Touchstone® File Format Specification

Version 2.1

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INTRODUCTION

A Touchstone file (also known as an SnP file) is an ASCII text file used for documenting the n-port network parameter data of an active device or passive interconnect network. While Touchstone files have been accepted as a de facto standard for the transfer of frequency dependent *n*-port parameters, up until the release of the Touchstone 2.0 document, no formal specification of the file format or syntax had been produced. The Touchstone 2.0 document, based upon information from Agilent Technologies, Inc. (the originator of Touchstone), was a formal specification of the Touchstone file format and was intended for use with documents and specifications produced by the IBIS Open Forum.

Version 2.0 was created based upon the original Agilent Technologies, Inc. documentation with added features in the style of IBIS (I/O Buffer Information Specification). Files written using the original syntax are compatible with the Version 2.0 specification and are referred to as Version 1.0 files, even though a Version 1.0 specification was never published.

In this document Version 1.0 is an *internal* designation for files which use the option line syntax that supports at most a single reference resistance for all ports.

Version 1.1 is an *internal* designation for files which use the option line syntax that supports independent reference resistances per port. Note that Version 1.0 or Version 1.1 files may require formatting changes and potentially numerical recalculation of some non-S-parameter data for conversion to Version 2.0 or 2.1 files.

In this document, if no differences are noted by a Version 1.1 rule, the statements designated as Version 1.0 also apply for Version 1.1 files.

Version 2.1 was created to make corrections to several examples, clarify the filename extensions used for Touchstone files, and permit more flexible definitions for network data reference resistances.

Except for the [Version] string argument "2.1" as described in this document, [Version] 2.1 files are identical to [Version] 2.0 files.

GENERAL SYNTAX RULES AND GUIDELINES

The following are the general syntax rules and guidelines for a Touchstone file.

1. Touchstone files are case-insensitive.

2. Only US-ASCII

   a)   graphic characters (i.e., code values 20h through 7Eh),
   b)   tab characters (09h), and
   c)   line termination sequences, e.g., LF (0Ah), CR+LF (0Dh + 0Ah), or CR (0Dh),

   each encoded in 8 bits as defined in ISO/IEC 8859-1:1998 are permitted in a Touchstone file.

3. Comments are preceded by an exclamation mark (!). Comments may appear on a separate line or after the last data value on a line. Comments are terminated by a line termination sequence (i.e., multi-line comments are not allowed).

4. Touchstone filenames have traditionally used a file extension of ".snp", where n is the number of network ports of the device or interconnect being described. For example, a Touchstone file containing the network parameters for a 2-port device would be named "filename.s2p", while a Touchstone file containing the data for a 3-port network would be named "filename.s3p", and so on.

   Since not all operating systems may recognize filename extensions with variable contents or length as a certain file type, the extension ".ts" is suggested for all versions of Touchstone files. However, to ensure maximum compatibility across operating systems and applications, the use of filename extensions other than those mentioned here is permitted by this specification.

   For Version 2.0 and Version 2.1 files, the [Number of Ports] keyword and argument establish the expected number of ports defined in the file.

5. All angles are measured in degrees.

6. Scientific notation is allowed (e.g., 1.2345e-12). No minimum or maximum limits are placed on numerical precision on individual data points.

7. Keywords (as used in Version 2.0 and Version 2.1 files) shall be enclosed in square brackets, "[" and "]", and shall start in column 1 of the line. No space or tab is allowed immediately after the opening bracket "[" or immediately before the closing bracket "]". The keyword syntax, including spelling of words and placement of non-alphabetic characters, shall follow exactly what is documented in this specification. If used, only one space (" ") or dash ("-") character separates the parts of a multi-word keyword.

8. Arguments after keywords shall be separated from the closing bracket of the keyword by at least one whitespace character. Except where otherwise noted, this whitespace separation shall not include carriage return or line feed characters.

9. Blank lines are permitted.

FILE FORMAT DESCRIPTION

Introduction

Touchstone data files consist of an "option line" followed by network parameters taken at specific frequencies. The option line specifies (among other things) the kind of *n*-port parameters the file contains (S-parameter, Z-parameter, etc.) and the format of the network data values (magnitude-phase, real-imaginary, etc.). Data is arranged into groups of *n*-port parameters preceded by the frequency at which the data was taken or derived. For each frequency, data for a 1-port or 2-port network is contained on a single data line while data for 3-port and above networks is arranged in a matrix row-wise order. The Touchstone format supports matrices of unlimited size.

Some keywords are required to be in a particular order and placed at the beginning of the file. These are shown below:

- [Version]   (required)
- # (option line)   (required)
- [Number of Ports]   (required)

The following keywords shall appear after [Number of Ports] and before [Network Data] but may appear in any order relative to each other.

- [Two-Port Data Order]   (required if a 2-port system is described)
- [Number of Frequencies]   (required)
- [Number of Noise Frequencies] (required if [Noise Data] is defined)
- [Reference]   (optional)
- [Matrix Format]   (optional)
- [Mixed-Mode Order]   (optional)
- [Begin Information]/[End Information]   (optional)

The Touchstone data in Version 2.0 and Version 2.1 files is positioned under two required keywords in the order shown below. Network data is required and positioned after the required [Network Data] keyword. The [End] keyword marks the end of the file and is placed last.

- [Network Data]   (required)
- [Noise Data]   (required only if [Number of Noise Frequencies] is given)
- [End]   (required)

Network data represents either conventional *n*-port parameters (corresponding to what is referred to as single-ended port configuration) or mixed-mode parameters associated with differential port configurations. The mixed-mode parameters may be the generalized mixed-mode parameters if not all single-ended ports are combined into differential ports. A differential port is formed from two single-ended ports having the same "reference" terminal (also referred to as the "-" terminal).

In addition to the above information (option lines, keywords, and network data), files that describe 2-port devices may also contain noise parameter data. Comment lines may be interspersed in the file as necessary.

These keywords and data formats are described in detail in the following sections.

Comment Lines

Touchstone data files may include comments. Comments are preceded by an exclamation mark (!). Comments may appear on a separate line, or after the last data value on a line. Comments are terminated by a line termination sequence or character (i.e., multi-line comments are not allowed).

The syntax rules for comments are identical for Version 1.0, Version 1.1, Version 2.0 and Version 2.1 files.

[Version]

Rules for Version 1.0 and Version 1.1 files:
The [Version] keyword is not permitted for Version 1.0 and Version 1.1 files.

Rules for Version 2.0 and Version 2.1 files:
The [Version] keyword is required with a string argument of "2.1" or "2.0" (without the quotation marks).
Note the syntax and rules are identical between [Version] 2.1 and 2.0 Touchstone files, so it does not make a difference which of these two arguments is used for the [Version] keyword in Touchstone files.

Each Touchstone Version 2.0 and Version 2.1 file shall contain one [Version] keyword and argument. These shall precede all other non-comment, non-blank lines. Both the opening and closing brackets are required. The [Version] keyword is followed by one string argument. The argument shall be preceded by whitespace.

The [Version] keyword provides information on the Version of the specification under which the file contents should be interpreted.

Option Line

For Version 1.0, Version 1.1, Version 2.0 and Version 2.1 files:
Each Touchstone data file shall contain an option line (additional option lines after the first one shall be ignored). The option line is formatted as follows:

<frequency unit> <parameter> <format> R *<n>*

where
#	marks the beginning of the option line.
frequency unit	specifies the unit of frequency. Legal values are Hz, kHz, MHz, and GHz. The default value is GHz.
parameter	specifies what kind of network parameter data is contained in the file. Legal values are: S for Scattering parameters, Y for Admittance parameters, Z for Impedance parameters, H for Hybrid-h parameters, G for Hybrid-g parameters. The default value is S.
format	specifies the format of the network parameter data pairs. Legal values are: DB for decibel-angle (decibel = $20 \times \log_{10}\lvert magnitude \rvert$) MA for magnitude-angle, RI for real-imaginary. Angles are given in degrees. Note that this format does not apply to noise parameters (refer to the "Noise Parameter Data" section later in this specification). The default value is MA.

For Version 1.0 files:

R n specifies the reference resistance in ohms, where n is a real, positive number. If R is omitted, the default reference resistance is 50 ohms for all ports.

For Version 1.1 files:

R n_1 ... n_p specifies the reference resistances in ohms, where the character "R" is followed by p real, positive numbers, where p is equal to the number of ports represented in the file. For Version 1.1 files, the character "R" shall be followed by as many values as the number of ports to serve as the per port reference resistance for each port, matched by order. In addition, for Version 1.1 files, "R" and the p values following it shall be placed at the end of the option line.

For Version 2.0 and Version 2.1 files:

R n specifies the reference resistance in ohms, where n is a real, positive number. For Version 2.0 and Version 2.1 files, this is overridden by the [Reference] keyword, if it exists, as described below. Note that, for Version 2.0 and Version 2.1 files, independent references per port are only supported through the [Reference] keyword.

For Version 1.0, Version 1.1, Version 2.0 and Version 2.1 files, option line parameters are separated by one or more whitespaces; the option line itself is terminated with a line termination sequence or character. If a parameter is missing, the default value is assumed. With the exception of the opening # (hash mark) character and the multi-valued per port reference resistance parameter ("R n_1 ... n_p"), option line parameters may appear in any order.

Rules for Version 1.0, Version 2.0, and Version 2.1 files:
In summary, the option line should read:

For 1-port files: # [Hz|kHz|MHz|GHz] [S|Y|Z] [DB|MA|RI] [R n]
For 2-port files: # [Hz|kHz|MHz|GHz] [S|Y|Z|G|H] [DB|MA|RI] [R n]
For 3-port and beyond files: # [Hz|kHz|MHz|GHz] [S|Y|Z] [DB|MA|RI] [R n]
For mixed-mode files: # [Hz|kHz|MHz|GHz] [S|Y|Z] [DB|MA|RI] [R n]

where the square brackets ("[", "]") indicate optional information; ...|...|...| means to select one of the choices; and n is replaced by a positive integer or floating-point number.

The one and only one reference resistance value specified in the option line applies to the network data for all ports, if [Reference] is not present.

Though specific cases are used for the units above and throughout this specification (e.g., "kHz"), Touchstone files are case-insensitive.

Rules for Version 1.1 files:
In summary, the option line should read:

For 1-port files: # [Hz|kHz|MHz|GHz] [S|Y|Z] [DB|MA|RI] [R n_1 ... n_p]
For 2-port files: # [Hz|kHz|MHz|GHz] [S|Y|Z|G|H] [DB|MA|RI] [R n_1 ... n_p]
For 3-port and beyond files: # [Hz|kHz|MHz|GHz] [S|Y|Z] [DB|MA|RI] [R n_1 ... n_p]
For mixed-mode files: # [Hz|kHz|MHz|GHz] [S|Y|Z] [DB|MA|RI] [R n_1 ... n_p]

where the square brackets ("[", "]") indicate optional information; ...|...|...| means to select one of the choices; and n_1 through n_p are replaced by positive integers or floating-point numbers. Though specific cases are used for the units above and throughout this specification (e.g., "kHz"), Touchstone files are case-insensitive.

Though specific cases are used for the units above and throughout this specification (e.g., "kHz"), Touchstone files are case-insensitive.

Rules for Version 1.0 and Version 1.1 files:
For Version 1.0 and Version 1.1 files, the option line shall precede any data lines and shall be the first non-comment, non-blank line in the file.

The option line reference resistance defines the reference for the S-parameter data and the normalization used on G-, H-, Y-, and Z-parameter data in Version 1.0 and Version 1.1 files.

Rules for Version 2.0 and Version 2.1 files:
For Version 2.0 and Version 2.1 files, the option line shall follow the [Version] keyword and argument and precede the [Number of Ports] keyword and argument.

For Version 2.0 and Version 2.1 files, the option line reference resistance defines the reference for the S-parameter data if the [Reference] keyword is not present. Network data for G-, H-, Y- and Z-parameters in Version 2.0 and Version 2.1 files is not normalized. Therefore, the option line reference resistance and [Reference] keyword have no impact on G-, H-, Y-, or Z-parameter data in Version 2.0 or Version 2.1 files. S-parameters are, by definition, normalized with respect to the reference resistance(s) and in this respect there is no difference between the treatment of S-parameters in Version 1.0, Version 1.1, Version 2.0 and Version 2.1 files. However, unlike Version 1.0 files, the S-parameters in Version 2.0 and Version 2.1 files are additionally affected by the presence of different port reference resistances. Touchstone files use the power wave definitions of the incident and reflected waves [1-3], as

incident waves:
$$a_i = (V_i + R_i I_i)/(2\sqrt{R_i})$$

reflected waves:
$$b_i = (V_i - R_i I_i)/(2\sqrt{R_i})$$

where i is the port index, R_i is the i-th port reference resistance, and V_i and I_i are the i-th port RMS voltage and current phasors, respectively. In Version 1.0 files all the reference resistances are equal and therefore the square root factors cancel out for

$$S_{ij} = b_j/a_i$$

If the [Mixed-Mode Order] keyword is present, mixed-mode network parameters are used in the file. Mixed-mode parameters are only supported for S-, Y-, and Z-parameter data.

Rules for Version 1.0, Version 2.0, and Version 2.1 files:
Per the defaults above, an empty option line (a single hash mark without any non-comment characters following it) in a Version 1.0 file would indicate that the file uses GHz units for frequency, single-ended S-parameters for the network data, magnitude-angle (MA) for the network data format and 50 ohms as the reference or normalization resistance. In a Version 2.0 or Version 2.1 file, the same defaults apply, except that no normalization is assumed on G-, H-, Y-, or Z-parameter data and the [Reference] keyword and argument(s) would supersede the 50-ohm reference resistance assumption.

Option Line Examples

For Version 1.0, Version 2.0, and Version 2.1 files:
Minimum required option line example, using all default values:
#

Frequency in GHz, S-parameters in real-imaginary format, referenced to 100 ohms:

```
# GHz S RI R 100
```

Different ordering from the previous example:
```
# S R 100 GHz RI
```

Frequency in kHz, Y-parameters in real-imaginary format, normalized to 100 ohms:
```
# kHz Y RI R 100
```

Frequency in Hz, Z-parameters in magnitude-angle format, normalized to 10 ohms:
```
# Hz Z MA R 10
```

Frequency in kHz, H-parameters in real-imaginary format normalized to 1 ohm:
```
# kHz H RI R 1
```

Frequency in MHz, G-parameters in decibel format normalized to 1 ohm:
```
# MHz G DB R 1
```

For Version 1.1 files:
Frequency in GHz, S-parameters in real-imaginary format, for a two-port network where port 1 is referenced to 0.1 ohm and port 2 is referenced to 75 ohms (note that R n_1 ... n_p is positioned as the last option line entry):
```
# S GHz RI R 0.1 75.0
```


[Number of Ports]

Rules for Version 1.0 and Version 1.1 files:
The [Number of Ports] keyword is not permitted in Version 1.0 and Version 1.1 files.

Rules for Version 2.0 and Version 2.1 files:
Each Touchstone Version 2.0 and Version 2.1 file shall contain one and only one [Number of Ports] keyword and argument. The [Number of Ports] keyword and argument define the number of single-ended ports represented by the network data in the file.

The [Number of Ports] keyword is followed by a single positive integer argument, separated from the keyword by whitespace.

The [Number of Ports] keyword is required for Version 2.0 and Version 2.1 files. It shall be the first keyword after the option line.

Example 1:
```
! 4-port S-parameter data
[Version] 2.1
# GHz S MA R 50
[Number of Ports] 4
```


[Two-Port Data Order]

Rules for Version 1.0 and Version 1.1 files:
The [Two-Port Data Order] keyword is not permitted in Version 1.0 and Version 1.1 files.

Rules for Version 2.0 and Version 2.1 files:
The [Two-Port Data Order] keyword is required only when the argument for the [Number of Ports] keyword is 2. Otherwise, it is not permitted. When required, the [Two-Port Data Order] keyword and

argument shall appear after the [Number of Ports] keyword and argument and before any network data. Multiple [Two-Port Data Order] keywords in the same file are not permitted.

The [Two-Port Data Order] keyword, in brackets as shown, is followed by one of two string arguments separated from the keyword by whitespace: 12_21 or 21_12.

The [Two-Port Data Order] keyword is used to signify the column ordering convention. The Version 1.0 and Version 1.1 convention for 2-port network data is N_{11}, N_{21}, N_{12}, N_{22}, where N_{11}, N_{12}, etc., represent pairs of data entries. However, some tools and users have adopted the convention N_{11}, N_{12}, N_{21}, N_{22} (a more natural order consistent with all the other n-port ordering conventions). The keyword makes the ordering of 2-port network data explicit and unambiguous in Version 2.0 and Version 2.1 files.

[Number of Frequencies]

Rules for Version 1.0 and Version 1.1 files:
The [Number of Frequencies] keyword is not permitted in Version 1.0 files.

Rules for Version 2.0 and Version 2.1 files:
The [Number of Frequencies] keyword and argument specify the number of frequency points, and therefore blocks of network parameters, listed in the file.

The [Number of Frequencies] keyword, in brackets as shown, shall be followed by an integer greater than 0.

The [Number of Frequencies] keyword is required in Version 2.0 and Version 2.1 files.

[Number of Frequencies] shall appear after the [Number of Ports] keyword and before any network data.

[Number of Frequencies] has no impact on noise parameters.

Example 2:
```
! 1-port Z-parameter file, multiple frequency points
[Version] 2.1
# MHz Z MA
[Number of Ports] 1
[Number of Frequencies] 5
```

[Number of Noise Frequencies]

Rules for Version 1.0 and Version 1.1 files:
The [Number of Noise Frequencies] keyword is not permitted in Version 1.0 and Version 1.1 files.

Rules for Version 2.0 and Version 2.1 files:
The [Number of Noise Frequencies] keyword and argument specify the number of noise frequency points, and therefore blocks of noise parameters, listed in the file.

The [Number of Noise Frequencies] keyword, in brackets as shown, shall be followed by an integer greater than 0.

The [Number of Noise Frequencies] keyword is required in Version 2.0 and Version 2.1 files only if noise parameter data is provided.

[Number of Noise Frequencies] shall appear after the [Number of Ports] keyword and before any network data.

Example 3:
```
! 2-port network, S-parameter and noise data
! Default MA format, GHz frequencies, 50-ohm reference, S-parameters
[Version] 2.1
#
[Number of Ports] 2
[Two-Port Data Order] 21_12
[Number of Frequencies] 2
[Number of Noise Frequencies] 2
```


[Reference]

Rules for Version 1.0 and Version 1.1 files:
The [Reference] keyword is not permitted in Version 1.0 and Version 1.1 files.

Rules for Version 2.0 and Version 2.1 files:
The [Reference] keyword and associated argument(s) provide a per-port definition of the reference environment used for the S-parameter measurements in the network data. They shall appear only once in the file.

The [Reference] keyword, in brackets as shown, shall be followed by one or more positive integer or floating-point numbers as arguments, separated from the keyword and each other by whitespace. [Reference] arguments shall not be mixed with arguments for any other keyword in the file. [Reference] and its arguments may span multiple lines.

Each of the arguments is a real-valued impedance (i.e., a resistance) and is assumed to be ordered per port numerically starting at 1 and ending with the value listed under [Number of Ports] (e.g., if [Number of Ports] contains the value "5", five arguments are expected under [Reference], ordered starting with port 1's reference resistance and ending with port 5's reference resistance). The [Reference] keyword arguments assume and refer to single-ended ports.

The units of the [Reference] argument reference resistances are ohms.

[Reference] shall only appear after the [Number of Ports] keyword and before any network data.

Note that complex and imaginary impedance values are not supported.

[Reference] is optional. If [Reference] is not present, the reference resistances for the S-parameter data are assumed to be defined by the option line. If [Reference] is present, it shall contain a reference resistance argument for every port represented in the data (for example, a 4-port data file using [Reference] shall contain four [Reference] resistance arguments).

The [Reference] keyword has no impact on G-, H-, Y-, or Z-parameter data.

[Reference] arguments may begin on the line following the closing bracket of the keyword (in other words, after a line termination character or sequence).

Example 4:
```
! 4-port S-parameter data
! Option line reference resistance is overridden by [Reference]
```

```
! Data cannot be represented using 1.0 syntax,
! but can be represented using 1.1 syntax
! Note that the [Reference] keyword arguments appear on a separate line
[Version] 2.1
# GHz S MA R 50
[Number of Ports] 4
[Reference]
50 75 0.01 0.01
[Number of Frequencies] 1
```

Example 5 (Version 1.1):
```
! 4-port S-parameter data
! Per port reference provided using Version 1.1 syntax
# GHz S MA R 0.01 0.01 50.0 50.0
```

[Matrix Format]

Rules for Version 1.0 and Version 1.1 files:
The [Matrix Format] keyword is not permitted in Version 1.0 and Version 1.1 files.

Rules for Version 2.0 and Version 2.1 files:
The [Matrix Format] keyword and argument specify whether an entire matrix or a subset of all matrix elements is given for single-ended data. The latter case is applicable to symmetric matrices for which either only the lower triangular part (including the diagonal), or only the upper triangular part (including the diagonal) is included. This assumption is most appropriate for interconnects. Note that all ports are always represented, but the format for the data takes advantage of symmetry to reduce the overall file size.

The [Matrix Format] keyword, in brackets as shown, shall be followed by one of three possible string arguments: "Full", "Lower", or "Upper".

[Matrix Format] shall appear after the [Number of Ports] keyword and before any network data.

[Matrix Format] is optional. If [Matrix Format] is not present, the network data included in the file is assumed to be of type "Full" and the network data for each port as specified under [Number of Ports] shall be specified for each frequency point.

[Matrix Format] has no effect on noise data.

[Network Data]

Rules for Version 1.0 and Version 1.1 files:
The [Network Data] keyword is not permitted in Version 1.0 and Version 1.1 files.

Rules for Version 2.0 and Version 2.1 files:
The [Network Data] keyword explicitly identifies the beginning of the network data in a Touchstone 2.0 file. Each Touchstone Version 2.0 and Version 2.1 file shall contain one and only one [Network Data] keyword.

The [Network Data] keyword is required for Version 2.0 and Version 2.1 files. It shall appear after the [Number of Ports] keyword and immediately before any network data.

Example 6:

```
! 4-port S-parameter data
! The option line reference resistance is overridden by the [Reference]
! keyword arguments
! Data cannot be represented using 1.0 syntax
! but can be represented using 1.1 syntax
[Version] 2.1
# GHz S MA R 50
[Number of Ports] 4
[Number of Frequencies] 1
[Reference] 50 75 0.01 0.01
[Matrix Format] Full
[Network Data]
5.00000 0.60 161.24 0.40 -42.20 0.42 -66.58 0.53 -79.34 ! row 1
        0.40 -42.20 0.60 161.20 0.53 -79.34 0.42 -66.58 ! row 2
        0.42 -66.58 0.53 -79.34 0.60 161.24 0.40 -42.20 ! row 3
        0.53 -79.34 0.42 -66.58 0.40 -42.20 0.60 161.24 ! row 4
[End]
```

Example 7:
```
! 4-port S-parameter data
! The option line reference resistance is overridden by the [Reference]
! keyword arguments
! Note that [Reference] arguments are split across two lines
! Data cannot be represented using 1.0 syntax
! but can be represented using 1.1 syntax
[Version] 2.1
# GHz S MA R 50
[Number of Ports] 4
[Number of Frequencies] 1
[Reference] 50 75
0.01 0.01
[Matrix Format] Lower
[Network Data]
5.00000 0.60 161.24                                     ! row 1
        0.40 -42.20 0.60 161.20                         ! row 2
        0.42 -66.58 0.53 -79.34 0.60 161.24             ! row 3
        0.53 -79.34 0.42 -66.58 0.40 -42.20 0.60 161.24 ! row 4
[End]
```

Example 8:
```
! 1-port Z-parameter file, multiple frequency points
[Version] 2.1
# MHz Z MA
[Number of Ports] 1
[Number of Frequencies] 5
[Reference] 20.0
[Network Data]
! freq   magZ11 angZ11
100     74.25    -4
200     60      -22
300     53.025  -45
400     30      -62
500      0.75   -89
[End]
```

Single-Ended Network Parameter Data

Following the option line (Version 1.0 and Version 1.1 files) or [Network Data] keyword (Version 2.0 and Version 2.1 files) are the network parameters (S-parameter, Z-parameter, etc.) of the type specified by the option line. Groups of *n*-port parameters are preceded by the frequency value for which the data was obtained, and the *n*-port parameters themselves are formatted as pairs of values (magnitude-angle, dB-angle or real-imaginary).

Network data is grouped into one or more lines which end with a line termination character or sequence. In Version 1.0 and Version 1.1 files, for each frequency, *n*-port parameters for 1-port and 2-port networks are contained on one data line, while data for 3-port and larger networks are arranged on multiple data lines in a matrix row-wise order.

In summary, there are five general rules for formatting network data into lines:

1. In Version 1.0 and Version 1.1 files, no more than four pairs of *n*-port parameters are allowed per network data line. No restriction exists on the number of data pairs on a line in Version 2.0 and Version 2.1files.
2. Individual network data entries are separated by whitespace.
3. A network data line is terminated by a line termination character.
4. All network data lines shall be arranged in increasing order of frequency.
5. Frequency values shall only appear at the beginning of lines, after the line termination sequence or character.

Detailed descriptions for arranging the data for various *n*-port networks follow.

Note that H- and G-parameters are defined for 2-port networks only. These hybrid parameters cannot be used to describe networks containing any other number of ports.

Rules for Version 2.0 and Version 2.1 files:
In Version 2.0 and Version 2.1 files, the data associated with any one frequency may be split across any number of lines or may be placed on a single line of arbitrary length. Network data in a Version 2.0 or Version 2.1 file is parsed using the [Number of Ports] keyword and argument and the [Matrix Format] keyword and argument. For a Full matrix, a new frequency point is expected every $2n^2 + 1$ values, where *n* is the number of ports, regardless of intervening line termination sequences or characters. For a Lower or Upper matrix, a new frequency point is expected every $n^2 + n + 1$ values.

Frequency points and the data that follows them may be in integer, floating point or scientific notation. If in floating point format, a single leading zero (i.e., a zero before the decimal point) may be present or omitted.

Note that data is represented in mixed-mode format when the [Mixed-Mode Order] keyword is present. Traditional (conventional) single-ended data used in Touchstone Version 1.0 and Version 1.1 files and the mixed-mode representation are mutually exclusive; the same file shall not contain both as separate sets of data, since the [Mixed-Mode Order] keyword and associated data may include single-ended network parameters.

1-port and 2-port Networks

Network parameter data for 1-port and 2-port networks at a single frequency may be contained on a single data line. As shown below, the data line consists of a frequency value followed by either one or four pairs of data values.

1-port data (line)

<frequency value> *<N_{11}>*

2-port data (line)
<frequency value> *<N_{11}>* *<N_{21}>* *<N_{12}>* *<N_{22}>*

where
frequency value   frequency at which the network parameter data was taken or derived.

N_{11}, N_{21}, N_{12}, N_{22} network parameter data points, where *Nij* represents a pair of data values.

Note that Version 2.0 and Version 2.1 files containing 2-port network data require the [Two-Port Data Order] keyword with the argument 21_12 to designate the order above. Use of the [Two-Port Data Order] keyword with the argument 12_21 permits the alternate order, shown below, to be used.

2-port data (line)
<frequency value> *<N_{11}>* *<N_{12}>* *<N_{21}>* *<N_{22}>*

where
frequency value   frequency at which the network parameter data was taken or derived.

N_{11}, N_{12}, N_{21}, N_{22} network parameter data points, where *Nij* represents a pair of data values.

Network parameter data points shall be in magnitude-angle, dB-angle or real-imaginary format (i.e., pairs of values) as specified by the option line. For 1-port networks, only "11" data is allowed for Full, Upper, or Lower format.

For Full 2-port networks, all four port data pairs are required. If [Matrix Format] is specified as Lower or Upper, 2-port network data includes only "11", "21", and "22" data, in that order (as "21" and "12" are assumed identical, Lower and Upper 2-port network data matrices are identical).

All entries in a data line are separated by one or more whitespace characters; a data line itself is terminated by a line termination sequence or character. Multiple data lines are allowed but, as mentioned above, they shall be arranged in increasing order of frequency.

Shown below are some examples of Touchstone files for 1-port and 2-port networks.

Example 9 (Version 1.0):
```
! 1-port S-parameter file, single frequency point
# MHz S MA R 50
! freq magS11 angS11
2.000 0.894  -12.136
```

In the above example, the value of S_{11} at a frequency of 2 MHz is given in magnitude-angle format. The reference resistance is 50 ohms.

Example 10 (Version 1.0):
```
! 1-port Z-parameter file, multiple frequency points
# MHz Z MA R 75
! freq  magZ11 angZ11
100    0.99   -4
200    0.80   -22
300    0.707  -45
400    0.40   -62
500    0.01   -89
```

Note that, in the above example, Z_{11} is normalized to 75 ohms, as given by the reference resistance (R 75) in the option line.

Example 11:
```
! 1-port Z-parameter file, multiple frequency points
[Version] 2.1
# MHz Z MA
[Number of Ports] 1
[Number of Frequencies] 5
[Reference] 20.0
[Network Data]
! freq  magZ11 angZ11
100    74.25    -4
200    60       -22
300    53.025   -45
400    30       -62
500     0.75    -89
[End]
```

This example duplicates the data in Example 10, using Version 2.0/Version 2.1 syntax. Note that normalization does not apply.

Example 12:
```
! 2-port H-parameter file, single frequency point
# kHz H MA R 1
! freq magH11 angH11 magH21 angH21 magH12 angH12 magH22 angH22
2 0.95 -26 3.57 157 0.04 76 0.66 -14
```

In the above example, the H-parameters are given in magnitude-angle format, normalized to 1 ohm.

Example 13:
```
! 2-port H-parameter file, single frequency point
[Version] 2.1
# kHz H MA R 1
[Number of Ports] 2
[Two-Port Data Order] 21_12
[Number of Frequencies] 1
[Matrix Format] Full
[Network Data]
! freq magH11 angH11 magH21 angH21 magH12 angH12 magH22 angH22
2 0.95 -26 3.57 157 0.04 76 0.66 -14
[End]
```

In the above example, the H-parameters are given in magnitude-angle format.

Example 14 (Version 1.0):
```
! 2-port S-parameter file, three frequency points
# GHz S RI R 50.0
! freq ReS11  ImS11    ReS21   ImS21   ReS12   ImS12  ReS22    ImS22
1.0000 0.3926 -0.1211 -0.0003 -0.0021 -0.0003 -0.0021 0.3926 -0.1211
2.0000 0.3517 -0.3054 -0.0096 -0.0298 -0.0096 -0.0298 0.3517 -0.3054
10.000 0.3419  0.3336 -0.0134  0.0379 -0.0134  0.0379 0.3419  0.3336
```

In the above example, the S-parameter data is given in real-imaginary format, with a 50-ohm reference resistance.

3-port and 4-port Networks

Rules for Version 1.0 and Version 1.1 files:
The network parameter data for a 3-port or 4-port network is arranged in a matrix row-wise order, with each line of data representing one row of the matrix. In other words (as shown below), the data for a 3-port network is entered as three lines of data, with each line containing three data pairs (i.e., a 3×3 matrix of network parameter pairs). Likewise, the data for a 4-port network is entered as four lines with four data pairs per line (a 4×4 matrix). As required by the general rules, each network parameter data group is preceded by the frequency value at which the data was taken.

3-port Full network description
<frequency value> $<N_{11}> <N_{12}> <N_{13}>$
$<N_{21}> <N_{22}> <N_{23}>$
$<N_{31}> <N_{32}> <N_{33}>$

4-port Full network description
<frequency value> $<N_{11}> <N_{12}> <N_{13}> <N_{14}>$
$<N_{21}> <N_{22}> <N_{23}> <N_{24}>$
$<N_{31}> <N_{32}> <N_{33}> <N_{34}>$
$<N_{41}> <N_{42}> <N_{43}> <N_{44}>$

where
frequency value   frequency at which the network parameter data was taken or derived.

N_{11}, N_{12}, etc.   network parameter data, where *Nij* represents a pair of data values.

As usual, network parameter data is entered in magnitude-angle, dB-angle, or real-imaginary format (i.e., pairs of values) as specified by the option line. All entries in a data line are separated by one or more whitespace characters; a data line itself is terminated by a line termination character or sequence.

Shown below is an example of an S-parameter description of a 4-port network.

Example 15 (Version 1.0):
```
! 4-port S-parameter data, taken at three frequency points
! note that data points need not be aligned
# GHz S MA R 50
5.00000 0.60 161.24 0.40 -42.20 0.42 -66.58 0.53 -79.34 ! row 1
        0.40 -42.20 0.60 161.20 0.53 -79.34 0.42 -66.58 ! row 2
        0.42 -66.58 0.53 -79.34 0.60 161.24 0.40 -42.20 ! row 3
        0.53 -79.34 0.42 -66.58 0.40 -42.20 0.60 161.24 ! row 4

6.00000 0.57 150.37 0.40 -44.34 0.41 -81.24 0.57 -95.77 ! row 1
        0.40 -44.34 0.57 150.37 0.57 -95.77 0.41 -81.24 ! row 2
        0.41 -81.24 0.57 -95.77 0.57 150.37 0.40 -44.34 ! row 3
        0.57 -95.77 0.41 -81.24 0.40 -44.34 0.57 150.37 ! row 4

7.00000 0.50 136.69 0.45 -46.41 0.37 -99.09 0.62 -114.19 ! row 1
        0.45  -46.41 0.50  136.69 0.62 -114.19 0.37 -99.09 ! row 2
        0.37  -99.09 0.62 -114.19 0.50  136.69 0.45 -46.41 ! row 3
        0.62 -114.19 0.37  -99.09 0.45  -46.41 0.50 136.69 ! row 4
```

Note that the data pairs do not have to be aligned in columns; the only requirement is that there be 3 (3-port networks) or 4 (4-port networks) pairs of *n*-port parameters per data line.

Rules for Version 2.0 and Version 2.1 files:
As noted earlier and as required by the general rules, each group of network parameter data is preceded by the frequency value at which the data was taken. The rest of the data for that frequency may follow on the same line or be split across multiple lines with intervening line termination sequence or character. Each frequency point shall begin after a line termination sequence or character, on the first column of the line.

For files using a [Matrix Format] of Lower or Upper, data is still represented in a row-wise format. "Row" here refers to the arrangement of port data into rows and columns by relationship, not in terms of actual lines of data in the Touchstone file text (e.g., S*ij* refers to the S-parameters from port *j* to port *i*; the data is therefore associated with row *i* and column *j*). In a Full Matrix, data for all elements in a matrix row shall be shown before data for the next row are shown.

Matrices using the Upper format shall include explicit data for row 1 ports (i.e., S_{11}, S_{12}…S_{1n}) before any data for row 2 is shown (i.e., S_{22}, S_{23}…S_{2n}). In the Upper format, each successive row shall contain one fewer element than the previous row. The element removed is the column number (current row – 1). For example, the first element of the second row of data is S_{22}. S_{21} is not shown, as it is assumed to be identical to S_{12} from symmetry. The final element in an Upper matrix shall be S_{nn}, where *n* is the total number of ports, representing the only data for that row.

In the Lower format, each successive row shall contain one more element than the previous row. The first row consists of only one element, S_{11}. The final row shall contain elements for each column from 1 to *n*, where *n* is the total number of ports.

Therefore, for a 3-port matrix, data would be ordered as shown below.

[Matrix Format] Lower *<frequency value>* *<N_{11}>* *<N_{21}>* *<N_{22}>* *<N_{31}>* *<N_{32}>* *<N_{33}>*

[Matrix Format] Upper *<frequency value>* *<N_{11}>* *<N_{12}>* *<N_{13}>* *<N_{22}>* *<N_{23}>* *<N_{33}>*

where
frequency value   frequency at which the network parameter data was taken or derived.

N_{11}, N_{12}, etc.   network parameter data, where N_{ij} represents a pair of data values.

5-port and Above Networks

The parameters for 5-port and above networks are also arranged in a matrix row-wise order.

Rules for Version 1.0 and Version 1.1 files:
Version 1.0 and Version 1.1 files are limited to a maximum of 4 network parameter data pairs per line, additional entries beyond the first four pairs in the matrix row shall be continued on the following line(s). Each row of the matrix shall start on a new line.

Rules for Version 2.0 and Version 2.1 files:
Version 2.0 and Version 2.1 files may continue data on the same line or across multiple lines. As usual, each group of network data pairs is preceded by the frequency value at which this data was taken.

For files using a [Matrix Format] of Lower or Upper, data is still represented in a row-wise format, as shown for 3- and 4-port networks above.

These rules are illustrated by showing the format for a 6-port network:

6-port Full network format (single frequency point)
$<frequency\ value>$ $<N_{11}>$ $<N_{12}>$ $<N_{13}>$ $<N_{14}>$! row 1
$<N_{15}>$ $<N_{16}>$
$<N_{21}>$ $<N_{22}>$ $<N_{23}>$ $<N_{24}>$! row 2
$<N_{25}>$ $<N_{26}>$
$<N_{31}>$ $<N_{32}>$ $<N_{33}>$ $<N_{34}>$! row 3
$<N_{35}>$ $<N_{36}>$
$<N_{41}>$ $<N_{42}>$ $<N_{43}>$ $<N_{44}>$! row 4
$<N_{45}>$ $<N_{46}>$
$<N_{51}>$ $<N_{52}>$ $<N_{53}>$ $<N_{54}>$! row 5
$<N_{55}>$ $<N_{56}>$
$<N_{61}>$ $<N_{62}>$ $<N_{63}>$ $<N_{64}>$! row 6
$<N_{65}>$ $<N_{66}>$

6-port Lower network format (single frequency point)
$<frequency\ value>$ $<N_{11}>$! row 1
$<N_{21}>$ $<N_{22}>$! row 2
$<N_{31}>$ $<N_{32}>$ $<N_{33}>$! row 3
$<N_{41}>$ $<N_{42}>$ $<N_{43}>$ $<N_{44}>$! row 4
$<N_{51}>$ $<N_{52}>$ $<N_{53}>$ $<N_{54}><N_{55}>$! row 5
$<N_{61}>$ $<N_{62}>$ $<N_{63}>$ $<N_{64}>$! row 6
$<N_{65}>$ $<N_{66}>$

6-port Upper network format (single frequency point)
$<frequency\ value>$ $<N_{11}>$ $<N_{12}>$ $<N_{13}>$ $<N_{14}>$! row 1
$<N_{15}>$ $<N_{16}>$
$<N_{22}>$ $<N_{23}>$ $<N_{24}>$! row 2
$<N_{25}>$ $<N_{26}>$
$<N_{33}>$ $<N_{34}>$! row 3
$<N_{35}>$ $<N_{36}>$
$<N_{44}><N_{45}>$ $<N_{46}>$! row 4
$<N_{55}>$ $<N_{56}>$! row 5
$<N_{66}>$! row 6

where
frequency value   frequency at which the network parameter data was taken or derived.

N_{11}, N_{12}, etc.   network parameter data, where N_{ij} represents a pair of data values.

In the example shown above, each row of matrix data extends over two lines of the file, and each new row of the matrix starts on a new line (this is optional and not a syntax requirement). As usual, *n*-port parameter values are entered in pairs according to the format specified in the option line and each value is separated by whitespace.

The following is a more detailed example illustrating the Full data matrix for a 10-port network. The Y-parameter data is in magnitude-angle format and is for a single frequency. Port numbers are separated by the colon character (:), for clarity only.

Example 16 (Version 1.0):
```
# frequency_unit Y MA R resistance
! 1st row
freq magY1:1 angY1:1 magY1:2 angY1:2 magY1:3 angY1:3 magY1:4 angY1:4
magY1:5 angY1:5 magY1:6 angY1:6 magY1:7 angY1:7 magY1:8 angY1:8
magY1:9 angY1:9 magY1:10 angY1:10
```

```
! 2nd row
magY2:1 angY2:1 magY2:2 angY2:2 magY2:3 angY2:3 magY2:4 angY2:4
magY2:5 angY2:5 magY2:6 angY2:6 magY2:7 angY2:7 magY2:8 angY2:8
magY2:9 angY2:9 magY2:10 angY2:10
! 3rd row
magY3:1 angY3:1 magY3:2 angY3:2 magY3:3 angY3:3 magY3:4 angY3:4
magY3:5 angY3:5 magY3:6 angY3:6 magY3:7 angY3:7 magY3:8 angY3:8
magY3:9 angY3:9 magY3:10 angY3:10
! 4th row
magY4:1 angY4:1 magY4:2 angY4:2 magY4:3 angY4:3 magY4:4 angY4:4
magY4:5 angY4:5 magY4:6 angY4:6 magY4:7 angY4:7 magY4:8 angY4:8
magY4:9 angY4:9 magY4:10 angY4:10
! 5th row
magY5:1 angY5:1 magY5:2 angY5:2 magY5:3 angY5:3 magY5:4 angY5:4
magY5:5 angY5:5 magY5:6 angY5:6 magY5:7 angY5:7 magY5:8 angY5:8
magY5:9 angY5:9 magY5:10 angY5:10
! 6th row
magY6:1 angY6:1 magY6:2 angY6:2 magY6:3 angY6:3 magY6:4 angY6:4
magY6:5 angY6:5 magY6:6 angY6:6 magY6:7 angY6:7 magY6:8 angY6:8
magY6:9 angY6:9 magY6:10 angY6:10
! 7th row
magY7:1 angY7:1 magY7:2 angY7:2 magY7:3 angY7:3 magY7:4 angY7:4
magY7:5 angY7:5 magY7:6 angY7:6 magY7:7 angY7:7 magY7:8 angY7:8
magY7:9 angY7:9 magY7:10 angY7:10
! 8th row
magY8:1 angY8:1 magY8:2 angY8:2 magY8:3 angY8:3 magY8:4 angY8:4
magY8:5 angY8:5 magY8:6 angY8:6 magY8:7 angY8:7 magY8:8 angY8:8
magY8:9 angY8:9 magY8:10 angY8:10
! 9th row
magY9:1 angY9:1 magY9:2 angY9:2 magY9:3 angY9:3 magY9:4 angY9:4
magY9:5 angY9:5 magY9:6 angY9:6 magY9:7 angY9:7 magY9:8 angY9:8
magY9:9 angY9:9 magY9:10 angY9:10
! 10th row
magY10:1 angY10:1 magY10:2 angY10:2 magY10:3 angY10:3 magY10:4 angY10:4
magY10:5 angY10:5 magY10:6 angY10:6 magY10:7 angY10:7 magY10:8 angY10:8
magY10:9 angY10:9 magY10:10 angY10:10
```

Introduction to Mixed-Mode Concepts

This section provides the basic definitions and terminology regarding mixed-mode *n*-port parameters.

A differential port is formed from two single-ended ports having the same "reference" terminal (also referred to as the "-" terminal). Electrical quantities associated with a differential port formed from two single-ended ports *i* and *j* are established from the single-ended port quantities V_i, I_i, V_j, and I_j as

common mode voltage	$V_{Ci,j} = (V_i + V_j)/2$	(*a*)
common mode current	$I_{Ci,j} = I_i + I_j$	(*b*)
differential mode voltage	$V_{Di,j} = V_i - V_j$	(*c*)
differential mode current	$I_{Di,j} = (I_i - I_j)/2$	(*d*)

The notation *Ci,j* and *Di,j* signifies the mode, common or differential, respectively, as well as the indices and the order of the single-ended ports from which the differential port is formed.

For mixed-mode S-parameters, the relationships between the mixed-mode incident and reflected waves and the aforementioned mixed-mode voltages and currents are similar to those for the conventional quantities, specifically

$$
\begin{array}{lll}
\text{common mode incident wave} & a_{Ci,j} = (V_{Ci,j} + R_{Ci,j}I_{Ci,j})/(2\sqrt{R_{Ci,j}}) & (e) \\
\text{common mode reflected wave} & b_{Ci,j} = (V_{Ci,j} - R_{Ci,j}I_{Ci,j})/(2\sqrt{R_{Ci,j}}) & (f) \\
\text{differential mode incident wave} & a_{Di,j} = (V_{Di,j} + R_{Di,j}I_{Di,j})/(2\sqrt{R_{Di,j}}) & (g) \\
\text{differential mode reflected wave} & b_{Di,j} = (V_{Di,j} - R_{Di,j}I_{Di,j})/(2\sqrt{R_{Di,j}}) & (h)
\end{array}
$$

In general, and as is the case for the conventional S-parameters, the mixed-mode reference resistances $R_{Ci,j}$ and $R_{Di,j}$ could be selected as any positive real numbers. However, this is further limited in Version 2.0 and Version 2.1 files, as explained below. Furthermore, complex reference impedances are not supported.

The relationships between the conventional and mixed-mode incident and reflected waves depend on the actual values of the reference resistances $R_{Ci,j}$ and $R_{Di,j}$ relative to the reference resistances R_i and R_j for the conventional incident and reflected waves for the two single-ended ports i and j forming the differential port. One common selection for this relationship is such that R_i and R_j are equal, $R_{Ci,j}$ is half that value and $R_{Di,j}$ is twice that value.

Specifically, if

Condition 1: $R_i = R_j = R$

and

Condition 2: $R_{Ci,j} = R/2$ and $R_{Di,j} = 2R$

then

$$
\begin{array}{ll}
a_{Ci,j} = (a_i + a_j)/\sqrt{2} & (i) \\
a_{Di,j} = (a_i - a_j)/\sqrt{2} & (j) \\
b_{Ci,j} = (b_i + b_j)/\sqrt{2} & (k) \\
b_{Di,j} = (b_i - b_j)/\sqrt{2} & (l)
\end{array}
$$

Version 2.0 and Version 2.1 files do not provide the means to specify directly the mixed-mode reference resistances $R_{Ci,j}$ and $R_{Di,j}$. Instead, the single-ended port reference resistances R_i and R_j are specified by means of the [Reference] keyword or by the option line. Thus, the mixed-mode reference resistances need to be unambiguously defined from the [Reference] data, and therefore **Condition 1** and **Condition 2** above are adopted for Version 2.0 and Version 2.1 files. Note that under these conditions the relationships (*i*)-(*l*) do not depend on the actual values of the reference resistances and take a very simple form.

The value R in **Condition 1** and **Condition 2** may be different for different pairs i, j of the single-ended ports forming different differential ports.

Similarly to the conventional *n*-port parameters the term mixed-mode *n*-port parameters refers to any one of the $n \times n$ matrices **S**, **Y**, or **Z** linking the voltages, currents, or the wave quantities as

$$\mathbf{V} = \mathbf{Z}\,\mathbf{I} \qquad \mathbf{I} = \mathbf{Y}\,\mathbf{V} \qquad \mathbf{b} = \mathbf{S}\,\mathbf{a}$$

The difference is that for the mixed-mode *n*-port parameters the vectors **V**, **I**, **b**, and **a** are defined using the aforementioned common and differential mode quantities while the single-ended port quantities are used in the conventional relationships. The mixed-mode *n*-port parameters may be the generalized mixed-mode parameters when not all single-ended ports are combined into differential ports. For those ports that remain single-ended, the single-ended quantities appear in the vectors **V**, **I**, **b**, and **a**.

All the single-ended ports of any *n*-port circuit characterized by the Touchstone files are assumed to be ordered with consecutive numbers from 1 to *n*. This is the "reference port order" which also determines the matrix entries in the conventional **S**, **Y**, or **Z** matrices. Specifically, the *k*th elements in the vectors **V**, **I**, **b**, and **a** in the conventional relationships are those of the *k*th single-ended port.

Version 2.0 and Version 2.1 files do not impose any specific order of the mixed-mode quantities in the vectors **V**, **I**, **b**, and **a** in the mixed-mode relationships. Instead, the [Mixed-Mode Order] keyword provides the means to specify how these quantities are ordered with respect to the reference port order. The only requirement is that the same order (specified by [Mixed-Mode Order]) applies to all the vectors **V**, **I**, **b**, and **a**.

Appendix A provides the formulas for the relationships between the conventional and mixed-mode *n*-port parameter for the case when the **Condition 1** and **Condition 2** are satisfied.

[Mixed-Mode Order]

Rules for Version 1.0 and Version 1.1 files:
The [Mixed-Mode Order] keyword is not permitted in Version 1.0 and Version 1.1 files.

Rules for Version 2.0 and Version 2.1 files:
The [Mixed-Mode Order] keyword and argument specify a list or vector of ports and port descriptors described with mixed-mode network data elsewhere in the file. The [Mixed-Mode Order] list determines the content and the row/column arrangement used for the network data.

The [Mixed-Mode Order] keyword is only required if mixed-mode data is present elsewhere in the file.

Port numbers used under [Mixed-Mode Order] are single-ended. No definition or syntax is used to define mixed-mode ports, only mixed-mode relationships between single-ended ports.

Every single-ended port (the number described under [Number of Ports]) shall be mentioned in a descriptor under [Mixed-Mode Order].

[Mixed-Mode Order] uses one of the following characters combinations to represent descriptors:

S*<port>*
C*<port>, <port>*
D*<port>, <port>*

where
C, D, S	specify whether the descriptor is common-mode, differential-mode or single-ended. Legal arguments are S (for single-ended), C (for common-mode), and D (for differential-mode). If the letter S is present and followed by a single integer, a single-ended descriptor is being defined. A letter shall not appear by itself, nor shall an integer appear by itself. When a pair of ports is present, the second port listed is assumed to be the reference port.
port	an integer, specifies the number of the single-ended port(s) described in the descriptor. Only non-zero integers shall be used. For single-ended descriptor groups, a single integer is used. For mixed-mode data, two port integers are used, separated by a single comma without whitespace, carriage returns, or line feeds. Multiple commas without separation by integers are not permitted.

Descriptor groups are separated by whitespace, including carriage returns and/or line feeds.

Note that any one port number shall only appear in one single-ended or two mixed-mode descriptors. Additionally, any common-mode descriptor present between ports necessitates that a differential-mode descriptor be present between the same ports, and vice-versa. For example, if D1,3 is included under [Mixed-Mode Order], C1,3 shall also be included. S3 would be prohibited. C2,3 would also be prohibited.

The number of ports described under the [Number of Ports] keyword shall match the number of descriptors described under [Mixed-Mode Order]. Similarly, the numeric value described under [Number of Ports] shall match the highest integer port number listed in any descriptor under [Mixed-Mode Order].

[Mixed-Mode Order], if used, shall appear after the [Number of Ports] keyword and before any network data.

[Mixed-Mode Order] arguments may begin on the line following the closing bracket of the keyword (in other words, after a line termination sequence or character).

Mixed-Mode Network Parameter Data

Rules for Version 1.0 and Version 1.1 files:
Mixed-mode data is not permitted in Version 1.0 files.

Rules for Version 2.0 and Version 2.1 files:
Mixed-mode data consists of matrices using the relationships and order described under the [Mixed-Mode Order] keyword.

Only S-, Y-, or Z-parameter data shall be represented using the mixed-mode format.

Note that the port numbering does not necessarily determine the arrangement of data under mixed-mode data. Only the [Mixed-Mode Order] keyword determines how mixed-mode data is arranged. Only relationships and ports specified under [Mixed-Mode Order] shall appear as part of mixed-mode data.

Reference resistances for mixed-mode data are assumed single-ended, as presented under the [Reference] keyword. For common-mode and differential-mode relationships, the same value of reference resistance shall be used under [Reference] for both ports. Differential-mode relationships assume an impedance across the ports of twice the single-ended value specified for either port in the relationship. Common-mode relationships assume an impedance across the ports of half the single-ended value specified for either port in the relationship.

The rules for presenting frequency, line breaks, and other aspects of formatting follow those for traditional single-ended network data.

[Matrix Format] may be used with mixed-mode data, so long as the data follows the keyword's symmetry requirements.

The mixed-mode matrix arrangement assumes that the vector in [Mixed-Mode Order] describes the diagonal of the mixed-mode matrix. In other words, the ith value of the vector is used for both the stimulus and response used for the resulting matrix value Nii. The matrix value Nij would result from vector value i as the response value in row i and the vector value j as the stimulus value in column j. This follows the stimulus-response convention used both widely in the industry for proprietary mixed-mode data formats, as well as the traditional Touchstone Version 1.0 and Version 1.1 single-ended data format.

For example, for a 3-port network, the [Mixed-Mode Order] keyword could contain the values:

D1,2 S3 C1,2

This specifies a differential relationship for ports 1 and 2, followed by a single-ended data relationship for port 3 and a common-mode relationship for ports 1 and 2. The mixed-mode data matrix would therefore use the following format:

<frequency value> $<D_{1,2}\ D_{1,2}>$ $<D_{1,2}\ S_3>$ $<D_{1,2}\ C_{1,2}>$
                      $<S_3\ D_{1,2}>$ $<S_3\ S_3>$ $<S_3\ C_{1,2}>$
                      $<C_{1,2}\ D_{1,2}>$ $<C_{1,2}\ S_3>$ $<C_{1,2}\ C_{1,2}>$

For each frequency value, where the "<" and ">" characters denote magnitude/angle or real/imaginary data pairs or a frequency value, only for the purposes of this example.

Example 17:
```
! 6-port component shown; note that all six ports are used in some
! relationship
[Version] 2.1
# MHz Y RI R 50
[Number of Ports] 6
[Number of Frequencies] 1
[Reference] 50 75 75 50 0.01 0.01
# MHz Y RI R 50

[Mixed-Mode Order] D2,3 D6,5 C2,3 C6,5 S4 S1
[Network Data]
5.00 8.0  9.0   2.0  -1.0  3.0 -2.0  1.0  3.0  1.0  0.1  0.2 -0.2
     2.0 -1.0  7.0   7.0  1.8 -2.0 -1.0 -1.0 -0.5  0.5  0.2 -0.1
     3.0 -2.0  1.8  -2.0  5.8  6.0  1.2  0.8  0.9  0.7  0.3 -0.5
     1.0  3.0 -1.0  -1.0  1.2  0.8  6.3  8.0  2.0 -0.5  1.5  0.6
     1.0  0.1 -0.5   0.5  0.9  0.7  2.0 -0.5  4.7 -6.0 -1.0  2.0
     0.2 -0.2  0.2  -0.1  0.3 -0.5  1.5  0.6 -1.0  2.0  5.5 -7.0
[End]
```

[Noise Data]

Rules for Version 1.0 and Version 1.1 files:
The [Noise Data] keyword is not permitted in Version 1.0 and Version 1.1 files.

Rules for Version 2.0 and Version 2.1 files:
The [Noise Data] keyword identifies the block of noise parameter data, if present in the file. Each Touchstone Version 2.0 and Version 2.1 file shall contain one and only one [Noise Data] keyword, if and only if [Number of Noise Frequencies] is defined.

[Noise Data] shall only appear after the [Network Data] keyword and arguments.

Example 18:
```
! 2-port network, S-parameter and noise data
! Default MA format, GHz frequencies, 50-ohm reference, S-parameters
[Version] 2.1
#
[Number of Ports] 2
[Two-Port Data Order] 21_12
[Number of Frequencies] 2
[Number of Noise Frequencies] 2
[Reference] 50 25.0
```

```
[Network Data]
2  0.95  -26 3.57 157 0.04 76 0.66 -14
22 0.60 -144 1.30   40 0.14 40 0.56 -85
[Noise Data]
4  0.7 0.64   69 19
18 2.7 0.46 -33 20
[End]
```

Noise Parameter Data

Noise parameters may be included in Touchstone files. However, they shall only be included in files describing 2-port networks. Noise parameters follow the G-, H-, S-, Y-, or Z-parameter data (Version 1.0 and Version 1.1 files) and the [Noise Data] keyword (Version 2.0 and Version 2.1 files) for all frequency points. Note that the rules for noise parameters are significantly different than the rules for the S-parameter, Z-parameter, etc., data elsewhere in Touchstone files.

Each line of noise parameters has the following five entries:
<x1> <x2> <x3> <x4> <x5>

where

x1	Frequency, in the units specified on the option line, or GHz, if no units are specified. The first group of noise data shall have a frequency less than or equal to the highest frequency used for the S-parameter, Z-parameter, etc. data earlier in the file.
x2	Minimum noise figure in decibels (dB).
x3	Source reflection coefficient to realize minimum noise figure. This is a magnitude, regardless of the format specified on the option line. The values used for *x3* and *x4* form a complex pair, taken with respect to the reference resistance value specified on the option line. If no resistance is listed on the option line, the assumed reference is 50 ohms.
x4	Phase of the reflection coefficient, in degrees. As noted above, this is taken with respect to the reference resistance specified on the option line or, if no resistance is listed, an assumed value of 50 ohms.
x5	Effective noise resistance, in ohms. A simulator may expect this parameter to meet physical requirements. If the user-supplied *x5* value is less than required, then a simulator may force this *x5* value to its lowest physical limit. For Version 1.0 files, *x5* is normalized to the resistance specified on the option line, or 50 ohms if no value is specified. For Version 1.1 files, *x5* is normalized to the resistance specified on the option line for port 1, or 50 ohms if no value is specified. No normalization is assumed for Version 2.0 and Version 2.1 files.

Note that all noise parameters assume that port 1 is the source.

The frequencies for noise parameters and network parameters need not match. The only requirement is that the first noise parameter frequency be less than or equal to the highest network parameter frequency. For Version 1.0 and Version 1.1 files, this allows the file processor to determine where the network parameters end and the noise parameters begin. For Version 2.0 and Version 2.1 files, the [Number of Frequencies] keyword specifies, the size of the network parameter data expected before any noise parameters begin. As with network parameter data, all noise parameter data shall be arranged in increasing order of frequency.

The [Number of Noise Frequencies] keyword is required if any noise parameters are present in the file. The [Number of Noise Frequencies] keyword is prohibited if no noise parameters are present in the file.

The [Reference] keyword has no effect on noise parameter data.

If noise parameters are present in the file, the [Number of Ports] keyword shall have "2" as its argument.

In Version 1.0, Version 1.1, Version 2.0 and Version 2.1 files, each noise parameter frequency and associated data shall be grouped into a single line, terminated with a line termination sequence or character. As in Version 2.0 and Version 2.1 [Network Data], noise data and their associated frequency points may be in integer, floating point or scientific notation. If in floating point format, a single leading zero (i.e., a zero before the decimal point) may be present or omitted.

Example 19 (Version 1.0):
```
! 2-port network, S-parameter and noise data
! Default MA format, GHz frequencies, 50-ohm reference, S-parameters
#
! NETWORK PARAMETERS
2  0.95  -26  3.57 157 0.04 76 0.66 -14
22 0.60 -144  1.30  40 0.14 40 0.56 -85
! NOISE PARAMETERS
4  0.7 0.64  69 0.38
18 2.7 0.46 -33 0.40
```

Example 20:
```
! 2-port network, S-parameter and noise data
! Default MA format, GHz frequencies, 50-ohm reference, S-parameters
[Version] 2.1
#
[Number of Ports] 2
[Number of Frequencies] 2
[Number of Noise Frequencies] 2
[Reference] 50 25.0
[Network Data]
! NETWORK PARAMETERS
2  0.95  -26 3.57 157 0.04 76 0.66 -14
22 0.60 -144 1.30 40  0.14 40 0.56 -85
[Noise Data]
! NOISE PARAMETERS
4  0.7 0.64  69 19
18 2.7 0.46 -33 20
[End]
```

[End]

Rules for Version 1.0 and Version 1.1 files:
The [End] keyword is not permitted in Version 1.0 and Version 1.1 files.

Rules for Version 2.0 and Version 2.1 files:
The [End] keyword defines the end of a Touchstone Version 2.0 and Version 2.1 file. Non-comment text appearing after the [End] keyword should be treated as an error.

The [End] keyword is required for Version 2.0 and Version 2.1 files. It shall be the last keyword in the file.

Example 21:
```
! 2-port network, S-parameters
! Default MA format, GHz frequencies, 50-ohm reference, S-parameters
[Version] 2.1
#
[Number of Ports] 2
[Number of Frequencies] 2
[Reference] 50 25.0
[Two-Port Data Order] 12_21
[Network Data]
! NETWORK PARAMETERS
2  0.95 -26  3.57 157 0.04 76 0.66 -14
22 0.60 -144 1.30  40 0.14 40 0.56 -85
[End]
```

INFORMATION DESCRIPTION

Introduction

This section is reserved for future expansion with new informational keywords for specific applications. While this information could be documented by comment lines, the keywords in this section allow descriptions to be standardized and to be electronically parsed. These keywords are optional and may be ignored or be overridden by external references to the Touchstone Version 2.0/Version 2.1 file.

[Begin Information], [End Information]

Rules for Version 1.0 and Version 1.1 files:
The [Begin Information] and [End Information] keywords are not permitted in Version 1.0 and Version 1.1 files.

Rules for Version 2.0 and Version 2.1 files:
The [Begin Information] keyword and associated data define information about the derivation and usage of Touchstone data for specific applications. The [Begin Information] and [End Information] keywords are optional for Version 2.0 and Version 2.1 files. If used, the keywords shall only appear after the [Number of Ports] keyword and before any network data. Each Touchstone Version 2.0 and Version 2.1 file shall contain one and only one [Begin Information] keyword. Each Touchstone Version 2.0 and Version 2.1 file that contains a [Begin Information] keyword shall also contain one [End Information] keyword. The [End Information] keyword shall follow the [Begin Information] keyword and shall occur before any network data.

The data between the [Begin Information] and [End Information] keywords shall consist of information keywords and arguments as defined below. The arguments associated with each information keyword may be on the same line as the information keyword or separated by line termination sequences or characters prior to the next keyword. Each keyword or keyword and arguments within [Begin Information] and [End Information] terminates either with another keyword or with the [End Information] keyword. Therefore, information keywords and their arguments may apply to fewer than the number of ports in the file documented by the [Number of Ports] keyword.

Information Keywords

This section is reserved for future expansion.

COMPATIBILITY NOTES

In the original proprietary Touchstone specification, several restrictions existed that may not apply across implementations and do not apply to Version 1.0, Version 1.1, Version 2.0 or Version 2.1 files:
- The dB/angle form was not allowed for G-, H-, Y-, and Z-parameters. Only magnitude/angle and real/imaginary pairs were permitted for non-S-parameter data.
- Y- and Z-parameters were not allowed for 3-port networks or larger.
- The total number of ports that could be represented in any Touchstone file was 99.

Version 1.0 and Version 1.1 files differ from Version 2.0 and Version 2.1 files in three additional respects:
- G-, H-, Y-, and Z- parameters are normalized in Version 1.0 and Version 1.1 but are not normalized in Version 2.0 and Version 2.1 files.
- Effective noise resistance in noise parameter data is considered normalized in Version 1.0 and Version 1.1 files but is not normalized in Version 2.0 and Version 2.1 files.
- Mixed-mode support is added in Version 2.0, so that network parameter data in the file is interpreted differently in the presence of the [Mixed-Mode Order] keyword.

REFERENCES

1. A. Ferrero and M. Pirola, "Generalized mixed-mode S-parameters," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, no. 1, pp. 458-463, Jan. 2006, doi: 10.1109/TMTT.2005.860497.
2. D. E. Bockelman and W. R. Eisenstadt, "Pure-mode network analyzer for on-wafer measurements of mixed-mode S-parameters of differential circuits," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 45, no. 7, pp. 1071-1077, July 1997, doi: 10.1109/22.598443.
3. G. Gonzalez, *Microwave Transistor Amplifiers: Analysis and Design*, Second Edition, Upper Saddle River, NJ, USA: Prentice Hall, 1997, p.299ff.
4. H. A. Haus et al., "Representation of Noise in Linear Twoports," in *Proceedings of the IRE*, vol. 48, no. 1, pp. 69-74, Jan. 1960, doi: 10.1109/JRPROC.1960.287381.

APPENDIX A: Examples of Mixed-Mode Transformations

Transformations Between Conventional and Mixed-Mode Matrices for a Pair of Ports

For the discussion below, the pair of single-ended ports is assumed to have a common reference and to be normalized to the same reference resistance value r_0. In its mixed-mode representation, the reference resistance for the differential and common mode components is assumed to be $2r_0$ and $r_0/2$ respectively.

Shown below are the relationships between the vectors and matrices for a port pair, participating in standard-to mixed-mode transformation.

For convenience, two matrices are used:

$$\boldsymbol{M} = \begin{bmatrix} \gamma & -\gamma \\ \gamma & \gamma \end{bmatrix} \text{ and } \boldsymbol{K} = \begin{bmatrix} 1/\gamma & 0 \\ 0 & \gamma \end{bmatrix}, \text{ where } \gamma = \frac{1}{\sqrt{2}}$$

The inverse of the matrix **M** is also its transpose: $\boldsymbol{M^{-1}} = \boldsymbol{M^t}$.

S-parameters

The incident and reflected waves in standard-mode (abbreviated with the subscript "std") and mixed-mode (abbreviated with the subscript "mm") format are related as follows:

$$\boldsymbol{a_{mm}} = \begin{bmatrix} a_{D1,2} \\ a_{C1,2} \end{bmatrix} = \boldsymbol{M} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \boldsymbol{M a_{std}} \tag{S1}$$

$$\boldsymbol{b_{mm}} = \begin{bmatrix} b_{D1,2} \\ b_{C1,2} \end{bmatrix} = \boldsymbol{M} \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \boldsymbol{M b_{std}} \tag{S2}$$

$$\boldsymbol{b_{std}} = \boldsymbol{S_{std} a_{std}} \tag{S3}$$
$$\boldsymbol{b_{mm}} = \boldsymbol{S_{mm} a_{mm}} \tag{S4}$$

By substituting (S1) and (S2) into (S4), it is possible to find the relations between the mixed-mode and standard-mode **S**-matrices:

$$\boldsymbol{S_{std}} = \boldsymbol{M^t S_{mm} M} \tag{S5}$$
$$\boldsymbol{S_{mm}} = \boldsymbol{M S_{std} M^t} \tag{S6}$$

Y- and Z-parameters

First, the mixed-mode voltages and currents (vectors) are expressed via standard-mode vectors.

$$\boldsymbol{V_{mm}} = \begin{bmatrix} v_{D1,2} \\ v_{C1,2} \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} 1/\gamma & 0 \\ 0 & \gamma \end{bmatrix} \begin{bmatrix} \gamma & -\gamma \\ \gamma & \gamma \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \boldsymbol{K M V_{std}}$$
(YZ1)

$$\boldsymbol{I_{mm}} = \begin{bmatrix} i_{D1,2} \\ i_{C1,2} \end{bmatrix} = \begin{bmatrix} 0.5 & -0.5 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} \gamma & 0 \\ 0 & 1/\gamma \end{bmatrix} \begin{bmatrix} \gamma & -\gamma \\ \gamma & \gamma \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \boldsymbol{K^{-1} M I_{std}} \tag{YZ2}$$

Then, relationships are defined between voltages and currents, in standard and mixed modes.

$$\boldsymbol{I_{std}} = \boldsymbol{Y_{std} V_{std}} \tag{YZ3}$$

$$V_{std} = Z_{std}I_{std} \tag{YZ4}$$
$$I_{mm} = Y_{mm}V_{mm} \tag{YZ5}$$
$$V_{mm} = Z_{mm}I_{mm} \tag{YZ6}$$

By substituting (YZ1) and (YZ2) into (YZ3-6), relationships can be found between the standard- and mixed-mode **Y-** and **Z**-matrices:

$$Y_{mm} = (K^{-1}M)Y_{std}(K^{-1}M)^t \tag{YZ7}$$
$$Y_{std} = (KM)^tY_{mm}(KM) \tag{YZ8}$$
$$Z_{mm} = (KM)Z_{std}(KM)^t \tag{YZ9}$$
$$Z_{std} = (K^{-1}M)^tZ_{mm}(K^{-1}M) \tag{YZ10}$$

Mutual Transformations in Cases of Several Port Pairs

All above relationships apply only to individual port pairs participating in mixed-mode to standard-mode transformations. In case of many such pairs, and also in the presence of single-ended components together with mixed-mode components, a more general description is needed. The transformation matrix in this case consists of several 2×2 diagonal blocks - each one for every mixed-mode port pair - and a unit matrix diagonal block that corresponds to single-ended ports.

For example, the combined mixed-mode vector X_{mm_blk} and single-ended component vector X_{std} could be related as:

$$X_{mm\_blk} = \begin{bmatrix} X_{D1,2} \\ X_{C1,2} \\ X_{D3,4} \\ X_{C3,4} \\ X_5 \end{bmatrix} = \begin{bmatrix} T_{X2} & 0 & 0 \\ 0 & T_{X2} & 0 \\ 0 & 0 & E_1 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix} = T_X X_{std\_blk} \tag{P1}$$

Here, T_{X2} is an elementary 2×2 transformation matrix block. Depending on the type of variables in X (incident or reflected wave, voltage or current), it is:

$$T_{A2} = T_{B2} = M \qquad \text{(for incident and reflected wave)} \tag{P2}$$
$$T_{V2} = KM \qquad \text{(for port voltage vector)} \tag{P3}$$
$$T_{I2} = K^{-1}M \qquad \text{(for port current vector)} \tag{P4}$$

E_1 is a 1×1 identity matrix. The size of it is defined by the number of individual single-ended ports in the left side "extended" mixed-model vector. The matrix components designated by zeros are square or rectangular all-zero block matrices. Their size is determined by the size of the corresponding diagonal blocks.

Note that (P1) only describes the case when variables on the left and right are "properly" ordered. The proposed standard allows arbitrary ordering of components in the mixed-mode vector. In addition to the block-wise transformation, as shown in (P1), a chain of several transformations may be considered, including permutations and mixed-to-standard-mode transformations:

$$X_{mm} \Leftarrow perm\_mm \Rightarrow X_{mm_{blk}} \Leftarrow mixed\_to\_standard\_mode \Rightarrow X_{std\_blk} \Leftarrow perm\_std \Rightarrow X_{std}$$

For example, possible transformations are:

$$\begin{bmatrix} X_{D3,2} \\ X_{D5,4} \\ X_1 \\ X_{C3,2} \\ X_{C5,4} \end{bmatrix} \Leftrightarrow \begin{bmatrix} X_{D3,2} \\ X_{C3,2} \\ X_{D5,4} \\ X_{C5,4} \\ X_1 \end{bmatrix} \Leftrightarrow \begin{bmatrix} X_3 \\ X_2 \\ X_5 \\ X_4 \\ X_1 \end{bmatrix} \Leftrightarrow \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix} \tag{P5}$$

Given a vector X_{mm} (on the left) with components ordered as defined in [Mixed-Mode Order], first those components are permuted so as to group the mixed-mode pairs and block of single-ended components (see X_{mm_blk}, next vector). Then, vector X_{mm_blk} is represented as a result of standard-to-mixed-mode transformation by way of (P1) applied to respectively grouped vector X_{std_blk}. Finally, the single-ended vector is permuted so as to get the components in X_{std} properly ordered.

Note that two permutations (with mixed-mode and standard-mode components) are independent and therefore require two permutation matrices, P_{std} and P_{mm} respectively. The chain of transformations in (P5), if seen from right to left becomes:

$$X_{std\_blk} = P_{std}X_{std} \tag{P6}$$
$$X_{mm\_blk} = T_X X_{std\_blk} \tag{P7}$$
$$X_{mm} = P_{mm}X_{mm\_blk} \tag{P8}$$

For example, the matrices used in (P5) are:

$$P_{std} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}, T_X = \begin{bmatrix} T_{X2} & 0 & 0 \\ 0 & T_{X2} & 0 \\ 0 & 0 & E_1 \end{bmatrix}, P_{mm} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

From (P6-P8):

(P9)
$$X_{mm} = (P_{mm}T_X P_{std})X_{std}$$

$$X_{std} = (P_{std}^t T_X^{-1} P_{mm}^t)X_{mm} \tag{P10}$$

For each type of data (S-, Y-, or Z-parameters) a certain type of input and output vectors has been defined. Assume that **X** is an input vector (**a**, **V**, or **I** respectively) and **U** is an output vector (respectively, **b**, **I**, or **V**). Then, similar to (P9) and (P10) relationships exist for the output vector:

(P11)
$$U_{mm} = (P_{mm}T_U P_{std})U_{std}$$

$$U_{std} = (P_{std}^t T_U^{-1} P_{mm}^t)U_{mm} \tag{P12}$$

Note, that permutation matrices are the same (since the components in the input/output vectors shall be identically ordered) but the block-wise transformation matrix could be different. As follows from (P3) and (P4), in case of Y- or Z-parameters, using different elementary transformation blocks for voltage and current vectors is necessary. However, in all cases the transformation matrices used in (P9-P12) obey the relations:

$$T_U^t = T_X^{-1} \tag{P13}$$
$$T_X^t = T_U^{-1} \tag{P14}$$

In addition to general type input and output vectors (general for **S/Y/Z** cases), general transformation matrices, F_{std} and F_{mm} may be defined (where **F** stands for **S**, **Y**, or **Z**):

$$U_{std} = F_{std}X_{std} \tag{P15}$$

$$U_{mm} = F_{mm}X_{mm}$$
(P16)

By substituting (P9) and (P11) into (P16):

$$F_{std} = (P_{std}^t T_U^{-1} P_{mm}^t) F_{mm} (P_{mm} T_X P_{std}) \qquad (P17)$$
$$F_{mm} = (P_{mm} T_U P_{std}) F_{mm} (P_{std}^t T_X^{-1} P_{mm}^t) \qquad (P18)$$

(P17) shows how the mixed-mode matrix, arbitrarily ordered, possibly with single-ended terms, is converted directly into properly ordered single-ended form. (P18) shows the reverse transformation.

Note that because of (P13) and (P14) the side matrices in (P17) and (P18) enclosed in parenthesis are mutually transposed: $P_{std}^t T_U^{-1} P_{mm}^t = (P_{mm} T_X P_{std})^t$, $P_{mm} T_U P_{std} = (P_{std}^t T_X^{-1} P_{mm}^t)^t$. The property is related to the fact that transformations (P17) and (P18) shall preserve matrix symmetry. For example, if the standard-mode matrix is symmetric, so should be the mixed-mode matrix, regardless of the permutations and the parameter type.

Example A-1:
If the vectors shown in (P5) correspond to incident and reflected waves, and the data consists of S-parameters, then the elementary transformation blocks are those of (P2), and therefore:

$$T_X = \begin{bmatrix} \gamma & -\gamma & 0 & 0 & 0 \\ \gamma & \gamma & 0 & 0 & 0 \\ 0 & 0 & \gamma & -\gamma & 0 \\ 0 & 0 & \gamma & \gamma & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Combining this matrix with permutation matrices shown above, (P15) reduces to:

$$S_{std} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ -\gamma & 0 & 0 & \gamma & 0 \\ \gamma & 0 & 0 & \gamma & 0 \\ 0 & -\gamma & 0 & 0 & \gamma \\ 0 & \gamma & 0 & 0 & \gamma \end{bmatrix} S_{mm} \begin{bmatrix} 0 & -\gamma & \gamma & 0 & 0 \\ 0 & 0 & 0 & -\gamma & \gamma \\ 1 & 0 & 0 & 0 & 0 \\ 0 & \gamma & \gamma & 0 & 0 \\ 0 & 0 & 0 & \gamma & \gamma \end{bmatrix}$$

Example A-2:
Let the Touchstone file contain Y-parameter data with mixed-mode order defined by:

[Mixed-Mode Order]
D2,3 D6,5 C2,3 C6,5 S4 S1

Let also the mixed-mode matrix at a certain frequency be defined as:

$$Y_{mm} = \begin{bmatrix} 8+9j & 2-j & 3-2j & 1+3j & 1+0.1j & 0.2-0.2j \\ 2-j & 7+7j & 1.8-2j & -1-j & -0.5+0.5j & 0.2-0.1j \\ 3-2j & 1.8-2j & 5.8+6j & 1.2+0.8j & 0.9+0.7j & 0.3-0.5j \\ 1+3j & -1-j & 1.2+0.8j & 6.3+8j & 2-0.5j & 1.5+0.6j \\ 1+0.1j & -0.5+0.5j & 0.9+0.7j & 2-0.5j & 4.7-6j & -1+2j \\ 0.2-0.2j & 0.2-0.1j & 0.3-0.5j & 1.5+0.6j & -1+2j & 5.5-7j \end{bmatrix}$$

By inspecting mixed-mode order, the mixed-mode permutation matrix P_{mm} may be defined as:

$$X_{mm} = P_{mm}X_{mm\_blk}, \text{ or } \begin{bmatrix} X_{D3,2} \\ X_{D6,5} \\ X_{C3,2} \\ X_{C6,5} \\ X_4 \\ X_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_{D3,2} \\ X_{C3,2} \\ X_{D6,5} \\ X_{C6,5} \\ X_4 \\ X_1 \end{bmatrix}$$

Similarly, the standard-mode permutation can be seen from:

$$X_{std\_blk} = P_{std}X_{std}, \text{ or } \begin{bmatrix} X_3 \\ X_2 \\ X_6 \\ X_5 \\ X_4 \\ X_1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \end{bmatrix}$$

The transformation matrices for voltage and current vectors are different:

$$T_V = diag\{KM, KM, E_2\} = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_I = diag\{K^{-1}M, K^{-1}M, E_2\} = \begin{bmatrix} 0.5 & -0.5 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & -0.5 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Since, for Y-parameters, voltage is considered as an "input" and current as "output", in (P17) T_X is replaced with T_V and T_U with T_I. Then, (P17) simplifies to:

$$Y_{std} = \begin{bmatrix} 0 & 0.5 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.5 & 1 \\ 0 & 0.5 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.5 & -1 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} Y_{mm} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 \\ 0.5 & 0 & 0.5 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0.5 & 0 & 0.5 & 0 & 0 \\ 0 & 1 & 0 & -1 & 0 & 0 \end{bmatrix}$$

Finally, with given complex Y_{mm}:

$$Y_{std} =$$
$$\begin{bmatrix} 9.35+5.75j & 0.725-0.075j & -4.05-4.25j & -0.075+1.025j & 0.7+0.3j & 4-2.5j \\ 0.725-0.075j & 5.675-6.5j & -0.775+0.225j & -4.325+5.5j & 2.5+0.35j & 0.7-0.15j \\ -4.05-4.25j & -0.775+0.225j & 5.75+9.75j & -0.375-0.675j & -1.7-1.3j & -2+1.5j \\ -0.075+1.025j & -4.325+5.5j & -0.375-0.675j & 7.675-10.5j & -0.5-0.85j & 0.3+0.25j \\ 0.7+0.3j & 2.5+0.35j & -1.7-1.3j & -0.5-0.85 & 6.3+8j & 1+3j \\ 4-2.5j & 0.7-0.15j & -2+1.5j & 0.3+0.25j & 1+3j & 8+9j \end{bmatrix}$$

APPENDIX B: TSIRDS Supported in this Release

Touchstone Issue Resolution Documents (TSIRDs) define the structure and rationale for changes to the Touchstone file format specification. These are reviewed and approved for inclusion by the IBIS Open Forum. TSIRDs may be viewed at https://ibis.org/tsirds; a template detailing how to write and submit TSIRD proposals is available at the same location.

Touchstone 2.1 includes the following TSIRDs:

- TSIRD 3: Clarify S-parameter Definition
- TSIRD 4.1: [End] Keyword Corrections and Other Editorial Changes
- TSIRD 5.1: Per Port Reference Resistance on the Option Line
- TSIRD 6: Clarify File Extension Rule for Touchstone 1.0 and 1.1 Files