Measurement of Balanced Antennas using Mixed-mode Network Parameters

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Abstract

Balanced antennas are conventionally measured using probe-integrated or external baluns between the unbalanced port of instrument and their balanced ports. This paper proposes a new measurement method based on mixed-mode parameters to experimentally characterize balanced antennas. With this method, the balanced antenna is measured as a single-ended two-port device and the need for baluns is suppressed, which increases the accuracy, enhances the frequency range, and reduces the cost and complexity of the measurement setup.

1 Introduction

Differential microwave components and systems are currently receiving increased interest, due to fundamental advantages over their single-ended counterparts, including intrinsic common noise rejection, higher dynamic range, superior structure performance, even-mode distortion suppression, etc [1]. As parts of differential wireless systems, balanced antennas have a symmetric configuration and exhibit symmetric radiation pattern, which lead to particularly efficient co-designed differential circuits.

Balanced antennas are conventionally excited by baluns in self-designed systems. However, baluns are not required in a fully-differential co-designed systems, where the conductor pairs of the balanced antennas are directly connected to differential circuits. In this case, the balanced antenna must be measured *without any balun* for accurate characterization. Since almost all the modern test equipment, such as vector network analyzers, have only single-ended ports, typically based on coaxial cable, they can not directly measure balanced antennas. Two traditional approaches exist to address this problem: 1) the mirror image method, which puts half of the balanced antenna above a large ground at the symmetry plane, so that the input impedance of the balanced antenna is twice that of the measured input impedance of the half unbalanced structure; 2) the measurement balun method [2], and the application of various subsequent corrections (possibly including the utilization of several baluns covering different frequency bands for broad-band antennas).

The mirror image method is very difficult to implement in practise since an infinite ground is theoretically required for accuracy. The balun method splits into two categories, one using internal integrated baluns, such as commercially available differential probes, and another using external baluns. However, these probes are expensive and difficult to use, especially when for measuring radiation patterns, which requires the rotation of the probe and the antenna. An antenna designer not equipped with a balun probe has to design his own external baluns. One example is the coaxial sleeve balun shown in Figure 1 used to measure the dipoles. The problems with such baluns are: 1) they are frequency dependent and require extra design effort; 2) they require a special calibration technique to remove their effects; 3) even with careful calibration, the balun imbalance produces common-mode signals, which may be reflected or radiated, affecting the measured impedance and radiation in both cases.

This paper proposes a new measurement technique using the mixed-mode impedance parameters [3]. This new measurement method does not require any additional balun and uses only normal two-port instruments and calibration standards.

2 Description of the Proposed Measurement Method

Figure 2 depicts the proposed method to measure the input impedance and the radiation patterns of balanced antennas. The two terminals of the balanced antenna under test (AUT), which may be either two free-standing wires

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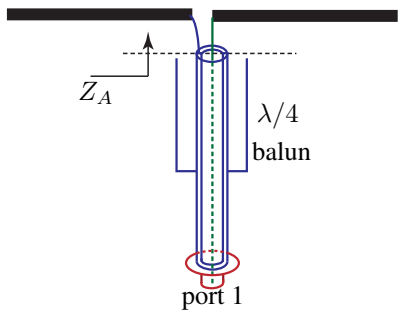

Figure 1: Conventional balanced antenna measurement method using coaxial sleeve balun.

or two wires with the common ground plane when it exists, are connected to a single-ended two-port instrument (typically a vector network analyzer) *as if they were single-ended terminals*.

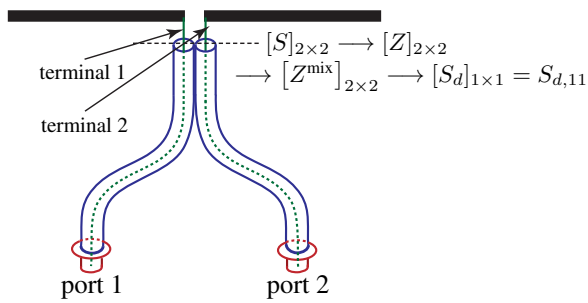

Figure 2: Proposed balanced antenna measurement method, using a two-port single-ended (unbalanced) instrument and performing the mixed-mode network impedance matrix conversion given by (5).

As a result of the single-ended setup of Fig. 2, the actual one-port differential network formed by the antenna, which will ultimately be characterized by its natural 1×1 differential scattering matrix, $[S_d]_{1\times1} = S_{d,11}$, is measured as a two-port network, leading to a 2×2 scattering matrix, $[S]_{2\times2}$. This matrix is straightforwardly converted into the corresponding impedance matrix $[Z]_{2\times2}$ using standard conversion formulas [4]. Next $[Z]_{2\times2}$ is transformed into a mixed differential-mode/common-mode 2×2 impedance matrix, $[Z^{\text{mix}}]_{2\times2} = [Z_{d1d1}, Z_{d1c1}; Z_{c1d1}, Z_{c1c1}]$, using a transformation formula which will be derived in Sec. 3. From this point, the differential input impedance of the antenna is Z_{d1d1}, and the differential return loss is straightforwardly found from Z_{d1d1}, computed as $S_{d,11} = (Z_{d1d1} - Z_{0d})/(Z_{d1d1} + Z_{0d})$, where Z_{0d} is the differential characteristic impedance. The measurement of the radiation patterns of the balanced antenna will be described in Sec. 3.

3 Single-Ended to Mixed-Mode Impedance Matrix Transformation

The conventional impedance matrix $[Z]$ of a two-port network relates the total (incident plus reflected) voltages and currents (flowing toward the network) at each port as

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}, \tag{1}$$

or, more compactly,

$$[V] = [Z][I]. \tag{2}$$

As explained in Sec. 2, this matrix is obtained from the two-port single-ended measurement setup of Fig. 2 by a standard conversion formula, namely $[Z] = Z_0 \{[I] + [S]\} \{[I] - [S]\}^{-1}$, where Z_0 is the reference impedance of the single-ended measurement instrument [4].

The actual one-port balanced antenna is characterized by the mixed-mode voltages and current [3]

$$\left[V^{\text{mix}}\right] = \begin{bmatrix} V_{d1} \\ V_{c1} \end{bmatrix}, \quad \left[I^{\text{mix}}\right] = \begin{bmatrix} I_{d1} \\ I_{c1} \end{bmatrix}, \tag{3}$$

which are defined in terms of the single-ended voltages and currents in (1) as

$$V_{d1} = V_1 - V_2, \tag{4a}$$

$$V_{c1} = \frac{V_1 + V_2}{2}, \tag{4b}$$

$$I_{d1} = \frac{I_1 - I_2}{2}, \tag{4c}$$

$$I_{c1} = I_1 + I_2, \tag{4d}$$

where the subscripts d and c stand for the differential-mode and common-mode quantities, respectively. Inserting (4) into (3), yields the following explicit relations between the mixed-mode and the single-ended voltages and currents:

$$\left[V^{\text{mix}}\right] = \begin{bmatrix} V_{d1} \\ V_{c1} \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = [W_V][V], \tag{5a}$$

$$\left[I^{\text{mix}}\right] = \begin{bmatrix} I_{d1} \\ I_{c1} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & -\frac{1}{2} \\ 1 & 1 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = [W_I][I]. \tag{5b}$$

At this point, we define, in analogy with (1), the mixed-mode impedance matrix $\left[Z^{\text{mix}}\right]$ from the relation

$$\begin{bmatrix} V_{d1} \\ V_{c1} \end{bmatrix} = \left[Z^{\text{mix}}\right] \begin{bmatrix} I_{d1} \\ I_{c1} \end{bmatrix} = \begin{bmatrix} Z_{d1d1} & Z_{d1c1} \\ Z_{c1d1} & Z_{c1c1} \end{bmatrix} \begin{bmatrix} I_{d1} \\ I_{c1} \end{bmatrix}. \tag{6}$$

Substituting (5) into (6), next substituting (2) in the resulting equation, and finally post-multiplying everything by $[W_I]^{-1}$ yields the sought after transformation formula from the single-ended matrix to the mixed-mode matrix

$$\left[Z^{\text{mix}}\right] = [W_V]\,[Z]\,[W_I]^{-1}, \tag{7}$$

from which the mixed-mode impedance matric $\left[Z^{\text{mix}}\right]$ obtained. If the scattering parameters are measured, they are first converted to impedance parameters, then applying the conversion in (7) will obtain $\left[Z^{\text{mix}}\right]$.

3.1 Radiation Pattern Measurement

The radiation patterns of balanced antennas can be measured using a similar setup as that shown in Fig. 2 using one receiver for each of the two terminals of the antenna, as illustrated in Fig. 3.

The radiation patterns $D_d(\theta)$ in a given (E or H) plane of the antenna is found by measuring the normalized squared differential-mode voltage (4a) as a function of the angle θ as

$$D_d(\theta) = \frac{V_{d1}^2(\theta)}{V_{d1}^2(\theta_{\text{max}})}, \tag{8}$$

where θ_{max} denotes the angle where the received power is maximum.

Some antennas provide circular polarization by using simultaneously the differential mode and the common mode of the structure [5]. In this case, the circular radiation patterns may be measured with the setup of Fig. 3 from two separate linear polarization measurements, the differential-mode linear polarization measurement, given by (8), and the common-mode linear polarization measurement, given by

$$D_c(\theta) = \frac{V_{c1}^2(\theta)}{V_{c1}^2(\theta_{\text{max}})}, \tag{9}$$

using (4b), where $V_{c1}^2(\theta_{\text{max}}) = V_{d1}^2(\theta_{\text{max}})$ for an ideal axial ratio of 1.

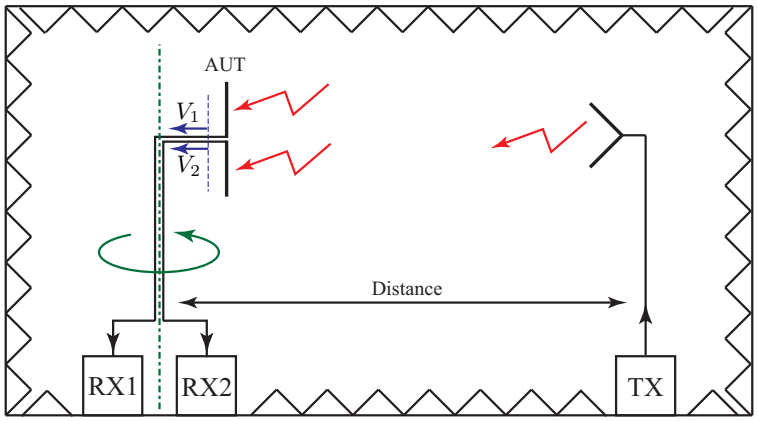

Figure 3: Radiation pattern measurement in anechoic chamber. The quantities used to plot the radiation pattern are calculated from the received signals, V_1 and V_2, at the antenna plane with (4a-b). If the antenna is perfectly balanced, $V_1 = -V_2$, resulting $V_d = 2V_1$ and $V_c = 0$.

4 Conclusion

A new measurement method for balanced antennas based on mixed-mode network parameters has been presented. This method provides both input impedance and radiation patterns measurements. In contrast to conventional techniques, it does not require any balun, which reduces the cost, improves the accuracy, allows broadband characterization, and easily adapts to any kind of differential antenna. It is particularly useful to the design of balanced antennas in co-designed differential microwave systems.

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