Cable Parameters Identification for DSL Systems

Gilvan Borges, Roberto M. Rodrigues, Claudomiro Sales*, Klas Ericson† and João Costa‡
* Institute of Technology, Federal University of Pará
66075-110 Belém, Brazil
Emails: gilvan@ufpa.br, menegues@ufpa.br, cssj@ufpa.br
‡Broadband Technologies Laboratory/Department
Ericsson AB, 23 16480 Stockholm, Sweden
Email: klas.ericson@ericsson.com
† Electrical Engineering Graduate Program
Institute of Technology, Federal University of Pará, 66075-110 Belém, Brazil
Email: jweyl@ufpa.br

***Abstract*—A method to identify some physical parameters of twisted-pair cables is presented in this paper. The parameters identification process is carried out from input impedance measurements, applying analytical approach and mean squared estimation. The obtained results indicate the accuracy and applicability of the proposed method.**

***Index Terms*—System identification, transmission line theory, twisted-pair cable, digital subscriber line.**

I. Introduction

The plain old telephone system (POTS) access network is essentially made up of twisted-pair cables. This kind of transmission line has been studied since many years ago [1] and with the advent of the digital subscriber line (DSL) access technology, many cable models were proposed and used in DSL-related applications like topology identification [2], [3] and estimation of the attenuation [4] of subscriber lines.

The cable models can be grouped in three categories: rational functions, semi-empirical and physical. The rational functions are flexible but not well suited for any application. The semi-empirical models employ heuristics and physical knowledge, but, in some cases, have inconsistencies like non-causal behavior [5]. The physical models are analytical and based on the cable geometry and properties of the materials used on manufacturing. The physical models are casual and facilitate investigation of the electrical behavior when a parameter, e.g. the wire diameter, is modified [6].

The methods for characterization of twisted-pair cables have focused on identification of the primary [7] or secondary parameters [8], achieving reasonable results. However, the geometry of a twisted pair largely determines its electrical characteristics [9]. The materials used in its manufacturing have the same importance. Therefore, the identification of physical parameters can provide updated information about it and results in an accurate characterization in electrical terms.

The present paper presents a method for identification of some physical parameters of twisted-pair cables from input impedance measurements. Such identification is carried out by a combination of analytical approach and optimization process. The proposed method is evaluated for two cables types.

The remainder of this paper is as follows: Section II describes the key-concepts used by the proposed method. Section III describes the proposed method. Section IV presents the obtained results while Section V presents the conclusions.

II. Theoretical Background

The modeling of twisted-pair cables at high frequencies is well-documented in previous works. Therefore, this section will only pin-point some key-concepts about that. These concepts are useful to understand the proposed method.

A certain twisted-pair subscriber line consists of two cylindrical conductors surrounded by a dielectric, where:

- σ_c is the conductivity of the conductors;
- μ_c is the effective conductors' magnetic permeability;
- ϵ is the effective electric permittivity of the dielectric;
- μ is the effective magnetic permeability of the dielectric;
- a is the radius of the conductors;
- D distance between the conductor centers.

The characteristic impedance Z_0 and the propagation constant $\gamma = \alpha + j\beta$ of this line are complex frequency-dependent quantities. They asymptotically converge to [2]

$$Z_0^{\infty} = \frac{1}{\pi}\sqrt{\frac{\mu}{\epsilon}}\, arccosh\left(\mathcal{R}\right) \tag{1}$$

and

$$\gamma^{\infty} = \left[\left(\frac{1}{2a}\,\frac{\mathcal{R}}{arccosh\left(\mathcal{R}\right)\sqrt{\mathcal{R}^2-1}}\sqrt{\frac{\pi\epsilon\mu_c}{\sigma_c\mu}}\right)\sqrt{f}\right] + j\left[\left(2\pi\sqrt{\mu\epsilon}\right)f\right] \tag{2}$$

for high frequencies, where $\mathcal{R}$ is defined as

$$\mathcal{R} = \left(\frac{D}{2a}\right). \tag{3}$$

If one assumes the cable's materials are non-magnetic (i.e. relative permeability equal to one) and the conductors' material is copper, (1) and (2) are respectively reduced to

$$Z_0^{\infty} = \frac{120}{\sqrt{\epsilon_r}}\, arccosh\left(\mathcal{R}\right) \tag{4}$$

and

$$\gamma^{\infty} = \left[\left(\frac{1}{2a} \frac{\mathcal{R}}{arccosh\,(\mathcal{R})\,\sqrt{\mathcal{R}^2 - 1}} \sqrt{\frac{\pi \epsilon_r \epsilon_0}{\sigma_{copper}}} \right) \sqrt{f} \right] + j \left[\left(\frac{2\pi}{c} \sqrt{\epsilon_r} \right) f \right], \quad (5)$$

where ϵ_r is the relative electrical permittivity of the dielectric, ϵ_0 the free-space electrical permittivity and c is the velocity of light in vacuum.

III. Proposed Method

The proposed method essentially exploits the asymptotic behavior of the secondary parameters in order to identify three physical parameters of the cable under test: the relative electric permittivity of the dielectric ϵ_r, the distance between the conductor centers D and the radius of the conductors a.

The method consists of two processes: initial estimation of the parameters via analytical approach and fine-tune of the estimated parameters via optimization. The Fig. 1 provides an overview about the proposed identification method which is described in more details in the following.

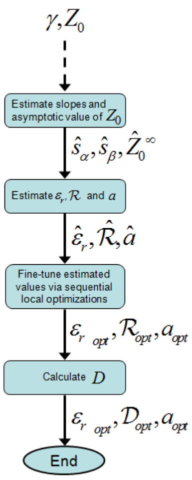

Fig. 1. Flowchart illustrating the proposed identification method.

A. Estimation Process

Initially, assume having measurements of characteristic impedance and propagation constant, ranging from DC to a given frequency f_{max}, for a certain twisted-pair cable. These measurements are the inputs of the proposed method. The cable under test is assumed to be a homogeneous line.

From (5), it is possible to note that, at high frequencies, the attenuation constant α has a linear behavior with respect to $\sqrt{f}$, similarly to the phase constant β with respect to f.

In this way, the slopes of the asymptotes of the attenuation and phase constants s_α and s_β, respectively, can be defined as

$$s_\alpha = \frac{1}{2a} \frac{\mathcal{R}}{arccosh\,(\mathcal{R})\,\sqrt{\mathcal{R}^2 - 1}} \sqrt{\frac{\pi \epsilon_r \epsilon_0}{\sigma_{copper}}} \quad (6)$$

and

$$s_\beta = \left(\frac{2\pi}{c} \sqrt{\epsilon_r} \right). \quad (7)$$

These linear behaviors allow the use of two linear least-squares fittings (LLSF). In special, these LLSF should be weighted by an increasing function in order to prioritize the high frequencies, where (6) and (7) are valid.

From that follows the relative electric permittivity can be estimated solving (7) for ϵ_r and applying the previously estimated $\hat{s}_\beta$ to the resulting equation, i.e.

$$\hat{\epsilon}_r = \left(\frac{\hat{s}_\beta\, c}{2\pi} \right)^2. \quad (8)$$

Similarly, solving (1) for the ratio $\mathcal{R}$ yields

$$\hat{\mathcal{R}} = \cosh \left(\frac{\hat{Z}_0^{\infty} \sqrt{\hat{\epsilon}_r}}{120} \right), \quad (9)$$

where $\hat{\epsilon}_r$ is the previously estimated permittivity and $\hat{Z}_0^{\infty}$ is the estimated asymptotic value of the characteristic impedance.

The radius of the conductors is estimated solving (6) for a and substituting the estimated permittivity and ratio $\hat{\mathcal{R}}$ in the resulting equation, i.e.

$$\hat{a} = \frac{1}{2 s_\alpha} \frac{\hat{\mathcal{R}}}{arccosh\left(\hat{\mathcal{R}}\right) \sqrt{\hat{\mathcal{R}}^2 - 1}} \sqrt{\frac{\pi \hat{\epsilon}_r \epsilon_0}{\sigma_{copper}}}. \quad (10)$$

Ending the estimation process, the distance between the conductors centers D is estimated by the expression

$$\hat{D} = 2\, \hat{a} \hat{\mathcal{R}}. \quad (11)$$

B. Fine-tuning Process

The measurements used in the estimation process should have a wide frequency range, so their asymptotic behavior can be correctly detected. However, depending on the DSL technology, the available frequency range may not fulfill such requirement. In this way, the initial estimations must be fine-tuned via optimization process.

According to (4) and (5), it can be noted that the phase constant β at high frequencies is only dependent of the relative permittivity ϵ_r. On the other hand, the characteristic impedance Z_0 at high frequencies is dependent of ϵ_r and the ratio $\mathcal{R}$ while the attenuation constant α at high frequencies is dependent of ϵ_r, $\mathcal{R}$ and the radius a. In spite of that, in case ϵ_r is known, Z_0 turns to be dependent only of the ratio $\mathcal{R}$. In the same way, α turns to be dependent of the radius a in case ϵ_r and $\mathcal{R}$ are known. Aiming at exploiting this reasoning, it was developed an iterative approach to fine-tune the initial estimations. Each iteration of this approach consists of a sequence of three one-dimensional local optimizations: one that fine-tunes only ϵ_r (block 1), one that fine-tunes only $\mathcal{R}$ (block 2) and one that fine-tunes only a (block 3).

In the first iteration, the input arguments of the approach are the parameters provided by the estimation process.

In each optimization block, the current set of input arguments are applied to a physical cable model which generates theoretical curves that are compared to the corresponding measurement, through the following criteria functions:

$$V_{\epsilon_r} = \sum_{k=1}^{K} w(f_k) \left|\beta(f_k) - \overline{\beta}(\epsilon_r, f_k)\right|^2 , \qquad (12)$$

$$V_{\mathcal{R}} = \sum_{k=1}^{K} w(f_k) \left|Z_0(f_k) - \overline{Z}_0(\mathcal{R}, f_k)\right|^2 \qquad (13)$$

and

$$V_a = \sum_{k=1}^{K} w(f_k) \left|\alpha(f_k) - \overline{\alpha}(a, f_k)\right|^2 , \qquad (14)$$

where β, Z_0 and α are the measurements while $\overline{\beta}$, $\overline{Z}_0$, $\overline{\alpha}$ are the theoretical counterparts and $w(f)$ is an increasing weighting function used to prioritize the higher frequencies.

After block 3, a pre-defined stop criterion is evaluated. In this work, the stop criterion is defined as the percent variation of the parameters under optimization between two successive iterations. The stop criterion is fulfilled whenever the three percent variations are less than a threshold δ, defined by the user. In case the criterion is not fulfilled, a new iteration takes place, where the input arguments are the set of fine-tunned parameters at the end of the previous iteration.

IV. Evaluation of the Proposed Method

A. Employed Cables and Measurement Procedure

In order to carry out the evaluation of the method, the cable plant in the DSL laboratory of the Federal University of Pará (UFPA) has been exploited. Two types of cables were used: an Ericsson TEL48102 and an Ericsson TEL313000, with specifications described in Table I.

TABLE I
Specifications of the employed twisted-pair cables.

Specification	Ericsson TEL48102	Ericsson TEL313000
Diameter (mm)	0.4	0.5
Pairs (mm)	16	30
Length (m)	400	500
Conductor	tin-plated copper wire	
Insulation	polyethylene	

For each cable, three quantities were measured: open-circuit input impedance, short-circuit input impedance and one-pot S_{11} scattering parameter. Each quantity was measured three times in order to have an estimate of its expected value and the considered frequency band for each measurement was the ADSL2+ one – i.e. from 4.3125 kHz to 2.208 MHz.

B. General Conditions for the Identification Process

The identification process for each cable was carried out assuming the conductivity of copper σ_{copper} is equal to $5.8 \times 10^{-7} S/m$, the free-space electrical permittivity ϵ_0 is equal to $\frac{1}{36\pi} \times 10^{-9}\ F/m$ and the velocity of light c is $3 \times 10^8\ m/s$.

Regarding the fine-tuning of the estimated parameters, the optimization technique employed in each block is Levenberg-Marquardt and the employed physical model is VUB0 [4]. VUB0 is a causal model that provides theoretical values for the secondary parameters according to the physical parameters of the chosen cable type. The threshold δ, used as stop criterion for the iterative approach, is 0.02.

Note that the inputs of the proposed methodare the secondary parameters of the cable under test. There are some methods to measure the secondary parameters [10]. However, the adopted strategy here is to estimate them from the classical "open-short" approach [2], i.e.

$$\hat{Z}_0(f) = \sqrt{Z_{oc}(f)\ \times\ Z_{sc}(f)}$$

and

$$\hat{\gamma}(f) = \frac{1}{l}\, arctanh\left(\sqrt{\frac{Z_{sc}(f)}{Z_{oc}(f)}}\right),$$

where $Z_{sc}(f)$ is the measured short-circuit input impedance, $Z_{oc}(f)$ the measured open-circuit input impedance, and l is the length of the cable under test, known in advance.

C. Results and Analysis

The tables II and III summarizes the nominal values of the parameters for TEL48102 and TEL313000 cables, presented in [11], the output of the identification process and the percentage deviation Δ in relation to the nominal values.

The identification of ϵ_r and a yielded values smaller than the nominal ones. On the other hand, the identification of D yielded greater values: 25.95 % (TEL48102) and 26.40 % (TEL313000). These divergent estimations occurred because the nominal values are derived assuming an idealized geometry of the cable, unlikely what is found in practice.

Regarding parameter D, the conductors are not perfectly close to each other along the cable length for many reasons: irregular twist of the pairs as result of limitations on the manufacturing process; slightly bends of the pair caused by the weight of the other pairs in the same cable; etc.All of this results in a mean distance between the conductor centers greater than the nominal value – assumed as two times the sum of the radius and the insulation thickness. That greater distance between the conductor centers found in practice also implies on the deviation of the relative electric permittivity from its nominal value. The cable models assume the conductors are surrounded by one dielectric (polyethylene, for instance) but, effectively, they are surrounded by a composition of the dielectric and air instead. This is the reason the estimated ϵ_r is less than the nominal value of the dielectric.

The discrepant estimation for radius a may be due to the industrial treatment applied to the conductors. In this paper, it has been assumed the conductivity of the pure copper, but the manufacturing of cooper conductors with industrial treatment (tin-plated wires) is widely used in order to prevent galvanic corrosion. Such a treatment causes a slight change on the conductivity of the conductor at its surface, where the current mainly flows at high frequencies (skin effect). This discrepancy between the assumed value and the actual one for the conductivity influences the estimation of the radius a.

TABLE II

NOMINAL VALUES AND OUTPUT OF THE PARAMETERS IDENTIFICATION PROCESS FOR THE TEL48102 CABLE.

Parameter	**Nominal value**	**Identified value**	$\Delta(\%)$
ϵ_r	2.2600	2.1636	-4.26
a **(mm)**	0.2000	0.1806	-9.70
D **(mm)**	0.6600	0.8313	+25.95

TABLE III

NOMINAL VALUES AND OUTPUT OF THE PARAMETERS IDENTIFICATION PROCESS FOR THE TEL313000 CABLE.

Parameter	**Nominal value**	**Identified value**	$\Delta(\%)$
ϵ_r	2.2600	2.1875	-3.21
a **(mm)**	0.2500	0.2239	-10.44
D **(mm)**	0.8000	1.0112	+26.40

D. Validation of the Identified Parameters

This section presents a validation of the proposed method. The aim is to show that the identified parameters also result in an accurate electrically characterization of the cables.

One quantity was arbitrarily chosen in order to carry out this validation: the one-port S_{11} scattering parameter. It was measured for the cables cited in previous section and compared to the theoretical counterparts, generated from both nominal and identified cable parameters via VUB0 cable model. In this way, each figure below shows the measured quantity, the prediction using the nominal parameters and the prediction using the optimized parameters, for each employed cable type.

Figs. 2 and 3 show the validation for the TEL48102 cable. It is possible to note the identified parameters provide a match to the measurement much better than the nominal parameters. The mean error on the magnitude of S_{11} provided by the identified parameters is below -24 dB. The identified parameters also have provided a good match for the phase.

Similar results were obtained for the TEL313000 cable.

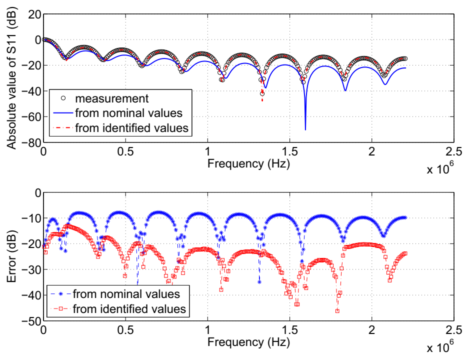

Fig. 2. Magnitude of S_{11} scattering parameter for TEL48102 cable.

V. CONCLUSIONS

This paper presented a method for identification of physical parameters of twisted-pair cables.

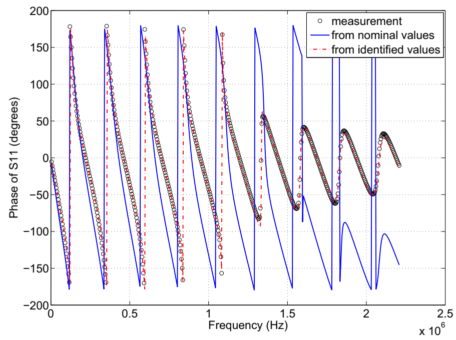

Fig. 3. Phase of S_{11} scattering parameter for TEL48102 cable.

The results for the analyzed cables indicate the proposed method provides reasonably accurate estimations of the cable parameters and the identified parameters lead to an accurate simulation of the electrical characteristics of the cable via physical cable models. A good match to the measured quantity (S_{11}) was achieved for both magnitude and phase.

ACKNOWLEDGMENT

The authors acknowledge the financial support received from the Research and Development Center, Ericsson Telecomunicações S.A., Brazil.

REFERENCES

[1] V. Belevitch. Theory of the proximity effect in multiwire cables – Part I. *Philips Res. Rep.*, 32:16–43, September 1977.

[2] Jason J. Yoho. *Physically-Based Realizable Modeling and Network Synthesis of Subscriber Loops Utilized in DSL Technology*. PhD thesis, Virginia Polytechnic Institute, 2001.

[3] C. Sales, R. M. Rodrigues, F. Lindqvist, J. Costa, A. Klautau, K. Ericson, J. R. i Riu, and P. O. Börjesson. Line Topology Identification using Multi-Objective Evolutionary Computation. *IEEE Transactions on Instrumentation & Measurement*, 59(3):715–729, March 2009.

[4] T. Bostoen, P. Boets, M. Zekri, L. Van Biesen, T. Pollet, and D. Rabijns. Estimation of the transfer function of a subscriber loop by means of a one-port scattering parameter measurement at the central office. *IEEE Journal on Selected Areas in Communications*, 20(5):936–948, June 2002.

[5] L. Heylen and J. Musson. *Cable Models Predict Physically Impossible Behaviour in Time Domain*. ETSI STC. TM6, 1999.

[6] P. Boets and L. Van Biesen. Metallic 2-wire parametric line models – a survey. *XVIII Imeko World Congress*, 2006.

[7] F. Hassoun, R. Tarafi, and A. Zeddam. Calculation of per-unit-length parameters for shielded and unshielded twisted pair cables. In *Electromagnetic Compatibility, 2006. EMC-Zurich 2006. 17th International Zurich Symposium on*, pages 250–253, February/March 2006.

[8] Woopoung Kim, Seock Hee Lee, Man Cheol Seo, M. Swaminathan, and R. R. Tummala. Determination of propagation constants of transmission lines using 1-port TDR measurements. In *ARFTG Conference Digest, Spring 2002. 59th*, June 2002.

[9] A. Lago, C. M. Penalver, J. Marcos, J. Doval-Gandoy, A. Melendez, O. Lopez, F. Santiago, F. D. Freijedo, J. M. Vilas, and J. C. Lorenzo. Geometric analysis and manufacturing considerations for optimizing the characteristics of a twisted pair. *IEEE Transactions on Electronics Packaging Manufacturing*, 32(1):22–31, January 2009.

[10] J. E. Schutt-Aine. High-frequency characterization of twisted-pair cables. *IEEE Transactions on Communications*, 49(4):598–601, April 2001.

[11] *Test procedures for digital subscriber line (DSL) transceivers*. ITU-T recommendation G.996.1, February 2001.