Single-Ended Transfer Function Estimation of Telephone Links for Deployment of xDSL Services

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***Abstract* — The transfer function (H_V) estimation is an essential procedure to qualify a twisted-pair loop for xDSL data transmission. The transfer function can be indirectly estimated via one-port scattering parameter (S_{11}), which fetches the commodities of single-ended measurements. For this purpose, the viability of the physical line model VUB0 was extensively tested on the parametric estimation of the S_{11} spectral behavior. The obtained parameters are then used to estimate H_V. The approach was improved to consider an arbitrary loop scenario, and empirically bettered initial guesses for the VUB0 parameters were employed to increase the consistency of the estimator for complex loops.**

***Index Terms* — Digital subscriber line, maximum-likelihood estimation, loop qualification, one-port scattering parameter, transfer function, single-ended tests.**

I. Introduction

Qualifying a twisted-pair loop for digital subscriber line (DSL) services consists on verifying its potentiality to transmit signals which are spectrally far beyond the plain-old-telephone-service (POTS) spectral band, in other to transmit data at high bit rates and provide fast and reliable Internet connections. Several impairments, such as load coils and bridged-taps, may appear along the twisted-pair loop and may affect critically the transmission at higher frequencies, needing to be located and removed by using classical techniques such as Time-Domain Reflectometry (TDR) or Frequency-Domain Reflectometry (FDR), for example. The line length and wire gauge changes are intrinsic loop characteristics that also increase the signal attenuation. The aforementioned aspects have their degrading impact on the transfer function, decreasing consequently the attainable channel capacity (in bit rate), which justifies the research for improvements on loop qualification techniques. By doing so, the efficacy of technical services could be increased, lowering the risks of installation delays, intermittent failures, or under-performing service, which implies in higher competitiveness and brings good reputation to the service company through an efficient support added to a reliable infrastructure. Other bottlenecks on achieving a satisfactory channel capacity are caused by crosstalk, radio frequency interferences and impulsive noises.

The single-ended line testing (SELT) is a primary expedient to pre-qualify the existent loops, since no DSL equipment is initially available at the costumers' premises (CP) to perform double-ended line testing (DELT) remotely. Moreover, dispatching technicians to the CP is more expensive and time consuming. On the other hand, SELT may not be adequate for services upgrades in speed, due to its inability to provide information about the noise at the CP side [1]. Therefore, built-in DELT capabilities comprising the installed DSL equipment at both sides are desirable in this case.

The transfer function of the loop can be derived from SELT measurements by using the tables of primary parameters (RLCG parameters) or some parametric line model. Despite the RLCG tables provide exact values and have been used on recommendations [2] and books [3]-[4], this way of defining the cable characteristics has some drawbacks: first, it is not specified how to interpolate or extrapolate, arising different interpretations when cable parameter values at intermediate frequencies or above the ADSL frequency band are needed, since those tables specify the primary parameters from dc to 1100 kHz; second, these parameters will result in non-causal time domain behavior. These problems can be addressed in some way by using a parametric transmission line model. Among the several proposed parametric line models – like BT, KPN0 and DTAG1 [5]-[6], for example – the VUB0 (*Vrije Universiteit Brussel*, Belgium) [7] seems to be the best choice, since it has less parameters (five for each line section) when compared with the other ones. Another advantage is the straightforwardness to determine good initial values for the parameters of this model, mitigating the problem of local minima during the parameter estimation procedure. Such a line model has been used in [7], where the transfer function of the loop under test is derived from one-port scattering parameter S_{11} measurements performed from the central office (CO).

In this work, the scattering parameter S_{11}, which is the ratio of the reflected wave and the incident wave at the same port, is also used to estimate the parameters of the physical model called VUB0. To achieve this goal, the known S_{11} data over frequency for standard topologies are the reference for the model, and the maximum likelihood estimator (MLE) is applied. A description about the VUB0 model, the generalization proposed in this work to estimate the transfer function for any topology and a summary about the MLE

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estimator are given in Section II. The results are shown in Section III. Finally, the conclusions are given in section IV.

II. METHODOLOGY

A. *The* VUB0 physical *model for a telephone transmission line*:

The VUB0 model was proposed in [7]-[8] to account a twisted-pair transmission line and has some advantages in comparison with other models, such as its relative simplicity and small number of unknown parameters to estimate. For a single line section, for instance, the parameters to be found can be represented by the five element vector **A** = [a_1 a_2 a_3 a_4 a_5]. Additionally, since VUB0 is a physical model, good initial values for the parameters can be set. In this work, the VUB0 model was generalized for any loop make-up, so that five unknown parameters are included per line section. The basic expressions for the VUB0 model are shown below.

The product of the propagation constant (γ) with the length (l) of a line section is given by [7]

$$\gamma l = \sqrt{a_4 s^2 + a_1 s\sqrt{-s}\, J_0/J_1 + a_1 a_3 s^2\,\Psi/2}\,, \tag{1}$$

where $s = j\omega$ (ω is the angular frequency), Ψ is defined by

$$\Psi = \frac{3a_2^3 J_3 J_2 + 2a_2 J_1 J_2 + a_2^2 J_0 J_3}{a_2^3 J_2 J_3 + a_2 J_1 J_2 + 3a_2^2 J_0 J_3 + J_0 J_1}\,, \tag{2}$$

and J_i are the Bessel functions such as $J_i = J_i(a_3\sqrt{-s})$, with $i = 0, 1, 2, 3$.

The transfer function of the line is given by $exp(-\gamma l)$ and the characteristic impedance can be written as

$$Z_0 = \sqrt{a_4 s^2 + a_1 s\sqrt{-s}\, J_0/J_1 + a_1 a_3 s^2\,\Psi/2}\Big/ a_5 s\,. \tag{3}$$

The VUB0 model also provides the initial guesses to be used as an input for the estimator in order to find the unknown parameters represented by the vector **A**, which were obtained by the parallel-line model shown in Fig.1, where σ, r and D are the conductivity, the radius and the separation between the conductors, respectively. The electric permittivity ε and the magnetic permeability μ are related to the dielectric material.

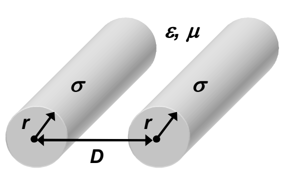

Fig. 1. The parallel-wire line used as reference.

Therefore, for estimation purposes, the starting point for the parameters of each line section that composes an arbitrary make-up is given by

$$\begin{aligned} a_1 &= \frac{k_{e1}}{r}\sqrt{\frac{\mu}{\sigma}}\frac{\varepsilon}{\operatorname{arccos}h(D/2r)}l^2, \\ a_2 &= (r/D)^2, \\ a_3 &= k_{e3} r\sqrt{\mu\sigma}, \\ a_4 &= k_{e4}\frac{a_1 a_3}{\ln\left(1/\sqrt{a_2}\right)}, \\ a_5 &= \frac{\pi\varepsilon}{\operatorname{arccos}h(D/2r)}l, \end{aligned} \tag{4}$$

The difference between (4) and the equations used in [7] is that the empirical factors k_{e1}, k_{e3} and k_{e4} were introduced to improve the initial guess, which is relevant for the most complex topologies, whose parameters are more difficult to estimate. The prediction of these factors is performed by observing the convergence of the parameters for single line topology cases. Since the VUB0 model for more complex make-ups can be built as a composition of single line cases, the empirical factors employment can be extended to an arbitrary topology.

Before obtaining the VUB0 expressions for the scattering parameter S_{11} and for the transfer function H_V, the transmission matrix (or ABCD matrix) for each line section was derived. For a serial line section, the ABCD matrix is given by

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Serial} = \begin{bmatrix} \cosh(\gamma l) & Z_0\sinh(\gamma l) \\ \frac{1}{Z_0}\sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix}, \tag{5}$$

whereas for a bridged-tap section, the ABCD matrix is

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Bridged-tap} = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_0}\tanh(\gamma l) & 1 \end{bmatrix}. \tag{6}$$

The ABCD representation for the load impedance Z_l at the termination is also needed:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Load} = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_l} & 1 \end{bmatrix}. \tag{7}$$

The equivalent ABCD matrix for an arbitrary topology can be found by multiplying the ABCD matrices of the individual elements in the order of their occurrence:

$$\begin{bmatrix} A_T & B_T \\ C_T & D_T \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_1 \begin{bmatrix} A & B \\ C & D \end{bmatrix}_2 \cdots \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{N_S} \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_l} & 1 \end{bmatrix}, \tag{8}$$

where N_S is the number of line sections. As reference, the ETSI (European Telecommunications Standards Institute) standard scenarios [2] are shown in Fig 2, where the adjustable lengths x_i (i = 1 to 8) are provided in [2], depending on the loop insertion loss at 300 kHz.

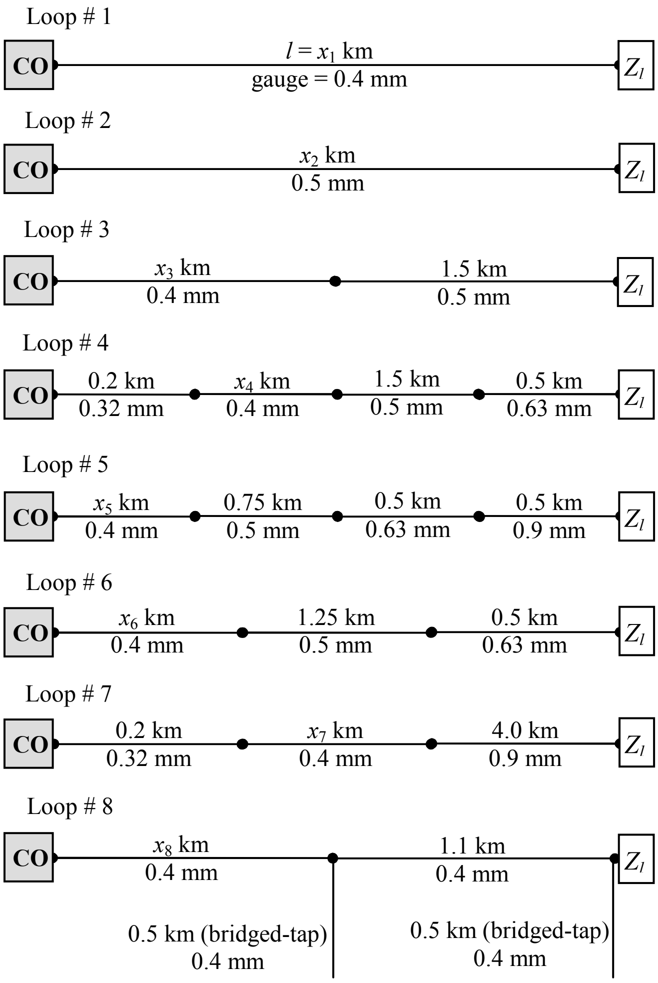

Fig. 2. The ETSI test loops. The central office (CO) contains the generator and its impedance Z_g.

The S_{11} and H_V parameters can be found from (8) by applying the following conversion rules:

$$S_{11}^{model} = \frac{A_T - Z_g C_T}{A_T + Z_g C_T}, \quad (9)$$

$$H_V^{model} = 1/A_T . \quad (10)$$

The impedance Z_g is related to the generator. The input impedance Z_{in} is another important loop characteristic, which can be found by

$$Z_{in}^{model} = A_T / C_T . \quad (11)$$

B. *Parametric estimation*:

Given the measured values of the scattering parameter S_{11} over frequency for a given topology, the estimator role is to find the unknown parameters by minimizing a cost function that compares the S_{11} values computed via VUB0 model with the measured ones. From obtaining the parameters via S_{11} estimation, they can now be used to predict the transfer function over the required frequency band. The maximum-likelihood estimator (MLE) is used because of its consistency and asymptotic efficiency, normal distribution and unbiasedness. The MLE cost function is given by [7]

$$V(\theta) = \sum_{k=1}^{N} \frac{\left| S_{11}^{model}(f_k, \theta) - S_{11,k}^{measurement} \right|^2}{\sigma_{S_{11},k}^2}, \quad (12)$$

being N the number of frequency samples, $S_{11}^{model}(f_k, \theta)$ is the parametric expression of the scattering parameter obtained from the VUB0 model, $S_{11,k}^{measurement}$ is the measured value for the *k*th frequency and $\sigma_{S_{11},k}^2$ is the estimated variance of the measured value for the *k*th frequency. The employed iterative optimization algorithm is based on the Levenberg-Marquardt (LM) method [9], which combines the Gauss-Newton and gradient descent techniques.

III. RESULTS

In this section, the reliability of the generalized VUB0 model on the estimation of the transfer function by using single-ended measurements is checked. In fact, in this first stage, the measured data was obtained from a ETSI loop simulator. The transfer functions for all eight ETSI scenarios were estimated by using the S_{11} estimator, which obtains the VUB0 model parameter from the measured data provided by the ETSI loop simulator.

The lengths x_i were adjusted in the ETSI loop simulator by considering an insertion loss of 36 dB at f = 300 kHz [2]. The impedances of the generator and the load are $Z_g = 100\Omega$ and $Z_l \rightarrow \infty$ (open-ended termination). The measured data were considered inside the ADSL spectral range from 12.9375 kHz up to 1.104 MHz with 254 frequency samples. Figure 3 shows the estimated scattering parameter S_{11}, the transfer function H_V and the input impedance Z_{in} compared with the data obtained from the loop simulator provided by Ericsson. The results related to the estimation performed without the empirical fix factors for the initial guesses are also shown, to confirm the improvements on the transfer function estimation brought by these factors. Results for all ETSI loops were obtained, but only the results for scenarios with more than one line section are shown (loops #3 to #8) for sufficiency. The results are only shown for magnitude, since this is the most interesting for the computation of the channel capacity [7]. However, the estimation process also accounts the phase, as can be concluded by observing the cost function (12).

The estimator managed to find the VUB0 parameters for all topologies, which were used to reconstruct the physical variables S_{11}, H_V and Z_{in}. The estimated variables matched very well with the reference, including for the make-up with bridged-taps (loop #8), where the oscillations in the transfer function, caused by the multipath characteristic of the loop, were identified. It was also observed that the successful estimation of H_V depends greatly on the initial guesses and better starting points are needed for topologies with more than two line sections. The empirically improved initial guesses allowed to increase the robustness on the parametric estimation for the most complex ETSI loops and all results could be obtained with a single numerical setting for the estimator.

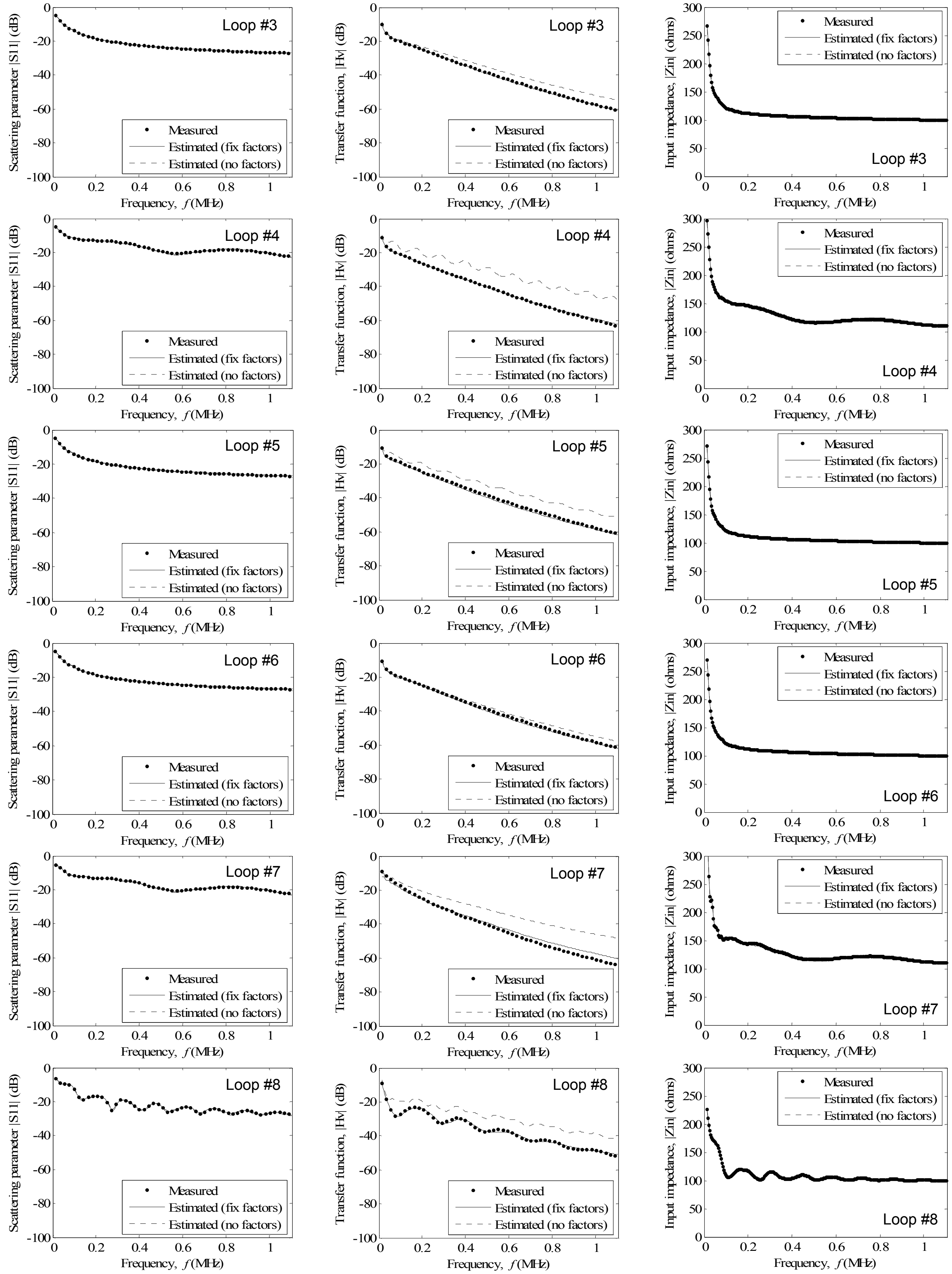

Fig. 3. Estimated S_{11}, H_V and Z_{in} of the ETSI loops #3 to #8, compared with the data from the ETSI loop simulator, considered as "measured" for convenience.

IV. CONCLUSION

A generalization of the VUB0 model for twisted-pair loops was proposed and tested on the estimation of the standard ETSI scenarios physical properties. The maximum likelihood estimator searches for the VUB0 parameters of each line section of a given scenario based on single-line measurements, more precisely, the measured S_{11} parameter over frequency. Since the successful convergence of the parameters depends greatly on their starting point, empirically improved initial guesses were introduced to increase the estimator robustness for more complex topologies. The estimated results agreed well with the measured data, which affirms the VUB0 model as a good choice to represent the transfer function and other physical characteristics of twisted-pair loops. The estimated transfer function can be used to compute the actual channel capacity and to analyze the viability of deployment of xDSL services.

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