DM port for pair connected to FWD1
2	CM port for pair connected to FWD1
3	DM port for pair connected to FWD2
4	CM port for pair connected to FWD2
5	DM port for pair connected to FWD3
6	CM port for pair connected to FWD3
7	DM port for pair connected to FWD4
8	CM port for pair connected to FWD4
9	DM port for pair connected to REV1
10	CM port for pair connected to REV1
11	DM port for pair connected to REV2
12	CM port for pair connected to REV2
13	DM port for pair connected to REV3
14	CM port for pair connected to REV3
15	DM port for pair connected to REV4
16	CM port for pair connected to REV4