Annex C

(informative)

Tutorial—Mixed-mode network parameters

Current and voltages at inputs with n ports can be transformed into the mixed-mode space or domain. Transformation to the mixed-mode space and back can be expressed as the following congruence transformation:

$$\begin{aligned} Z_{mm} &= M_V \times Z \times M_I^{-1} = M_V \times Z \times M_V^t \\ Z &= M_V^{-1} \times Z_{mm} \times M_I = M_I^t \times Z_{mm} \times M_I \\ Y_{mm} &= M_I \times Y \times M_V^{-1} = M_I \times Y \times M_I^t \end{aligned} \tag{C.1}$$

where

MV is the voltage transformation matrix defined for a two-port as

$$M_V = \begin{bmatrix} 1.0 & -1.0 \\ 0.5 & 0.5 \end{bmatrix} \tag{C.2}$$

M_I is the current transformation matrix defined for a two-port as

$$M_I = \begin{bmatrix} 0.5 & -0.5 \\ 1.0 & 1.0 \end{bmatrix} \tag{C.3}$$

Transformation matrices have the following properties:

$$M_V^{-1} = M_I^t, \quad M_I^{-1} = M_V^t \tag{C.4}$$

They relate currents and voltages in the terminal and in the mixed-mode spaces as follows:

$$\begin{bmatrix} V_d \\ V_c \end{bmatrix} = M_V \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}, \quad \begin{bmatrix} I_d \\ I_c \end{bmatrix} = M_I \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{C.5}$$

where

V_1 is voltage in the terminal space

V_2 is voltage in the terminal space

I_1 is current in the terminal space

I_2 is current in the terminal space

V_d is the voltage of the differential mode

I_d is the current of the differential mode

V_c is the voltage of the common mode

I_c is the current of the common mode

The difference of these modes with the odd and even mode in a symmetrical two-conductor transmission line case is just normalization of the columns in the transformation matrices M_V and M_I. For an arbitrary multiport, the first columns of M_V and M_I correspond to the differential port position, and the second columns to the common-mode port position in the mixed-mode matrices Z_{mm} and Y_{mm}. The numbers of the first and second rows of M_V and M_I correspond to the number of the original ports in the terminal space in the original matrices Z and Y.

Incident and reflected waves at inputs with two ports can be transformed into the mixed-mode space or domain similar to the currents and voltages. Transformation to mixed-mode space and back can be expressed as the following congruence transformation:

$$S_{mm} = T_S \times S \times T_S^t, \quad S = T_S^t \times S_{mm} \times T_S \tag{C.6}$$

where

S_{mm} is the mixed-mode S-parameter matrix

T_s is the orthogonal wave transformation matrix $T_{S-1} = T_S^t$

For two-port interconnects the transformation matrix can be written as follows:

$$T_S = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \tag{C.7}$$

It relates incident and reflected waves in the terminal and mixed-mode spaces as follows:

$$\begin{bmatrix} b_d \\ b_c \end{bmatrix} = T_S \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \tag{C.8}$$

For an arbitrary multiport, the first row of T_s corresponds to the differential port position, and the second row to the common-mode port position in the mixed-mode matrix S_{mm}. The numbers of the first and second columns of T_s correspond to the number of the original ports in the terminal space in the original matrix S. In case of multiple mixed-mode ports, transformation can be done either transforming one port at a time or by constructing united transformation matrices. Numeration of the ports in the mixed-mode form can be defined as in the generalized mixed-mode S-parameters described in Ferrero and Priola [B13]. All differential ports are numbered first, then common-mode ports, and only after that all single-ended or other ports are numbered.

Annex D

(informative)

Tutorial—Calibration and de-embedding basics

D.1 Overview

The vector network analyzer (VNA) calibration removes effects from the internal circuitry of the instrument (directional couplers, the transmission lines, discontinuities from physical signal transitions), and establishes a measurement reference plane. The reference plane can be moved onto a test fixture using de-embedding. De-embedding is a second-tier calibration that removes test fixtures or other interconnects that are between the VNA coaxial reference plane and the desired measurement reference plane. Further, measurements considered direct measurements, such as micro-probe measurements, have artifacts that are not negligible at 50 GHz.

D.2 Calibration with coaxial connection

High-frequency S-parameter measurement equipment uses phase stable, mechanically reliable, precision coaxial cables to connect the internal circuitry to test points TP0 and TP5 (see Annex E for test point definitions). While phase stable cables are required, phase-matched cables are not.

VNAs capture S-parameters directly, while time-domain reflectometers (TDRs) capture frequency domain S-parameters indirectly by using appropriate software. Calibration moves the reference plane from TP0 to TP1 and TP5 to TP4, and removes the influence of the internal circuitry of the instrument. A 12-term short-open-load-thru (SOLT) calibration (see Keysight Technologies [B22]) is the preferred method for this reference plane shift. Mechanical or electrical calibration standards are used with connector types that match the coaxial test leads to perform a SOLT calibration.

The following recommended practices will help achieve an accurate calibration:

- Apply uniform torque to all connections between coaxial cables and calibration standards, using a calibrated torque wrench.
- Ensure the cables and standards are free of debris and contaminants. Examine calibration standards for damage, such as bent or missing pins.
- Female standards are susceptible to damage from turning the male connector during insertion. To prevent damage, hold the male cable with a wrench while turning the threaded nut of the connector to tighten it.

D.3 Thru-reflect-line (TRL)

The TRL method calculates a fixture model using three or more standard measurements of two-port S-parameters. Three two-port measurements provide more equations than unknowns in this method, thus the fixture model solution has multiple approaches. This method assumes that the test fixture is identical to the calibration structure, and often leads to non-causal results when that assumption is not borne out in the implementation. For more information on the TRL calibration method, see Engen and Hoer [B12] and DeGroot, Jargon, and Marks [B7]. The bandwidth of the fixture model is directly related to the length of the line standard, and each line has a minimum and maximum usable frequency (see Annex E). The usable frequency band for a line standard is the range of frequencies over which the phase of the line standard is between zero and 180 degrees. In practice, a guard band of at least 20 degrees (phase between 20 degrees to 160 degrees) should be used in calculating the valid bandwidth. Multiple lines are used to achieve the desired bandwidth.

The line standard is impractically long to achieve a usable fixture model at frequencies as low as 10 MHz. In that case, the line-reflect-match (LRM) method, a form of TRL, is used to calculate the fixture model at low frequencies. With the LRM method, a load standard is used instead of a line standard, and a line length of infinity is used in the equation for the load standard.

D.4 De-embedding past the calibration plane

The procedure described in D.2 sets the measurement reference plane to the end of the VNA coaxial cable assembly, at test points TP1 and TP4. This annex contains instructions to place the reference plane at the device under test (DUT), at test points TP2 and TP3. This step is sometimes referred to as a second-tier calibration.

The test fixture model is removed from a FIX-DUT-FIX by means of matrix algebra. Simply convert the fixture model S-parameters to T-parameters as described in Frei, Cai, and Muller [B14], invert the fixture model, and multiply the fixture model T-parameters by the FIX-DUT-FIX T-parameters; see Equation (D.1).

$$T_D = T_F^{-1} T_{FDF} T_{F'}^{-1} \tag{D.1}$$

where

T_D is the DUT T-parameters

T_F is the fixture model T-parameters

T_{FDF} is the Fixture-DUT-Fixture T-parameters

These T-parameters are 2×2 in the two-port, or single-ended, case or 4×4 in the four-port, or mixed-mode, case.

The de-embedding process for odd numbers of ports is unique, and is described in Tsiklauri and Dikhaminjia [B33].

D.5 De-embedding tools overview

This subclause describes the six de-embedding methods that are included in this standard. Those de-embedding methods are TRL, 2X-Thru, 1X-Reflect, impedance-corrected de-embedding, full 3D wave simulation, and port extension.

D.6 Overview of generic de-embedding methods

D.6.1 2X-Thru de-embedding

The 2X-Thru method uses a 2X-Thru standard to create the fixture model (Keysight Technologies [B22]). The assumptions are the following:

- The test fixture has the same impedance, delay, and loss as the standard.
- The reference plane of the DUT in time is at one-half of the delay of the 2X-Thru standard.
- Each half of the 2X-Thru is symmetric.

All fixture model elements are found, and this concludes the algorithm. The expected accuracy of this method is better than −20 dB absolute error.

D.6.2 1X-Reflect de-embedding

The 1X-Reflect method uses the DUT test fixture itself to estimate the de-embedding S-parameters, avoiding in this way the requirement of a separate de-embedding test structure like the 2X-Thru. This method requires the DUT to be removable and uses a 1X-Reflect standard to create all the terms in the fixture model (Keysight Technologies [B22]), as shown in Figure D.1. The termination of the reflect should be an open or short. If an open and a short are available, use both to achieve higher accuracy.

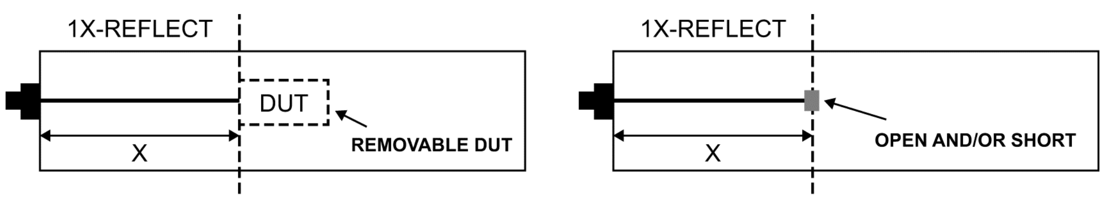

Figure D.1—1X-Reflect methodology requires a test fixture with a removable DUT that can be exchanged for an open or a short

As with the 2X-Thru method, transform the 1X-Reflect S-parameters into the time-domain Equation (D.1), while assuming the dc point is that of a Thru. Find the point in time where the impulse response is at its maximum for an open, or minimum for a short. The result is the middle reference point. Make the values of the 1X-Reflect time-domain impulse response equal to zero from several points before the middle reference point to the last point. The exact point to start the zeros will depend on the maximum available frequency.

When a short and an open are available, find the test fixture model with the following alternate approach. The expected accuracy of using an open and short together is higher than using only a short or an open. Commercial de-embedding software packages—such as those described in Dunsmore, Cheng, and Zhang, [B10] and Huang [B20]—use complex de-embedding algorithms. Combining 1X-Reflect and impedance-corrected methods can improve de-embedding accuracy further.

The accuracy of the 1X-Reflect method depends significantly on the quality of the implemented open or short and of the signal path, especially if a large number of discontinuities are present. Since a full S-parameter reference measurement is not available (like on the 2X-Thru case), this makes it very hard to define a set of normative parameters for the 1X-Reflect. Therefore, it is not included in the main body of this standard, and only described in an informative way in this section. But given its advantages, especially for socketed parts, the user for a given application might start with both 2X-Thru and 1X-Reflect de-embedding approaches to gain confidence on the results correlation, and then later move to a 1X-Reflect only methodology for future test fixtures intended for the same application space.

When using a 1X-Reflect for bidirectional test fixtures (e.g., bidirectional I/O testing using unidirectional test equipment), only a short should be used to avoid a double reflection as shown in Figure D.2.

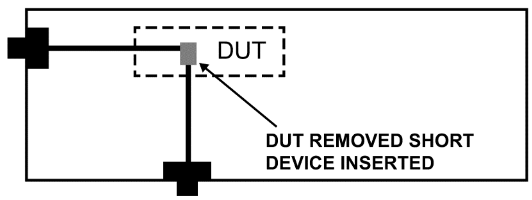

Figure D.2—1X-Reflect topology for bidirectional test fixture where only a short can be used

D.6.3 Impedance-corrected 2X-Thru de-embedding

This method creates a test fixture model that matches the return loss of the fixture to be removed (instead of using the return loss of 2X-Thru structure), and using S_{11}^{1x} and S_{22}^{1x} from this fixture model together with the measured S_{21}^{2x} to compute S_{21}^{1x}.

By using the text fixture model that matches the impedance profile of FIX-DUT-FIX, instead of the 2X-Thru, the de-embedding error due to impedance mismatch between 2X-Thru and FIX-DUT-FIX are minimized.

Various de-embedding tools may have different algorithms for impedance-corrected 2X-Thru de-embedding, and the discussion of algorithm is beyond scope of this document.

D.6.4 Electromagnetic simulation

The geometry of the fixture is imported into a 2.5D or 3D full-wave simulation tool and the resultant S-parameters are the fixture model. Material properties, mesh, boundary conditions, and ports need to be defined carefully, as the accuracy of the fixture model is directly related to the accuracy of the simulation. The simulation can be altered by iterative means to match the time and frequency domain signatures of the fixture to be removed. The accuracy of the simulation model can be improved by measuring a simple structure, such as a Line or Beatty structure using that fixture, and tuning the simulation model to match the measured results.

D.6.5 Port extension

Port extension removes the delay effects and, optionally, the loss of the test fixture by assuming the fixture is a perfect transmission line and using a transmission line model as the fixture model. It should only be used when there is very little return loss from test fixture impedance discontinuities.

D.7 Mixed-mode fixture model calculation

During multi-mode fixture model calculations, the coupling within a differential pair is considered as well as the transmission path. Use the same techniques above with the guidance below to create the mixed-mode fixture model.

Create the differential and common quadrants separately by assuming the reference impedance is 100 Ohm and 25 Ohm respectively. These are the values for standard test equipment. Non-standard reference impedances can be used as well, but are outside of the scope of this specification. Create the differential to common and common to differential quadrants by assuming all zeros.

Use the guidance in Annex C to convert from mixed-mode back to single-ended then de-embed using Equation (D.1). Alternatively, de-embed the differential or common-mode quadrant independently using Equation (D.1) with the differential or common-mode T-parameters of the fixture model and FIX-DUT-FIX.

D.8 Example implementation

An example implementation of the content in this annex is available at Ellison and Tsiklauri [B11].

Annex E

(informative)

Test fixture definition

E.1 Overview

Test fixtures are structures that provide connection to a component or interconnect to be characterized. The component to be characterized is commonly referred to as the device under test (DUT). A test fixture is required in scenarios where measurement equipment cannot be directly connected to the DUT.

The test fixture influences the measurement result. As frequencies increase, the attenuation and reflections created by the fixture increasingly mask the performance of the DUT. De-embedding removes these unwanted effects and isolates the DUT. Figure E.1 and Figure E.2 show examples of test fixtures and the reference planes before and after de-embedding of two measurement scenarios. Connections to the DUT can be proliferated if needed.

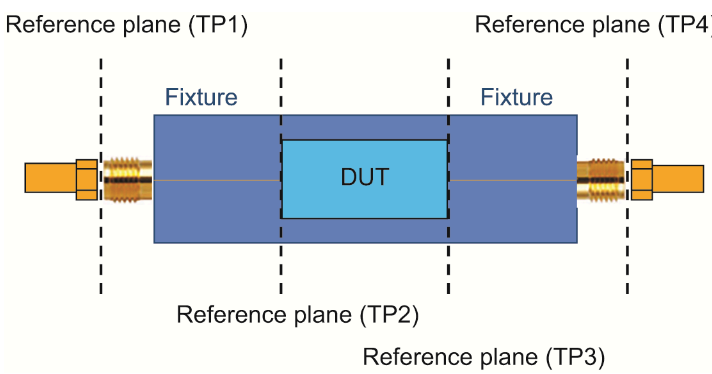

Figure E.1—Coaxial connectors on a printed circuit board (PCB) with microstrip traces connected to a DUT

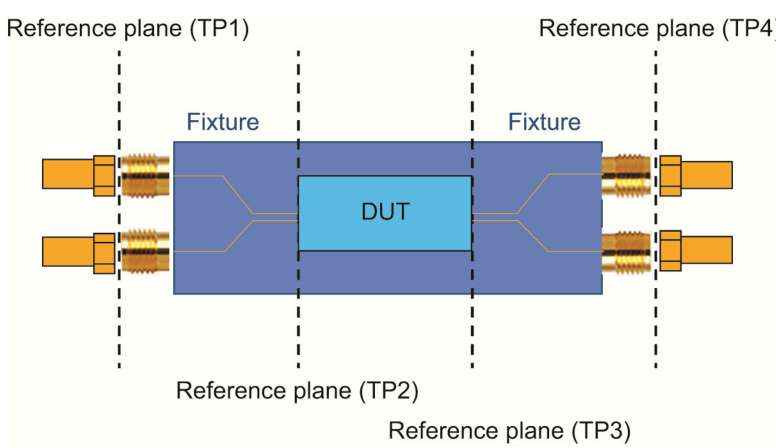

Figure E.2—Coaxial connectors on a PCB with differential microstrip traces to a DUT

E.2 Single-ended de-embedding

E.2.1 Test points

S-parameter measurements are taken at a reference plane. The calibration process moves the reference plane to a physical location with known reference impedance. The reference planes associated with measured S-parameters are TP0 and TP5 or TP1 and TP4, shown in Figure E.1. TP0 and TP5 are the locations inside the vector network analyzer (VNA) before applying a 12-term error model to account for the VNA architecture. The 12-term model and its associated formulas are outside the scope of this specification. TP1 and TP4 are at the end of the transmission line starting at TP0 and TP5 respectively. Typically, this is a coaxial connector, but may also be a probe tip or other physical connection. TP2 and TP3 are the beginning of the DUT where the fields are transverse electromagnetic (TEM). Moving from TP1 to TP2 or TP4 to TP3 requires a calculated or modeled fixture model. Figure E.3 illustrates the test points in a signal flow graph.

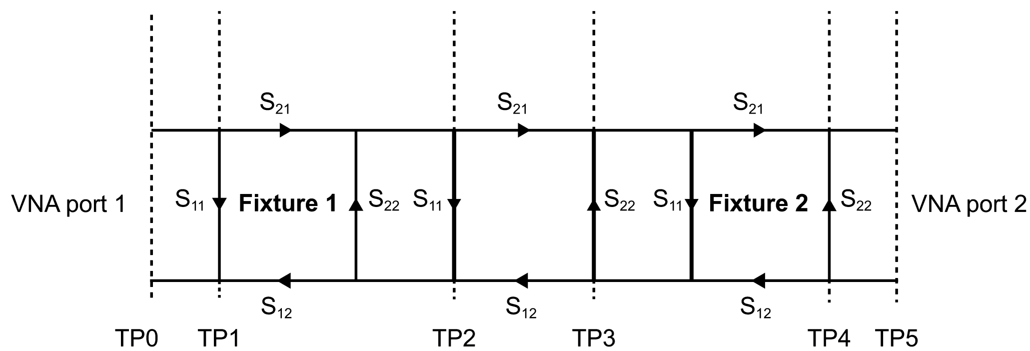

Figure E.3—Measurement diagram with test points

E.2.2 Calibration standards

Fixture models are created from custom user-defined standards. Thru-reflect-line/line-reflect-match (TRL/LRM), multiline modeled fixture models, and 2X-Thru based calibration structures are defined below.

2X-Thru calibration methods require one 2X-Thru standard measurement to create the fixture model. The 2X-Thru is a transmission line that is twice the length of the transmission line to be removed. Typically, a connector transitions the test lead coaxial transmission line to the transmission line connected to the DUT. Figure E.4 shows the signal flow diagram of a 2X-Thru, and Figure E.5 shows the side view of a 2X-Thru on a PCB.

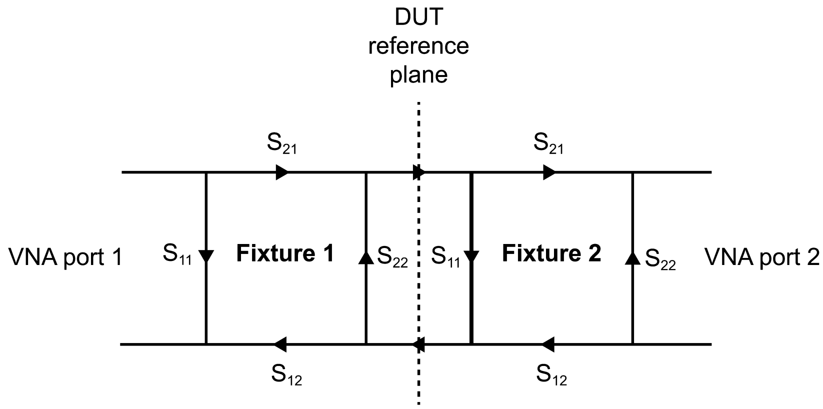

Figure E.4—2X-Thru standard signal flow graph

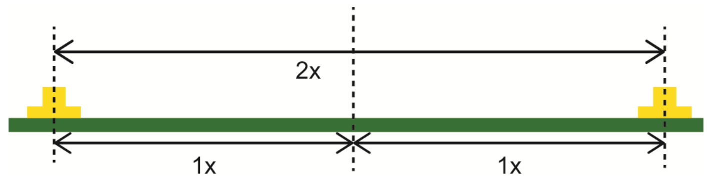

Figure E.5—2X-Thru standard on PCB

TRL/LRM calibration requires a line, reflect, 2X-Thru, and load standard.

The line standard is a transmission line twice the length of the line to be removed with an extra length l. l is valid at frequencies where its phase is between 20° and 160°.

The phase θ of a line standard is determined using Equation (E.1) with frequency as the independent variable:

$$\theta = \frac{F \times l \times 360\sqrt{\varepsilon_r}}{c} \tag{E.1}$$

where

θ is the phase of the standard in degrees

F is frequency in Hz

l is the length of the extra transmission line in meters

ε_r is the effective relative permittivity of the transmission line medium

c is the speed of light, in m/s

Figure E.6 shows a signal flow graph of the line standard, and Figure E.7 shows a line standard side view on a PCB. Design around the highest frequency and work backward toward the lowest frequency.

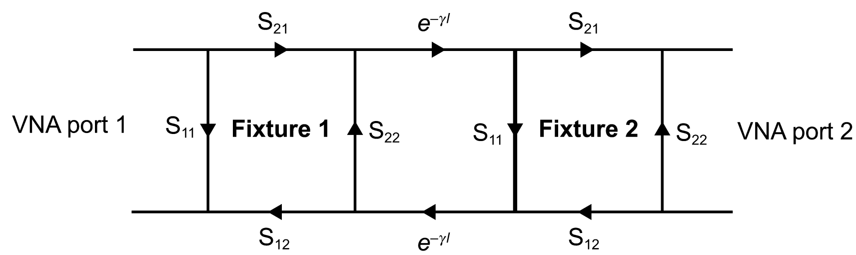

Figure E.6—Line standard signal flow graph

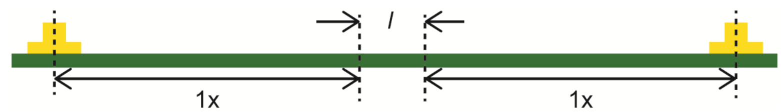

Figure E.7—Line standard on PCB

A TRL line length design example follows:

$\varepsilon_r = 4$, $F_{max} = 50$ GHz, θ_{max} is 160°. Assume the LRM fixture model is valid to 1 GHz.

Step 1. Calculate the shortest line length, l_1

$$l_1 = \frac{\theta_{max} c}{360 \times F_{max} \sqrt{\varepsilon_r}} = \frac{160 \times 300e6}{360 \times 50e9 \times \sqrt{4}} = 1.33 \text{ mm} \qquad \text{(E.2)}$$

Step 2. Calculate the minimum frequency for that line. This will be the maximum frequency for line 2.

$$F_{min} = \frac{\theta_{min} c}{360 \times l_1 \sqrt{\varepsilon_r}} = \frac{20 \times 300e6}{360 \times 0.00133 \times \sqrt{4}} \qquad \text{(E.3)}$$

Step 3. Calculate l_2 by using 6.25 GHz as F_{max}.

$$l_2 = \frac{\theta_{max} c}{360 \times F_{max} \sqrt{\varepsilon_r}} = \frac{160 \times 300e6}{360 \times 6.25e9 \times \sqrt{4}} = 10.67 \text{ mm} \qquad \text{(E.4)}$$

Step 4. Calculate the associated minimum frequency for that line.

$$F_{min} = \frac{\theta_{min} \times c}{360 \times l_2 \times \sqrt{\varepsilon_r}} = \frac{20 \times 300e6}{360 \times 0.01067 \times \sqrt{4}} = 781 \text{ MHz} \qquad \text{(E.5)}$$

Since F_{min} is below the LRM maximum frequency, 1 GHz, line 2 is the last line. In summary, the LRM fixture model is valid from dc to 1.5 GHz, the line 1 fixture model is valid from 781 MHz to 6.25 GHz, and the line 2 is valid from 6.25 GHz to 50 GHz. There is overlap between the line 2 fixture model and the