

S Parameter Extraction Approach to the Reduction of Dipole Antenna Measurements *

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Modern test equipment used for antenna measurements, such as vector network analyzers (VNA), generally provide un-balanced coaxial measurement ports. This presents a problem when performing measurements on devices such as dipole antennas, which present a balanced input. A balun must be used to interface the dipole to the VNA. Since there is no straightforward way to include the balun in the standard VNA calibration procedure, the calibration, and thus the measurement is referenced to the un-balanced input of the balun. However, it is desired to measure the antenna response at its input terminals, which are on the output side of the balun. Therefore, it is necessary to account for the balun response in VNA measurements of dipole antennas. Methods based upon scattering parameter, or S-parameter analysis are discussed here for this purpose. First the reduction of measurements from a single dipole to determine input impedance is considered. Then the reduction of measurements from a pair of dipoles to determine the coupling between them is considered.

1 Reduction of Dipole Antenna Input Impedance Measurement

A typical test setup used to measure the input impedance of a dipole antenna is shown in Figure 1. A VNA is connected to the unbalanced side of a balun. The balun is assumed to have coaxial connectors on all three ports. Short adapter cables are used to connect the ports on the balanced side of the balun to the dipole radiating elements. It is assumed that these adapter cables each consist of a coaxial connector, in order to mate to the balun ports, and a short bare conductor, in order to mate to the dipole elements.

It is desired to determine the complex reflection coefficient at the antenna terminals, from which antenna input impedance can be determined. However, the VNA complex reflection coefficient measurement is referenced to the unbalanced side of the balun. In general, if the S-parameters for the cascade of components between the balun input and the antenna terminals are known, it is possible to determine the reflection coefficient at the antenna terminals, Γ_{ant} , from the VNA measured reflection coefficient, Γ_{meas} . A standard three port model for the balun is shown in Figure 2(a) where the balun S-parameters are denoted as \mathbf{S}'' . All ports are assumed to be referenced to a common characteristic impedance of Z_0 . Analysis is greatly simplified by converting the S-parameters corresponding to the three port model, \mathbf{S}'' , to those corresponding to an equivalent two

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port model, \mathbf{S}' , depicted in Figure 2(b). The transform between these two models is given by [2]

$$\mathbf{S}' = \begin{bmatrix} S''_{11} & \frac{S''_{12} - S''_{13}}{2} \\ S''_{21} - S''_{31} & \frac{S''_{22} + S''_{33} - S''_{23} - S''_{32}}{2} \end{bmatrix}. \quad (1)$$

Note that this transform assumes that the balun exhibits perfect amplitude and phase balance between the two ports of the balanced output. Also note that in the two port model, the input side is referenced to a characteristic impedance of Z_0 while the output side is referenced to $2Z_0$.

The pair of short adapter cables between the balun and dipole terminals are modeled as a single lossless transmission line of length, L , and characteristic impedance, Z_{0k} . This model is meant to account for the phase delay due to the coaxial connectors and any coaxial cabling that make up the adapter cables. The S-parameters for a lossless transmission line are [3]

$$\mathbf{S}^* = \begin{bmatrix} \frac{j(\bar{Z}_{0k}^2 - 1) \sin \beta L}{2\bar{Z}_{0k} \cos \beta L + j(\bar{Z}_{0k}^2 + 1) \sin \beta L} & \frac{2\bar{Z}_{0k}}{2\bar{Z}_{0k} \cos \beta L + j(\bar{Z}_{0k}^2 + 1) \sin \beta L} \\ \frac{2\bar{Z}_{0k}}{2\bar{Z}_{0k} \cos \beta L + j(\bar{Z}_{0k}^2 + 1) \sin \beta L} & \frac{j(\bar{Z}_{0k}^2 - 1) \sin \beta L}{2\bar{Z}_{0k} \cos \beta L + j(\bar{Z}_{0k}^2 + 1) \sin \beta L} \end{bmatrix} \quad (2)$$

where $\bar{Z}_{0k} = Z_{0k}/Z_0$. It is assumed that $\beta = 2\pi/\lambda_0$ where λ_0 is the free space wavelength of the operating frequency. There may be some reactance due to the unshielded ends of the adapter cables which interface to the dipole elements. However, this reactance is assumed to be small and is ignored here.

An S-parameter model for the combination of balun and adapter cables is shown in Figure 3. To determine the response of the combination of the balun and adapter cables, it is necessary to convert the S-parameters of each component, \mathbf{S}' and \mathbf{S}^* , to their corresponding scattering transfer parameters, or T-parameters, \mathbf{T}' and \mathbf{T}^* as described in [4]. The cascaded response is then given by

$$\mathbf{T} = \mathbf{T}'\mathbf{T}^*. \quad (3)$$

This result is then converted to the corresponding S-parameters, \mathbf{S} . The reflection coefficient at the antenna terminals can be determined using [5]

$$\Gamma_{ant} = \frac{S_{11} - \Gamma_{meas}}{S_{11}S_{22} - S_{22}\Gamma_{meas} - S_{12}S_{21}}. \quad (4)$$

Finally, the desired antenna input impedance is given by

$$Z_{ant} = 2Z_0 \frac{1 + \Gamma_{ant}}{1 - \Gamma_{ant}}. \quad (5)$$

The above procedure is now applied to the reduction of impedance measurements of an inverted-V wire dipole antenna. The antenna considered has a total length of roughly 3.6 m, with elements made of wire 4 mm in diameter and which are drooped down by 45° . The antenna is operated directly over an Earth ground. The characteristic impedance of all VNA measurements is $Z_0 = 50\Omega$. The full three-port S-parameters of the balun, \mathbf{S}'' , are first measured. The electrical length of the adapter cable coaxial connectors are then measured. This is accomplished by soldering two such connectors back to back, and measuring the electrical delay of the connector pair, τ , using a VNA. The electrical length of one connector is then $L_c = \tau c/2$ where c is the speed of light. In Equation 2, it is assumed that $L = L_c$ and $Z_{0k} = 2Z_0$. The antenna impedance determined by accounting for both the balun and adapter cables using the reduction procedure described in this

section, by accounting for the balun but not the adapter cables (setting $L=0$ in Equation 2), and by accounting for neither the balun or adapter cables (replacing Γ_{ant} with Γ_{meas} in Equation 5) are compared in Figure 4. The result from NEC2 simulation is also included for reference. As can be seen, when the effects of the balun and adapter cables are ignored in measurement data reduction, the measured impedance bears no resemblance to the simulated impedance. By properly accounting for the balun in data reduction, the measured impedance exhibits similar characteristics as the simulated impedance. In this case, however, the measured resistance peak is shifted down in frequency significantly, by roughly 14%, and is narrower as compared with the same feature in simulation. When the effects of both the balun and adapter cables are included in data reduction, the measured and simulated impedances agree reasonably well over the entire frequency range.

It is evident in Figure 4 that the resistance peak in the final reduced measurement is still shifted down by about 5.5% compared with simulation. Some of this disagreement is likely due in part to not modeling in simulation the supporting structure of the constructed dipole, which includes the mast made out of four inch diameter PVC tube. Previous measurements have suggested that this mast could shift the peak resistance down in frequency by 2%. The other most likely causes of discrepancy are not accounting for all of the delay in the adapter cables, and simulation error.

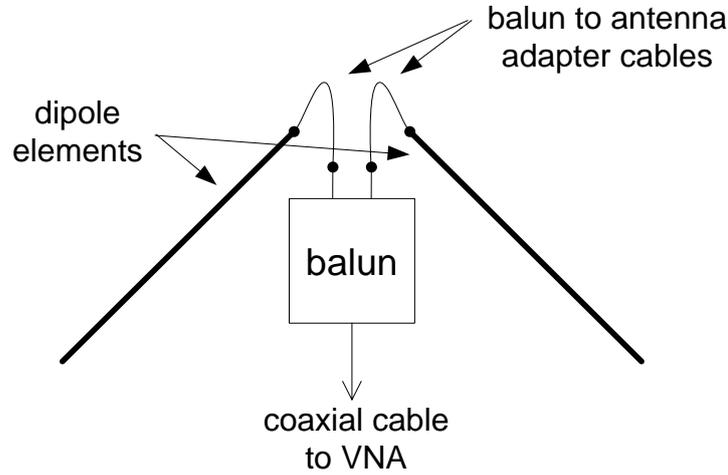


Figure 1: Test setup for measurement of dipole antenna input impedance.

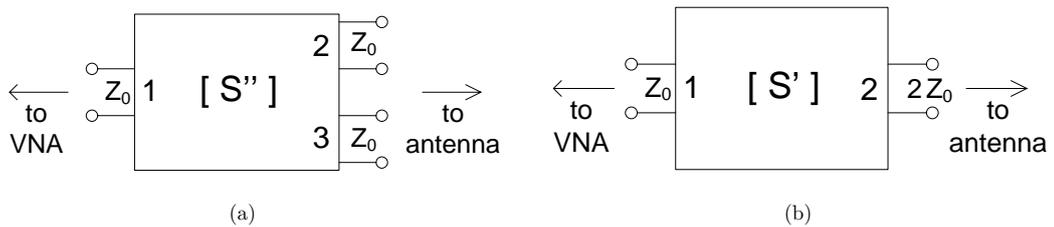


Figure 2: S parameter models for balun. (a) Three port model, (b) equivalent two port model.

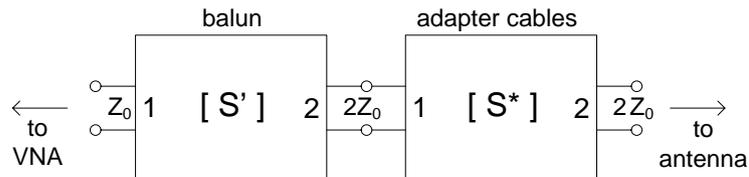


Figure 3: S parameter model for the combination of balun and adapter cables.

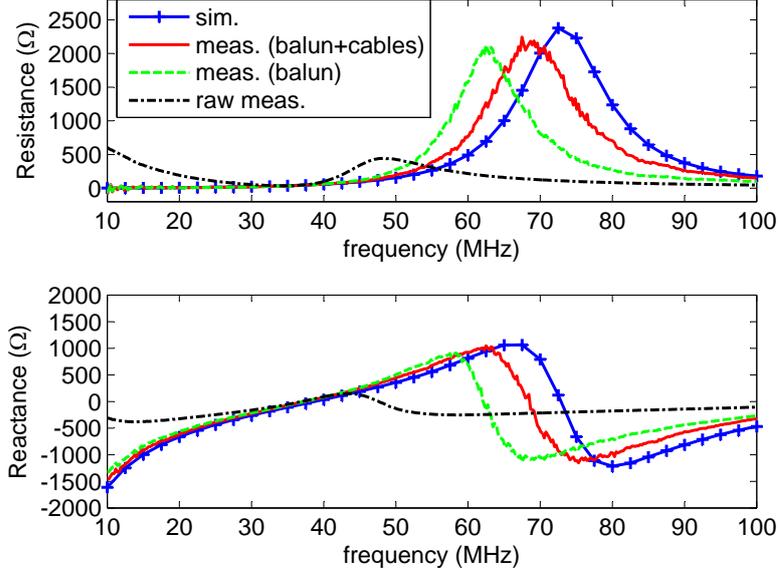


Figure 4: Comparison of measurement and simulation of the input impedance of a wire inverted-V dipole antenna. ‘meas. (balun+cables)’ is the measurement result when the effects of both the balun and adapter cables are taken into account. ‘meas. (balun)’ is the measurement result when the effects of only the balun are taken into account. ‘raw meas.’ is the measurement result when the effects of neither the balun or adapter cables are taken into account.

2 Reduction of Coupling Measurements Between Dipole Antennas

A typical test setup used to measure coupling between two dipole antennas is shown in Figure 5. Each antenna is connected through a balun to a measurement port of the VNA, which is used to measure the S-parameters of the antenna pair. Note that, as discussed in Section 1, short adapter cables are used to interface each balun with its corresponding dipole. The effects of the adapter cables are ignored initially in this development for simplicity, but will be addressed later in this section. A simple analytical model for the test setup in Figure 5 is shown in Figure 6. The baluns are modeled as two port devices with S-parameters \mathbf{S}_A and \mathbf{S}_C , which are calculated from the measured three port S-parameters of each balun using Equation 1. The combination of the two antennas and the propagation channel between them, here termed the antenna pair, is also modeled as a two port device with S-parameters, \mathbf{S}_B . The desired coupling between antennas is defined here as

$$C = |S_{B,21}|^2. \quad (6)$$

However, the S-parameters measured by the VNA, \mathbf{S}_m , are due to the cascade of the two baluns and the antenna pair.

To extract the desired coupling between antennas, it is first necessary to convert the S-parameters \mathbf{S}_m , \mathbf{S}_A , \mathbf{S}_B , and \mathbf{S}_C to their corresponding T-parameters \mathbf{T}_m , \mathbf{T}_A , \mathbf{T}_B , and \mathbf{T}_C . The T-parameters are related by the following expression

$$\mathbf{T}_m = \mathbf{T}_A \mathbf{T}_B \mathbf{T}_C \quad (7)$$

which may be expressed explicitly in terms of matrix components as

$$\begin{bmatrix} T_{m,11} & T_{m,12} \\ T_{m,21} & T_{m,22} \end{bmatrix} = \begin{bmatrix} T_{A,11} & T_{A,12} \\ T_{A,21} & T_{A,22} \end{bmatrix} \begin{bmatrix} T_{B,11} & T_{B,12} \\ T_{B,21} & T_{B,22} \end{bmatrix} \begin{bmatrix} T_{C,11} & T_{C,12} \\ T_{C,21} & T_{C,22} \end{bmatrix}. \quad (8)$$

Equation 8 can be rewritten as a system of equations of the form

$$\mathbf{Ax} = \mathbf{b} \quad (9)$$

where

$$\mathbf{A} = \begin{bmatrix} T_{A,11}T_{C,11} & T_{A,11}T_{C,21} & T_{A,12}T_{C,11} & T_{A,12}T_{C,21} \\ T_{A,11}T_{C,12} & T_{A,11}T_{C,22} & T_{A,12}T_{C,12} & T_{A,12}T_{C,22} \\ T_{A,21}T_{C,11} & T_{A,21}T_{C,21} & T_{A,22}T_{C,11} & T_{A,22}T_{C,21} \\ T_{A,21}T_{C,12} & T_{A,21}T_{C,22} & T_{A,22}T_{C,12} & T_{A,22}T_{C,22} \end{bmatrix}, \quad (10)$$

$$\mathbf{b} = \begin{bmatrix} T_{m,11} & T_{m,12} & T_{m,21} & T_{m,22} \end{bmatrix}^T, \quad (11)$$

$$\mathbf{x} = \begin{bmatrix} T_{B,11} & T_{B,12} & T_{B,21} & T_{B,22} \end{bmatrix}^T, \quad (12)$$

and the T superscript denotes a vector transpose. Note that the components of \mathbf{x} are the T-parameters of the antenna pair, which are determined by solving the system of equations 9 using

$$\mathbf{x} = \mathbf{A}^{-1}\mathbf{b} \quad (13)$$

where $^{-1}$ denotes matrix inversion. The T-parameters, \mathbf{T}_B , of the dipole pair are then converted back to the S-parameters, \mathbf{S}_B , and the coupling between dipoles is calculated using Equation 6.

If the phase component of the antenna pair response is of interest, for instance, in order to determine the mutual impedance between the antennas, it may be necessary to include the effects of the adapter cables between the baluns and antennas in the above development. This can be done by simply inserting terms in Equation 7 between \mathbf{T}_A and \mathbf{T}_B and between \mathbf{T}_B and \mathbf{T}_C corresponding to lossless transmission line models of the adapter cables, as discussed in Section 1. Other than re-writing the matrix \mathbf{A} in order to include these terms, the rest of the development follows as described above.

The above procedure is now applied to the reduction of coupling measurements between a pair of inverted-V wire dipole antennas. The antennas considered each have a total length of roughly 3.6 m, with elements made of wire 4 mm in diameter and which are drooped down by 45° . The antennas are placed 4 m apart, and are oriented to be parallel with one another. The antennas are operated directly over an Earth ground. The characteristic impedance of all VNA measurements is $Z_0 = 50\Omega$. The full three port S-parameters of the two baluns are first measured and converted to their two port equivalents, \mathbf{S}_A and \mathbf{S}_C . Then the S-parameters of the antenna pair, \mathbf{S}_m , are measured. The antenna coupling determined by accounting for the baluns as described above, and by not accounting for the baluns (replacing \mathbf{S}_B with \mathbf{S}_m in Equation 6) are compared in Figure 7. The result from NEC2 simulation is also included for reference. As can be seen, when the baluns are not included in measurement data reduction, the measured coupling has a similar frequency response as simulation. However, the measured coupling is shifted down in amplitude as compared with simulation by up to 3 dB, which is due to not accounting for the mismatch and insertion losses of the baluns. When the effects of the baluns are taken into account, the measured and simulated coupling agree much better over the entire frequency range. The remaining discrepancies between the two results are believed to be due to scattering effects from near-by buildings in the measurement, and to simulation error.

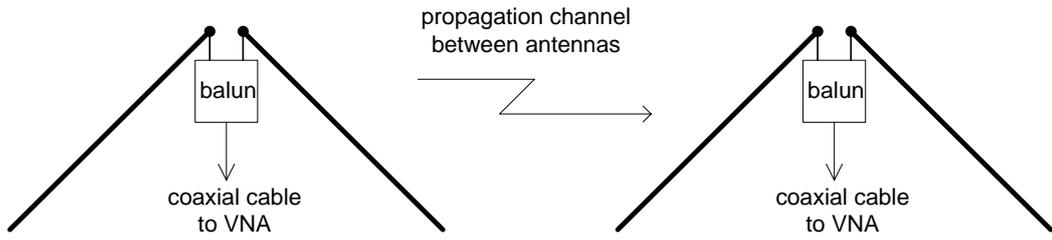


Figure 5: Test setup for measurement of coupling between two dipole antennas.

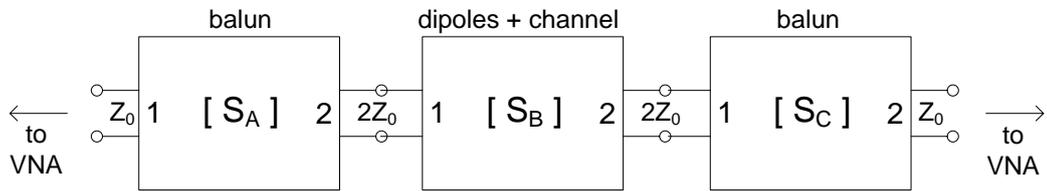


Figure 6: S parameter model for dipole coupling test setup.

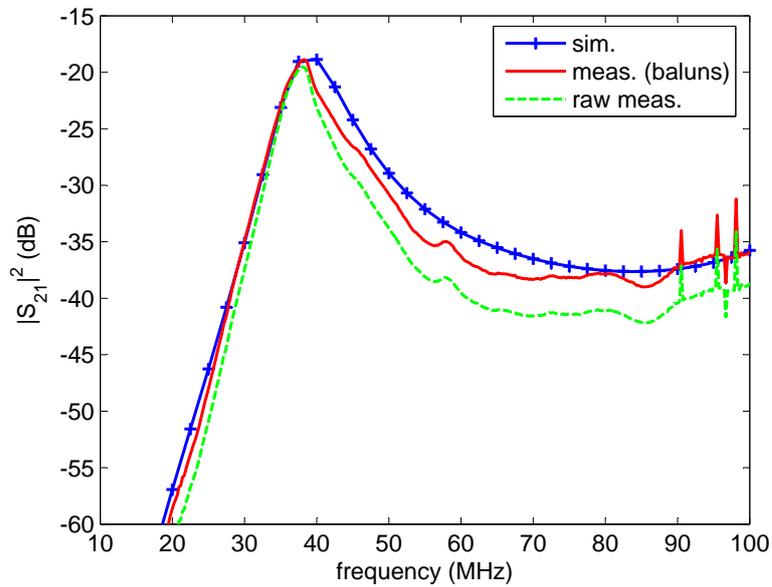


Figure 7: Comparison of measurement and simulation of coupling between two wire inverted-V dipoles oriented parallel to one another. ‘meas. (baluns)’ is the measurement result when the effects of the baluns are taken into account. ‘raw meas.’ is the measurement result when the effects of the baluns are not taken into account.

References

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