Characterization of Balanced Transmission Line by Microwave Techniques

Paul D. Teal, Neil L. Scott, and Rodney G. Vaughan

***Abstract*— This paper presents a method of experimentally characterizing a balanced transmission line using microwave techniques. An unbalanced measurement instrument and the transmission line under test must be connected by a balun, and the effect of the balun must be removed from the measured data. Deembedding techniques are discussed briefly, and several baluns are evaluated. Two methods of performing the measurement are presented. The first uses a one-port measurement where known loads are measured from the end of various lengths of transmission line. The second uses two-port measurements with different transmission-line lengths, and is more effective for measurement of line loss. Experimental results are presented for 2-mm toughened plastic sheath (TPS) "twin and earth" power cable for the range of 0.3–300 MHz.**

***Index Terms*— Balanced transmission line, balun, characteristic impedance, power cable, propagation constant.**

I. Introduction

There is interest in modeling indoor domestic power distribution as a medium for wide-band data transmission. In order to construct a model, it is desirable to determine the characteristic impedance (Z_0) and the propagation constant $(\gamma = \alpha + j\beta)$ of a typical power distribution cable. The following techniques were used to determine the transmission-line characteristics:

1) mathematical modeling;
2) one-port measurement with different loads at two different line lengths;
3) two-port measurement with different line length through connections.

The two measurement techniques were developed to find properties of the cable from measurements which include properties of both the balun and cable. There is little information published on how to perform this measurement ([1] describes a modal decomposition technique, which requires a four- or eight-port test set).

A cross section of the cable tested is presented in Fig. 1. Also presented are the three configurations in which connections were made to the cable. The first two require a balun. The first configuration (phase-neutral) is not truly balanced because of the asymmetry caused by the earth conductor, but is treated as a balanced line.

II. Mathematical Modeling

The transmission-line parameters Z_0 and γ are readily calculated [2] from the distributed parameters of the transmission line: resistance, inductance, conductance, and capacitance, all per unit length. For a balanced line of two circular conductors, these can, in turn, be calculated from the separation, radius, permeability, and conductivity of the conductors, the permittivity, permeability, and conductivity of the dielectric, and the frequency.

Where it was feasible to perform this calculation, there was close agreement between the calculated values and those obtained by measurement (see below). In some cases, however, applying such

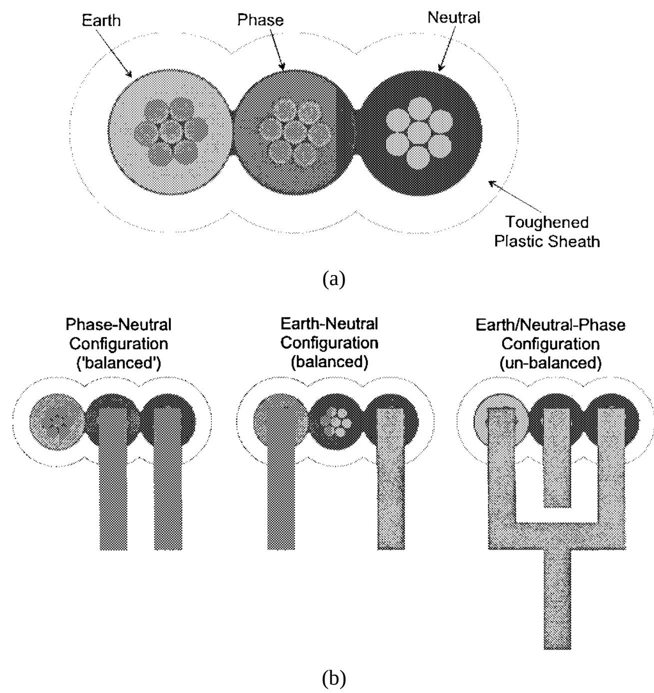

Fig. 1. The connection configurations. (a) Cable cross section. (b) Transmission configurations.

calculations may be inadequate and measurement may be desirable. Some of the factors requiring consideration are as follows.

1) The conductors of the toughened plastic sheath (TPS) are stranded and twisted, hence, it is difficult to define their exact radius and separation.
2) The geometry of the system is increased in complexity by the presence of a third parallel conductor.
3) The geometry is also increased in complexity by the presence of two different dielectric [polyvinyl chloride (PVC)] materials as well as air.
4) No accurate data was available for the conductivity of the two different dielectric materials.

III. Measurement Techniques

When the cable is used as a *balanced* transmission line, a balun is required to connect to the unbalanced coaxial cable of the network analyzer. The connecting cables and balun(s) are here referred to as the *embedding network*. The aim of the techniques presented is to extract the properties of the cable from the measured data, which will include the properties of the embedding network, as well as those of the cable.

A. One-Port with Different Loads at Two Different Lengths

In this technique, three different loads are used to characterize the embedding network. Two different loads on a longer length of cable are then used to find the properties of the additional cable length (see Fig. 2). The embedding network is modeled as a two-port. Combining the equation for the reflection coefficient Γ_{in} of a load, and the equation for this load as it appears when a load Z_L is connected to the remote side of a two-port network [3], we can obtain

$$Z_L p + \Gamma_{\text{in}} q + r - Z_L \Gamma_{\text{in}} = 0 \tag{1}$$

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The authors are with Industrial Research Limited, Lower Hutt, New Zealand (e-mail: p.teal@irl.cri.nz).
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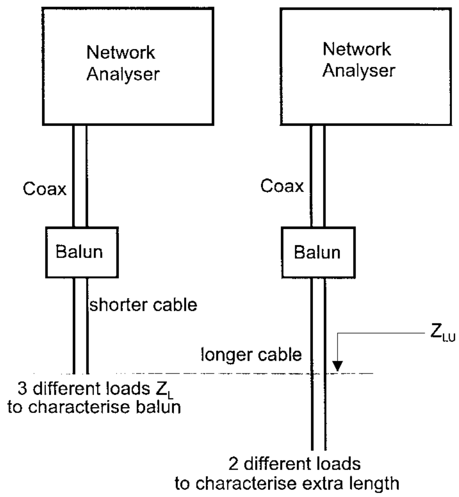

Fig. 2. The one-port measurement technique.

where p (dimensionless), q, and r (in ohms) are three constants defining the embedding network. p, q, and r can be found from three equations of this sort. These were obtained by connecting three known resistive loads to the end of the shorter length of the TPS cable, and were solved separately for each of the test frequencies. The resistors used were surface-mount metal-film resistors, which have little reactance up to the frequencies of interest. The resistance values used ranged between 10–2200 Ω. Although the equations are simpler if two of the loads are open or closed circuit, it was found that the results were more repeatable if resistances were always used; inductances and capacitances associated with the load, although present, are then practically identical for each measurement.

Once p, q, and r are known, an unknown load Z_{LU} can be calculated by measurement of Γ_{in} and rearrangement of (1). This calculation can be applied to the longer cable as if the extra length of cable were included in the load. The impedance Z_{LU}, thus measured at a point equivalent to the length of the shorter cable, when the longer cable is terminated in a load Z_r, is given by [4]

$$Z_{LU} = Z_0 \frac{\frac{Z_r}{Z_0} + \tanh(\gamma l)}{1 + \frac{Z_r}{Z_0}\tanh(\gamma l)} \tag{2}$$

where l represents the difference in the lengths of the two cables.

Two different loads, Z_{r1} and Z_{r2}, can be connected to the end of the longer cable and the impedances calculated from the measurement are Z_{L1} and Z_{L2}, respectively. This gives two equations of the form of (2), which can be solved for $\tanh(\gamma l)$ (and, thus, γ) and Z_0

$$Z_0^2 = \frac{Z_{L2}Z_{r2}(Z_{r1} - Z_{L1}) - Z_{L1}Z_{r1}(Z_{r2} - Z_{L2})}{(Z_{r1} - Z_{L1}) - (Z_{r2} - Z_{L2})} \tag{3}$$

$$\tanh(\gamma l) = Z_0 \frac{Z_{r1} - Z_{L1}}{Z_{L1}Z_{r1} - Z_0^2}. \tag{4}$$

B. Two-Port with Different Length Through Connections

In this technique, only the propagation constant is determined. The technique is more applicable to longer cables, and thus to more accurate measurement of the cable attenuation.

Two baluns are required, and several different lengths of cable are used to connect the balanced sides of the baluns together. The four scattering parameters of the resulting two-port are measured, and then converted to transmission (or cascade) parameters using the transformation [4]

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \frac{1}{S_{21}} \begin{bmatrix} S_{12}S_{21} - S_{11}S_{22} & S_{11} \\ -S_{22} & 1 \end{bmatrix}. \tag{5}$$

This transmission matrix can be considered to be the product of the transmission matrices of the three elements of balun, cable, and balun arranged in cascade fashion. We can define

$$M_{ij} = M_j (M_i)^{-1} \tag{6}$$

where M_i and M_j are the measured transmission matrices with two different transmission cables designated i and j. Marks [5] has shown that the eigenvalues of M_{ij} are the same as those of a measurement without the baluns. Thus, if the eigenvalues of M_{ij} are λ_1 and λ_2, then the propagation constant can be calculated from

$$\gamma = \frac{\ln(\lambda_1)}{l_i - l_j} = \frac{1}{(l_i - l_j)\ln(\lambda_2)}. \tag{7}$$

IV. Baluns

Various baluns were trialed, including: 1) a 4 : 9 coax transformer built using "MCX" 75-Ω coax cable, on ferrite toroids [6], [7]; 2) a coax transformer of the same design using "RG-11" 75-Ω coax cable, with no core; 3) no balun; 4) a 1 : 1 copper-wire Guanella [8] balun wound on various ferrite toroids and rods; 5) a conventional transformer wound on a high-frequency ferrite toroid; and 6) a 1 : 1 "MCX" coax Guanella balun wound on various ferrite toroids and rods. Each balun was tested for the effectiveness of its balance by direct measurement of the terminal voltages with an oscilloscope, and the level of imbalance was compared with the measurements made using that balun. It was found that while the measurement of Z_o and β were relatively insensitive to imbalance, the measurement of the attenuation in the cable was quite sensitive. This is because once there is an imbalance of the currents on the cable, the cable no longer behaves purely as a transmission line, and begins to radiate. This radiation is indistinguishable (to this technique) from increased line attenuation.

The calculations described are applied separately to each measurement frequency, so the balun need not have a flat response over a large frequency range. There is also no requirement that the balun output impedance closely matches that of the unknown transmission line under test. Similarly, the efficiency of the balun is not a prime requirement for this application, as there is plenty of measurement power available.

It was found that the measurements were more repeatable for higher permeability cores: the higher reactance of the balun at low frequencies results in improved balance [8]. The higher inductance obtained from a toroid core compared to a rod core was also beneficial to the repeatability, as was the tighter coupling, and more consistent impedance of wound coax (compared to wound parallel wires).

The most reliable balun was found to be a simple 1 : 1 Guanella balun, consisting of 24 turns of "MCX" 50-Ω cable on a 35-mm outside diameter toroid of relative permeability 5000 (initial relative permeability quoted for 25 °C, $f \leq 10$ kHz).

V. Measurement Results

An HP-8753C network analyzer was used for the scattering parameter measurement. 50-Ω n-type connectors were used for unbalanced cables, and direct soldered connections from the balun were used for balanced cables. The frequency scan (0.3–300 MHz) was performed with a 300-Hz intermediate-frequency bandwidth and power of 0 dBm, and the data used was the average of 16 scans. All the resistance values used in the calculations were the dc values of the surface-mount resistors measured with a standard meter.

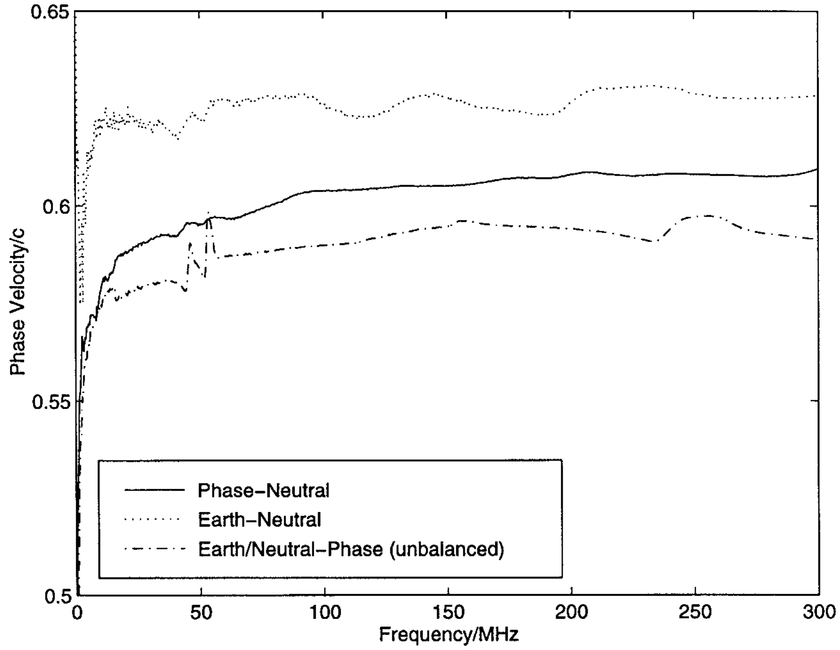

Fig. 3. Phase velocity in TPS.

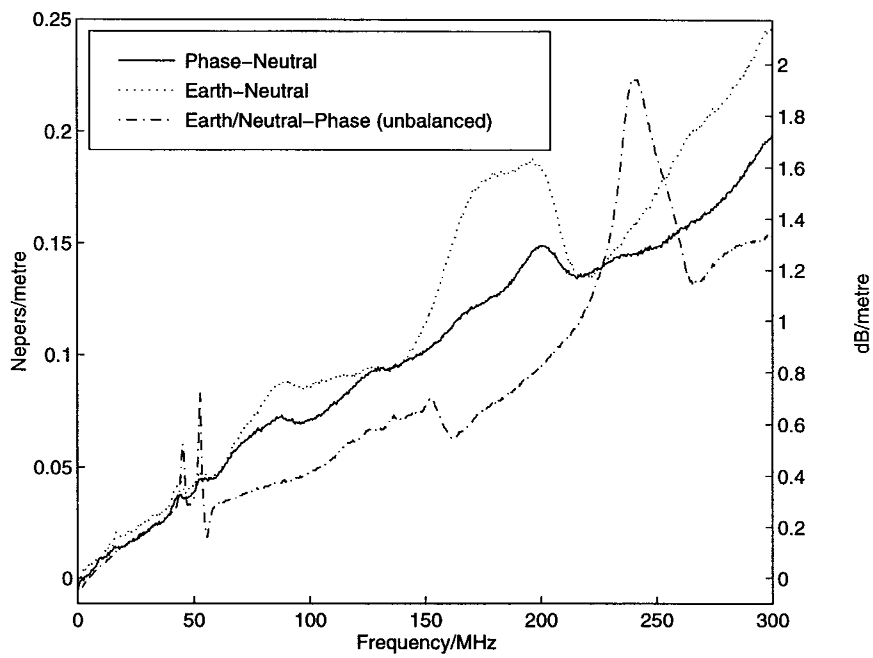

Fig. 4. Attenuation constant for TPS based on one-port measurement.

To avoid ill conditioning in the mathematical processing, cable lengths must be chosen that are not multiples of a half-wavelength at any of the frequencies of interest.

As a test of the one-port measurement technique described above, it was applied to a piece of transmission line composed of parallel solid-brass rods of known dimensions. The agreement of the measured results ($Z_0 = 150 \pm 4 - j(2 \pm 5)\ \Omega$) with values calculated from the transmission-line geometry (153±3 Ω) was very good, confirming the validity of the measurement method.

A. Characteristic Impedance

The reactance part of the characteristic impedance was found for all transmission configurations to be very close to zero. The resistance component was independent of frequency at 90±2 Ω (phase-neutral), 139 ± 3 Ω (Earth-neutral) and 52±1 Ω (Earth/neutral-phase). The error figure in each case is two standard deviations $(\pm 2\sigma)$ calculated across the frequencies used.

B. Phase Constant

The phase constant (β) increases approximately linearly with frequency. The line is practically dispersionless and, thus, except for amplification of the noise caused by differentiation to find the group velocity, the phase and group velocities are very similar. The phase velocity is shown in Fig. 3, presented as a proportion of the velocity in free space. The mean phase velocities for the range 90–300 MHz are

$1.810 \pm 0.002 \times 10^8$ ms^{-1}, $1.87 \pm 0.01 \times 10^8$ ms^{-1}, and $1.768 \pm 0.002 \times 10^8$ ms^{-1}.

The phase velocity indicates the relative containment of the electromagnetic field within the dielectric. As might be expected, the Earth-neutral configuration, using the outer two conductors of the cable, has a greater proportion of field in air and, hence, the effect of the dielectric in decreasing the velocity is smaller. The unbalanced (Earth and neutral-phase) configuration has the greatest containment of the field and, hence, the effect of the dielectric is largest.

C. Attenuation Constant

The attenuation constant α was also found to rise with increasing frequency (see Fig. 4). A first estimate of this loss is the range 4.3–7.7 $\times 10^{-9}$ dB/Hz/m. Considering the relative containment of the field in the dielectric, we might expect the balanced configurations to exhibit less loss than the unbalanced configurations. However, the increased loss of the balanced configurations appears to be an indication of the radiated energy due to common-mode current, resulting from the lack of perfect balance. It is to be expected that the phase-neutral configuration cannot make a perfectly balanced transmission line because of the asymmetry caused by the presence of a third conductor.

The two-port method using different cable lengths gave similar results for the attenuation constant.

Both the one- and two-port measurements show a much larger loss (dielectric and/or radiated) than calculation based only on the conductivity of the copper. The calculation gives an attenuation at 300 MHz of 0.01 Np/m^{-1} (0.09 dBm^{-1}), compared to the measured value of about 0.2 Np/m^{-1} (1.8 dBm^{-1}).

VI. Conclusions

A one- and two-port method for measuring the characteristics of a balanced line, embedded behind some network (balun), were presented and applied to measurements of domestic power cabling. Though this application used submicrowave frequencies, the techniques are applicable to higher (including microwave) frequencies. The two-port method only gives the propagation constant, but is superior for attenuation measurements.

To obtain repeatable measurements, a good balun is necessary. This is because any common-mode current component is prone to radiate. It was found that a fine coax wound on a high-permeability toroid made a suitable balun.

The three conductor line under test was connected in three different connection configurations. The characteristic impedance was found to be almost purely resistive, and varies very little with frequency. The phase constant increases almost lineally with frequency, indicating a constant phase velocity. The phase velocity is lower for the configurations having a higher proportion of the electromagnetic field contained within the cable insulation, as expected. The attenuation also shows an increase with frequency, although with a much greater fluctuation. Most of this loss appears to be caused by the cable insulation, with a small component of copper loss, and some radiation caused by imperfection in the transmission balance.

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Crossed Dipoles Fed with a Turnstile Network

Robert K. Zimmerman, Jr.

***Abstract*—A "turnstile network" is introduced which may be conveniently used for circular polarization synthesis. The network, outfitted with proper phasing stubs, forms a balanced quadrature hybrid; for an antenna with less than a perfect reflection coefficient, the reflected power will appear at an isolated port, which may be terminated, resulting in good polarization properties coupled with good input voltage standing-wave ratio. A crossed-dipole array is used as a test-bed to demonstrate the turnstile network.**

***Index Terms*—Antenna components, antenna feeds, circular polarization.**

I. Introduction

Dicke invented the waveguide turnstile during World War II at the Massachusetts Institute of Technology (MIT) Radiation Laboratory, Cambridge [1]–[3]. The device was patented [4] in 1954 as a network for exciting circularly polarized waves in circular waveguide. Turnstile theory is discussed in some detail in [5].

Presented here is a simple coaxial network which provides the same turnstile function, *but not in waveguide*. Where Dicke's turnstile used reflective waveguide stubs for polarization synthesis, this network uses reflective coaxial stubs.

II. Proposed Network and Feed

Fig. 1 shows the proposed network and feed. The feed is a crossed-dipole array residing within a cavity. The turnstile network comprises four coaxial transmission-line segments, each $\lambda/4$ in length at center frequency, and which, for this discussion, are assumed to have a 50-Ω characteristic impedance. The four segments of transmission line form a star network: all four shields are connected together and all four inner conductors are joined at the bottom of the network. The network has fourfold rotational symmetry, as required by theory [1].

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The author was with the Arecibo Observatory, Arecibo, PR 00614 USA. He is now with the Los Alamos National Laboratory, LANSCE 5, MS H827, Los Alamos, NM 87545 USA.

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