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Experimental Test of Propagation-Parameter Calculations for Shielded Balanced Pair Cables

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Experimental verification is presented for a recently developed method for calculating propagation parameters, such as loss and phase-shift per length, of uniform cables. For the shielded balanced pair (SBP), a computer program has been written to carry out the calculations. In this paper, these calculations are compared with measurements of three different cables that can be modeled as SBPs. Agreement between calculation and measurement was within 3.3 percent over the frequency range 50 Hz to 10 MHz. The greatest deviation occurred in a cable with substantial air space in the interstitial dielectric; for the other two cables agreement was within 2 percent.

I. INTRODUCTION

A method for calculating propagation parameters of uniform cables is presented in Ref. 1. The method depends on algorithms for determining the charge densities on the wires and shield, and this is presented in Ref. 2. For the shielded balanced pair (SBP) in particular, a computer program has been written to carry out the required calculations. To test the method, three different SBP cables were fabricated and, with the cables laid straight, their attenuation and phase-shift per length were measured over a broad range of frequencies and then compared with calculated values. The results of this experimental test are presented in this paper.

The three cables were constructed to conform to the SBP model. In this model, the two wires are identical, they are straight and parallel, and they are symmetrically located inside a cylindrical, metallic shield of uniform thickness. Also, the dielectric material separating the wires and shield is homogeneous and isotropic. A cross section of an ideal SBP is shown in Fig. 1.

The first cable is an untwisted version of a standard twisted-pair cable built by Western Electric, called the 754E. This cable deviates somewhat

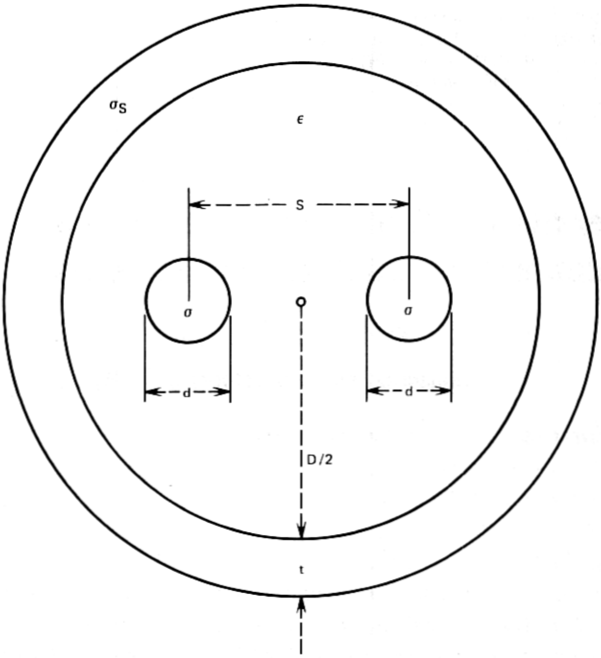
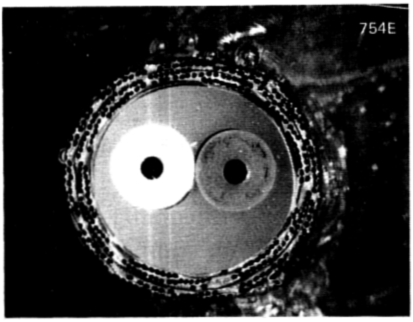


Fig. 1—Cross section of a typical shielded balanced pair.

from the SBP model since its shield instead of being solid is braided from fine Cu wires coated with Ag. The second cable was constructed by Bell Laboratories and is called the FOCAL cable. For this cable, a polyethylene belt was extruded over two insulated 19-gage wires (as in the 754E cable) and bordered by two polyethylene rods for stability, resulting in substantial air space. This was then covered by a solid Al shield. The third cable was also constructed by Bell Laboratories; it was designed to accentuate the proximity effect by having the wires and shield relatively close to each other. This is called the proximity cable. Photographs of the cross sections of each cable are shown in Fig. 2.

The geometric and material parameters used in the SBP model for these three cables correspond to certain electrical measurements of the cable. Though the parameters are specified, in practice the nominal values are neither accurate nor constant enough along the cable to permit testing the model. Also, the SBP model, though essentially descriptive of the cable, does not account for any unbalance, air spaces in the dielectric, eccentricity of the wires and shield, axial variations of the wires and other nonuniformities along the cable, and other practical matters. Accordingly, with the exception of cable length, the input parameters are computed (in a way now to be described) as average values from electrical measurements.



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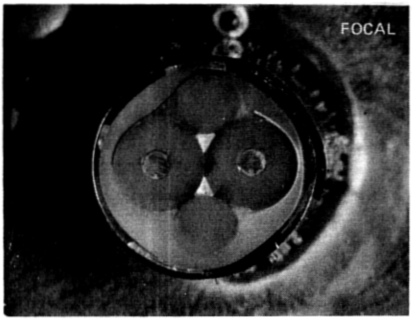

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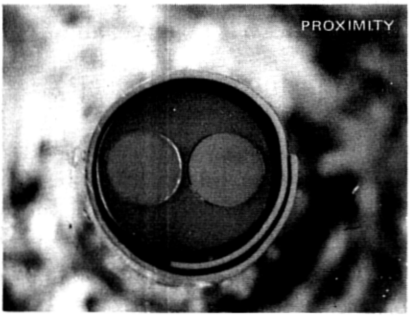

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Fig. 2—Photographs of cable cross sections.

For each cable, the wires were made of Cu; and when the temperature and purity are known, the conductivity, σ, is determined to within 0.5 percent. The temperature is assumed to be 73°F, which corresponds to a σ of 5.73749 mho/m. The diameter of the wires d is computed from the measurement of their DC resistance by the formula,

$$R_{\mathrm{DC}} = \frac{\ell}{\sigma(\mathrm{Area})} = \frac{4\ell}{\pi\sigma d^2} \text{ or } d = 2\left(\frac{\ell}{\pi\sigma R_{\mathrm{DC}}}\right)^{1/2}, \tag{1}$$

where ℓ denotes the length of the cable. The distance S separating the two wire centers is computed from the measurement of low-frequency inductance L by the formula,

$$L = \frac{\mu_0}{\pi} \ell n \left(\frac{2S}{d}\right) + \frac{\mu_0}{4\pi} \text{ or } S = \frac{d}{2} \exp\left[\frac{\pi L}{\mu_0} - 1/4\right], \tag{2}$$

where μ_0 denotes the free-space permeability (see Ref. 3, page 155). This formula assumes that the materials comprising the cable are nonmagnetic. It also assumes that the wires are straight; so the cable must be unreeled to get the proper measurement of L.

The "effective" dielectric constant ϵ of the model is chosen so that the measured and calculated values of the phase shift per mile β agree at a frequency of 10 MHz. In the FOCAL and proximity cables there were air spaces in the cable, and the effective dielectric constant for these represents a kind of average of the dielectric constants for air and polyethylene. The value of ϵ is estimated from the formula,

$$\beta(10 \text{ MHz}) = \omega\sqrt{\epsilon\mu_0} + \delta = 337.286 \sqrt{\frac{\epsilon}{\epsilon_0}} + \delta, \tag{3}$$

in units of radians per mile, where ω denotes the excitation frequency in radians per second, ϵ_0 denotes the free-space permittivity, and δ is a positive number that corrects for proximity effect (e.g., calculation has shown this is approximately 4 rad/mi for the 754E cable and 36 rad/mi for the proximity cable). Since δ is positive, an upper bound for ϵ is

$$\epsilon_u = [\beta(10 \text{ MHz})/337.286]^2 \epsilon_0.$$

Experience has shown that, apart from ϵ, δ is relatively insensitive to changes in the input parameters; hence, it can be estimated as the calculated β at 10 MHz (with nominal dimensions and with $\epsilon = \epsilon_u$) minus the measured β at 10 MHz. When this estimate of δ is inserted into eq. (3), an estimate of ϵ can be obtained that usually gives a calculated β at 10 MHz within 1 percent of measurement.

The inside diameter of the shield D is chosen so that the calculated mutual capacitance matches the measured value (though a variation of this is used for the FOCAL cable). This calculation presumes that the parameters d, S, and ϵ have already been obtained. The thickness t and the conductivity σ_s of the shield are selected to match the DC resistance of the shield according to the formula,

$$R_{\text{DC,S}} = \frac{\ell}{\sigma_s(\text{Area})} = \frac{\ell}{\sigma_s \pi t(D + t)}. \tag{4}$$

There is one degree of freedom left in selecting the pair (σ_s,t); this is used to minimize the deviation between measured and calculated values of

Table I — Initial measurements on 754E cable

Length	R_{DC} Cond. 1	R_{DC} Cond. 2	R_{DC} Shield	C_m	C_{1g}	C_{2g}	$L_{50\text{ Hz}}$
1043 ft	9.009Ω	8.700Ω	1.0044Ω	13.072 nf	18.24 nf	18.02 nf	0.2706 mh

loss per mile (α) over the range of frequencies for which there are measurements.

By means of this procedure a set of input parameters was chosen for each cable. Parameters for which there was latitude in choosing were selected by trial and error, and the result is not optimal in any respect.

In general, it was found that calculations of α agreed with measurements to within 3.3 percent for frequency samples over the range 50 Hz to 10 MHz. The best agreement was for the proximity cable, which had a deviation within 1.6 percent over the range 5 kHz to 10 MHz. For β, agreement was always within 1 percent.

In the next section, the detailed results of the experiment are presented. In the final section, conclusions are drawn and application to multipair cables is discussed.

II. RESULTS

In this section, the results of the experimental test are presented. First, initial measurements were made on a Wheatstone bridge of mutual capacitance, capacitance to ground of both wires, DC resistances, and low-frequency inductance for the three cables. These, together with the length of the samples, are shown in Tables I, IV, and VII for the 754E, FOCAL, and proximity cables, respectively.

Next, measurements of loss α in dB/mi and phase-shift β in rad/mi were made on the computer-operated transmission measuring set[4] (COTMS) corrected for varying terminal impedance at low frequency[5] for frequencies from 4 kHz to 10 MHz. For lower frequencies, 50 Hz to 10 kHz, values of α and β were deduced from bridge measurements of AC resistance, AC inductance, and capacitance. It was found in this

Table II — Parameter estimates for 754E cable

	Description	Estimates
σ	Cu wire at 73°	5.73749×10^7 mho/m
d	19 gage (35.9 mils)	34.84 mils
S	117 to 127 mils	116 mils
ϵ	Polyethylene	2.288 ϵ_0
D	290 mils	280 mils
t	Shield has braided wire construction	38 mils
σ_s	about 32 mils thick	1.292×10^7 mho/m

Table III — Calculated vs measured α and β for 754E cable

	Calc. α (dB/mi)	Meas. α (dB/mi)	Diff. (%)	Calc. β (rad/mi)	Meas. β (rad/mi)	Diff. (%)
50 Hz	0.267	0.265	<1	0.0309	0.0305	1
100 Hz	0.376	0.376	<1	0.0438	0.0437	<1
500 Hz	0.826	0.822	<1	0.0998	0.0992	<1
1 kHz	1.143	1.135	<1	0.1446	0.1438	<1
5 kHz	2.209	2.169	1.8	0.387	0.386	<1
10 kHz	2.700	2.682	<1	0.649	0.656	<1
20 kHz	3.047	3.074	<1	1.176	1.185	<1
50 kHz	3.507	3.580	2.0	2.817	2.809	<1
80 kHz	4.013	4.045	<1	4.457	4.437	<1
100 kHz	4.372	4.383	<1	5.53	5.52	<1
500 kHz	9.391	9.263	1.4	26.54	26.52	<1
1 MHz	13.109	13.085	~1	52.48	52.45	<1
5 MHz	28.85, $F_p = 0$ 29.97, $F_p = 1000$ μrad	29.830	—	258.38	258.06	<1
10 MHz	40.66, $F_p = 0$ 42.88, $F_p = 1000$ μrad	42.796	—	514.84	514.09	<1

process that the COTMS measurements of α at low frequencies had to be increased (~1 percent for 10 kHz and ~2 percent for 5 kHz) for the 754E and FOCAL cables, presumably because the low-loss values went beyond the sensitivity of the machine, which is $1/100$ dB. The losses in the proximity cable were large enough at all frequencies to be within the range of sensitivity for COTMS.

The parameters of the SBP model for the three cables were calculated as indicated in the introduction when feasible. But each cable deviated to some extent from the model, so there were some exceptions and extra considerations to accommodate the deviations. This is discussed in the appendix. The parameters selected for the SBP model are given in Tables

Table IV — Initial measurements on FOCAL cable

Length	R_{DC} Cond. 1	R_{DC} Cond. 2	R_{DC} Shield	C_m	C_{1g}	C_{2g}	L_{50Hz}
249.2 ft	2.0086Ω	2.0083Ω	0.3968Ω	2.956nf	4.098nf	4.069nf	0.065mh

Table V — Parameter estimates for FOCAL cable

	Description	Estimates
σ	Cu wire at 73°	5.73749×10^7 mho/m
d	19 gage (35.9 mils)	36.068 mils
S	125 mils	119.27 mils
ϵ	Polyethylene & air spaces	$2.06\ \epsilon_0$
D	280 mils	278 mils
t	Solid Al sheet 10-mil thick with overlap	9.22 mils
σ_s		3.54×10^7 mho/m

Table VI — Calc. vs measured α and β for FOCAL cable

	Calc. α (dB/mi)	Meas. α (dB/mi)	Diff. (%)	Calc. β (rad/mi)	Meas. β (rad/mi)	Diff. (%)
50 Hz	0.247	0.251	1.5	0.029	0.029	—
100 Hz	0.349	0.354	1.5	0.041	0.041	—
500 Hz	0.764	0.775	1.5	0.093	0.094	1
1 kHz	1.054	1.069	1.5	0.134	0.136	1
5 kHz	2.012	2.034	1	0.364	0.370	1
10 kHz	2.491	2.516	<1	0.617	0.628	1
20 kHz	2.890	2.799	3.3	1.117	1.124	<1
50 kHz	3.339	3.268	2.1	2.651	2.677	<1
80 kHz	3.764	3.735	<1	4.192	4.223	<1
100 kHz	4.069	4.076	<1	5.213	5.223	<1
500 kHz	8.397	8.229	2.1	25.122	25.071	<1
1 MHz	11.751	11.421	2.9	49.714	49.752	<1
5 MHz	25.757, $F_p = 0$ 26.289, $F_p =$ 500 μrad	25.884	—	244.973	245.048	<1
10 MHz	35.260, $F_p = 0$ 37.320, $F_p =$ 500 μrad	37.194	—	488.238	488.179	<1

II, V, and VIII for the 754E, FOCAL, and proximity cables, respectively.

Calculations of α and β for the model over the range of measured frequencies are given in Tables III, VI, and IX for the 754E, FOCAL, and proximity cables, respectively. These tables also give the measured values and the percent deviation in the comparison of calculated and measured values.

The calculations for the models agreed with measurement for all frequencies considered and all cables to within 3.3 percent for α and within 1 percent for β. For the 754E cable, calculation of α agreed with measurement to within 2 percent, and for the proximity cable, agreement

Table VII — Initial measurements on proximity cable

Length	R_{DC} Cond. 1	R_{DC} Cond. 2	R_{DC} Shield	C_m	C_{1g}	C_{2g}	$L_{50\ Hz}$
634.4 ft	3.273 Ω	3.267 Ω	4.63 Ω	43.396 nf	30.59 nf	28.80 nf	0.0773 mh

Table VIII — Parameter estimates for proximity cable

	Description	Estimates
σ	Cu wire at 73°	5.73749×10^7 mho/m
d	17 gage (45.3 mils)	45.06 mils
S	50.3 mils	47.74 mils
ϵ	Polyethylene with air spaces	$2.132\epsilon_o$
D	105.6 mils	109.9 mils
t	4-mil-thick Al	5.3 mils
σ_s	Shield with overlap	3.365×10^7 mho/m

Table IX — Calculated vs measured α and β for proximity cable

	Calc. α (dB/mi)	Meas. α (dB/mi)	Diff. (%)	Calc. β (rad/mi)	Meas. β (rad/mi)	Diff. (%)
5 kHz	4.109	4.096	<1	0.671	0.671	<1
10 kHz	5.284	5.310	<1	1.118	1.114	<1
20 kHz	7.150	7.122	<1	1.970	1.976	<1
50 kHz	11.998	11.895	<1	4.211	4.229	<1
80 kHz	15.817	15.670	<1	6.241	6.263	<1
100 kHz	18.016	18.037	<1	7.538	7.573	<1
500 kHz	44.219	44.953	1.6	31.338	31.248	<1
1 MHz	67.295	67.498	<1	59.445	59.231	<1
5 MHz	181.01, $F_p = 0$ 181.60, $F_p = 500$ μrad	179.42	~1	271.03	270.957	<1
10 MHz	270.02, $F_p = 0$ 271.34, $F_p = 500$ μrad	267.18	~1	528.09	528.12	<1

was within 1.6 percent. Agreement between calculation and measurement for the FOCAL cable was the poorest of the three (with a maximum deviation of 3.3 percent). This may be attributed to the presence of substantial air space in the dielectric region and to the short length of the sample (249.2 ft). Since the sensitivity of COTMS is $1/100$ dB, for this cable the measurements are uncertain to about (249.2/5280) (1/200) $\simeq$ 0.1 dB/mi, an amount which exceeds the difference of calculation and measurement for frequencies below 500 kHz.

The power factor F_p of the dielectric is generally important to the loss of a cable when the frequency exceeds 1 MHz. Since an independent measurement of F_p was not available for this experiment, α is calculated for power factors equal to 0 and to some upper bound. This gives an interval of possible values for α. As shown in Table III, the measured loss for the 754E cable at 5 MHz and 10 MHz lies in such an interval when $0 \leqq F_p \leqq 1000$ μrad. This range of F_p is within the usual range of values estimated from measurements of pairs in a multipair cable.[6] The measured loss for the FOCAL cable at 5 MHz and 10 MHz lies within the calculated range when $0 \leqq F_p \leqq 500$ μrad, as shown in Table VI. The calculated loss for the proximity cable at 5 MHz and 10 MHz (assuming $F_p = 0$) exceeds the measurements, so no estimate of F_p is possible for this cable. If, however, F_p is assumed to be 500 μrad, for example, then the error is 1.5 percent at 10 MHz.

III. SUMMARY AND CONCLUSIONS

The SBP model has been used to represent three different single-pair cables. Though each of these departs from the model to some extent, the cables are close enough to SBPs so that the model represents them with sufficient accuracy for engineering purposes. The calculations agreed with measurement in all cases and all frequencies considered to within 3.3 percent, and usually it was closer. Though more controlled tests may be devised to test the SBP theory, the tests presented here indicate enough agreement between theory and practice that it could be used to predict the electrical behavior of a nominally balanced pair in a shield.

By a similar controlled experiment, the theory of the uniform cable[1,2] might be checked for unbalanced pairs in a shield and for other uniform cables. Given a test cable, the DC resistances would give the wire diameters of the model, the low-frequency inductances would give the wire separations, the capacitance measurements would give the size and location of the shield, and the range of phase velocities would give an effective dielectric constant. The shield thickness and conductivity could be estimated as before. In general, there will be several excitation modes having distinct propagation constants; their measurements could then be compared with calculations on the deduced model, as was done for the SBP.

The major application of the theory of the SBP, or more generally, of uniform cables is to a pair in a multipair cable. This extension is complicated by these factors:

(*i*) Nonuniformities along the cable arise from twisting, stranding, cabling, and various perturbations.

(*ii*) The shield of a pair effectively consists of the other pairs around it; thus, the effective shield is caged, not solid.

(*iii*) Small unbalance of 1 to 2 percent is almost always present.

(*iv*) The dielectric materials around the wires often are inhomogeneous.

Detailed consideration of points (*ii*), (*iii*), and (*iv*) in the context of uniform cables is in progress, but consideration of twisting and stranding goes beyond the scope of the uniform cable model.

IV. ACKNOWLEDGMENTS

The author wishes to acknowledge R. C. Sacks for many discussions on this work and experimental support.

APPENDIX A

Details of Parameter Selection for the Model

Each of the three cables deviates from the SBP model to some extent. In this appendix, details are provided of the parameter selection process used to accommodate these deviations.

Initial measurements of the 754E cable indicated a resistive unbalance of 3 percent. This means the wire diameter d and, hence, the wire separation S could not be exactly determined. Instead, a range of possible values for d and S was indicated, and selection was made within these ranges to give acceptable agreement between calculated and measured values of α for the frequencies considered.

The FOCAL and proximity cables have insignificant resistive unbalance; hence, unambiguous values of d and S can be calculated for them as indicated in the introduction. Though all the cables have some capacitive unbalance (with a maximum of 5 percent for the proximity cable), this has no direct effect on the selection of parameters for the model.

A significant departure from the model is the presence of air spaces in the dielectric region for the FOCAL and proximity cables. This is indicated by the photographs in Fig. 2 and by the effective dielectric constants, $2.06\epsilon_0$ for the FOCAL cable and $2.132\epsilon_0$ for the proximity cable, which are lower than the dielectric constant of polyethylene ($2.29\epsilon_0$). The air spaces cause no direct ambiguity in selecting parameters for the model, as did the resistive unbalance, but they do seem to affect the appropriateness of the model itself. For the FOCAL cable in particular, a set of parameters for the model could not be found that satisfies all the conditions of the introduction and that gives a loss (α) within 5 percent of measurement for all frequencies considered. Instead, a compromise model is used whose mutual capacitance is 2.8-percent lower than measured.

For the proximity cable, no compromise model is required despite the presence of some air space, and the mutual capacitance of the model agrees with measurement to within 0.1 percent. The effective dielectric computed for the 754E cable indicates an absence of air space, and again the mutual capacitance of the model agrees with measurement to within 0.1 percent.

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