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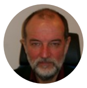

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KHM Cable Model Parameters for ITU-T G.fast Reference Loops

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***Abstract*—G.fast is a new standard for fixed broadband access that aims at achieving bit rates of 1 Gb/s over short copper loops. In order to give support to simulation, design and performance evaluation tests, the G.fast recommendation presents examples of some wiring topologies and reference loops describing configurations expected to be found in real G.fast deployments. Our work describes results of modeling some types of lines adopted in these reference loops by means of a low complexity and causal parametric cable model. The results indicate that the modeling approach proposed in this work is accurate for all the analyzed cases, which include high quality, medium quality and low quality cables.**

I. Introduction

In December of 2014 the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) finished the first versions of the G.9700 and G.9701 recommendations [1], [2], which define the power spectral density and the physical layer specifications for the G.fast standard. G.fast is a new broadband access technology that aims at achieving 1 Gb/s from the last distribution point using existing infrastructure of copper wires [3], [4]. To reach such data rates, G.fast transceivers use bandwidths of up to 106 MHz or up to 212 MHz for signaling. Even though the signal attenuation over copper lines increases with both frequency and cable length, this is feasible over short loops, e.g. up to 250 m.

Since the concept behind G.fast is reusing the existing metallic infrastructure, it is designed to work over loops containing a variety of cable types and arrangements including, for example, artifacts such as bridged taps. In this context, the G.9701 recommendation (Appendix I) presents examples of wiring topologies[1] and reference loops describing configurations expected to be found in real G.fast deployments [2]. These reference loops are used in many cases to facilitate computer-based performance evaluation simulations. For example, in such experiments the electrical characteristics of each line that composes the topologies can be derived using parametric cable models. Two-port network modeling of these loops give some key transmission features associated to them [6], like their frequency responses (or transfer functions) in frequency domain and impulse responses in time domain, which can be subsequently used in channel capacity evaluations [7], [8].

To the best of our knowledge, today, only two parametric cable models proved to be fully adapted for simulations involving G.fast systems in both frequency and time domains. The first one is the model standardized by the ITU in [2], which was presented first in [9] and further modified in [10]. The other one is the KHM model, which was presented in part in [11] and then completed in [12]. Although both models lead to equivalent results in both frequency and time domains, it was clearly shown in [12] the benefits of using the KHM model in situations in which the associated computational cost is important (for example, when performing loop topology identification procedures). Such advantage is related to its reduced number of parameters as well as its simple equations and easy techniques for fitting the values of its parameters to measurement data.

This paper is an extension of [12]. In [12], we presented a set of parameter values for modeling CAD55 cables using the KHM model. The CAD55 cable is a typical aerial drop cable in the United Kingdom (UK) which is adopted in the G.fast reference loops [2]. In this paper, for completeness, we present parameter values for modeling some other types of lines described in [2], by means of the KHM cable model. The values were fitted to each cable under analysis using the same optimization techniques previously described in [11] and [12], and are valid for frequencies up to 500 MHz.

The rest of this work is organized as follows: Section II presents an overview of the reference model for FAST Digital Access over Short Subscriber Loops (DASSL) adopted in the G.9701 recommendation. The makeup for both the final drop and in-premises portions of the G.fast metallic access link are discussed. Section III reviews the parametric cable model currently standardized by the ITU for simulating the electrical characteristics of copper lines operating over the G.fast spectra. Continuing, Section IV reviews the KHM cable model and Section V discusses the techniques adopted for fitting the values of its parameters to some types of lines

[1]The term wiring topology refers to the orientation of the cables as they run from the distribution point (DP) toward the end user [5].

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described in the G.9701 recommendation. Further, Section VI presents experimental results for validating the modeling approach proposed in this work and, finishing, Section VII discusses the conclusions.

II. The G.fast Wiring Topologies and Reference Loops

The simplified reference model for FAST DASSL defined in the G.9701 recommendation is illustrated in Fig. 1 [13]. It describes arrangements for both the final drop and in-premises portions of the G.fast metallic access link.[2] In general, the final drop, that is the wiring portion installed from the DP to the copper network terminator (NTc), is composed by three distinct sections: patch section, proximal section and radial section. The in-premises wiring, on the other hand, contains a cascade of star sections, where a G.fast terminal can be attached to any of the links in a star section.

In practice, a diversity of scenarios can be created by mixing distinct copper lines in each cable section composing the reference model illustrated in Fig. 1. For simplicity, eight combinations are highlighted in the G.9701 recommendation, which allow easy DP-end-to-terminal-end testing. Fig. 2 illustrates them [2].

From Figs. 1 and 2, it can be inferred that the following cable types (wire types) are used in the final drop sections: A26u, A26j, A24u, B05, B05a, B05u, T05u and T05b.[3] For the in-premises wiring we have the following cable types: CAT3, CAT5, B5cw and T05h. These cable types are associated with real lines commonly installed in the copper access networks of some countries. By performing such connection, proper simulation models can be implemented in computer environment. In this context, Table I succinctly describes the real lines that make reference to the cable types CAT5, B05a, T05b, T05h and T05u.

It should be noted that although a dozen of distinct cable types had been defined in [2], only the five ones highlighted in Table I are completely associated with a real line and thus with an underlying parametric model for computer-based simulations. In the next section, we review the cable model standardized by the ITU for such purposes, together with the corresponding set of parameter values for simulating the cable types CAT5, B05a, T05b, T05h and T05u.

III. The Standardized G.fast Cable Model

A cable model is assumed to be composed by a set $\mathbf{\Theta} = \{\Theta_1, \ldots, \Theta_M\}$ of M parameters and an associated set $\mathbf{\Gamma} = \{\Gamma_1, \ldots, \Gamma_N\}$ of N synthesis equations that are functions of the parameters $\mathbf{\Theta}$ [12]. Typically, the synthesis equations describe the electrical characteristics of a given line in terms of its frequency dependent primary coefficients, the series resistance $R(f)$, series inductance $L(f)$, shunt conductance $G(f)$ and shunt capacitance $C(f)$, which compose the series impedance $Z(f) = R(f) + j2\pi f L(f)$ and shunt admittance $Y(f) = G(f) + j2\pi f C(f)$. Alternatively, the synthesis equations can describe the frequency dependent secondary coefficients, the characteristic impedance $Z_0(f)$ and the propagation constant $\gamma(f)$.

It was agreed by the ITU that the TNO/EAB cable model presented in Definition 1 should be used in order to accurately characterize the primary coefficients of the cable types adopted in the G.fast reference loops.

Definition 1 (TNO/EAB)**.** *The primary coefficients are modeled by*

$$Z(f) = j2\pi f L_\infty + R_{s0}\left(1 - q_s.q_x + \sqrt{q_s^2.q_x^2 + 2\frac{j2\pi f}{\omega_s}.\left(\frac{q_s^2 + \frac{j2\pi f}{\omega_s}.q_y}{\frac{q_s^2}{q_x} + \frac{j2\pi f}{\omega_s}.q_y}\right)}\right), \quad (1)$$

$$Y(f) = j2\pi f C_{p0} \times (1 - q_c) \times \left(1 + \frac{j2\pi f}{\omega_d}\right)^{\frac{-2\phi}{\pi}} + j2\pi f C_{p0} \times q_c, \quad (2)$$

where

$$L_{s\infty} = \frac{1}{\eta_{VF} \times c_0} Z_{0\infty}, \quad (3)$$

$$C_{p0} = \frac{1}{\eta_{VF}.c_0} \times \frac{1}{Z_{0\infty}}, \quad (4)$$

$$q_s = \frac{1}{q_H^2.q_L}, \quad (5)$$

$$\omega_s = q_H^2.\omega_{s0} = q_H^2.\left(\frac{4\pi.R_{s0}}{\mu_0}\right), \quad (6)$$

$$\omega_d = 2\pi f_d. \quad (7)$$

□

The TNO/EAB model is composed by a set of 10 empirical parameters, such that $\mathbf{\Theta} = \{Z_{0\infty}, \eta_{VF}, R_{s0}, q_L, q_H, q_x, q_y, \phi, f_d, q_c\}$. Some of them are strongly linked to physical meanings, while some others are fine tuning shaping parameters (used in shaping functions), whose goal is to improve the results when fitting the model curves to measurement data. The theoretical background behind the meaning of each one of these parameters can be found in [9] and [10], and their values defined in the G.9701 recommendation for modeling the cable types CAT5, B05a, T05b, T05h and T05u, are presented in Table II.

In the next section, we review the KHM cable model, which can be alternatively used for modeling the cable types defined in the G.9701 recommendation, especially in cases in which the computational cost is an issue.

IV. The KHM Cable Model

The KHM model is a cable model with a reduced number of parameters in $\mathbf{\Theta}$, which is valid for frequencies up to hundreds of MHz and also for time domain procedures since it reproduces causal impulse responses [12]. Furthermore, beyond being adapted for both frequency and time domains, it is attractive due to its low computational cost and closed-form expressions for fitting the values of its parameters to measurement data. Definition 2 reviews the synthesis equations that compose the KHM model.

[2]The final drop and especially the in-premises wiring portions, can vary considerably between countries. However, such reference model can be used as a representative picture of typical cases.

[3]Note that for the final drops D3 and D4 the initial wire is not completely defined yet, and is specified as B05???, without the suffix 'a' or 'u' [14].

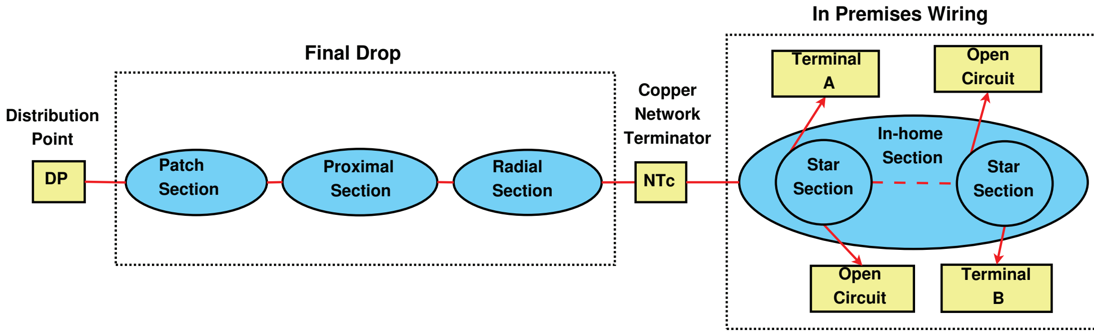

Fig. 1. DASSL model as defined in [13].

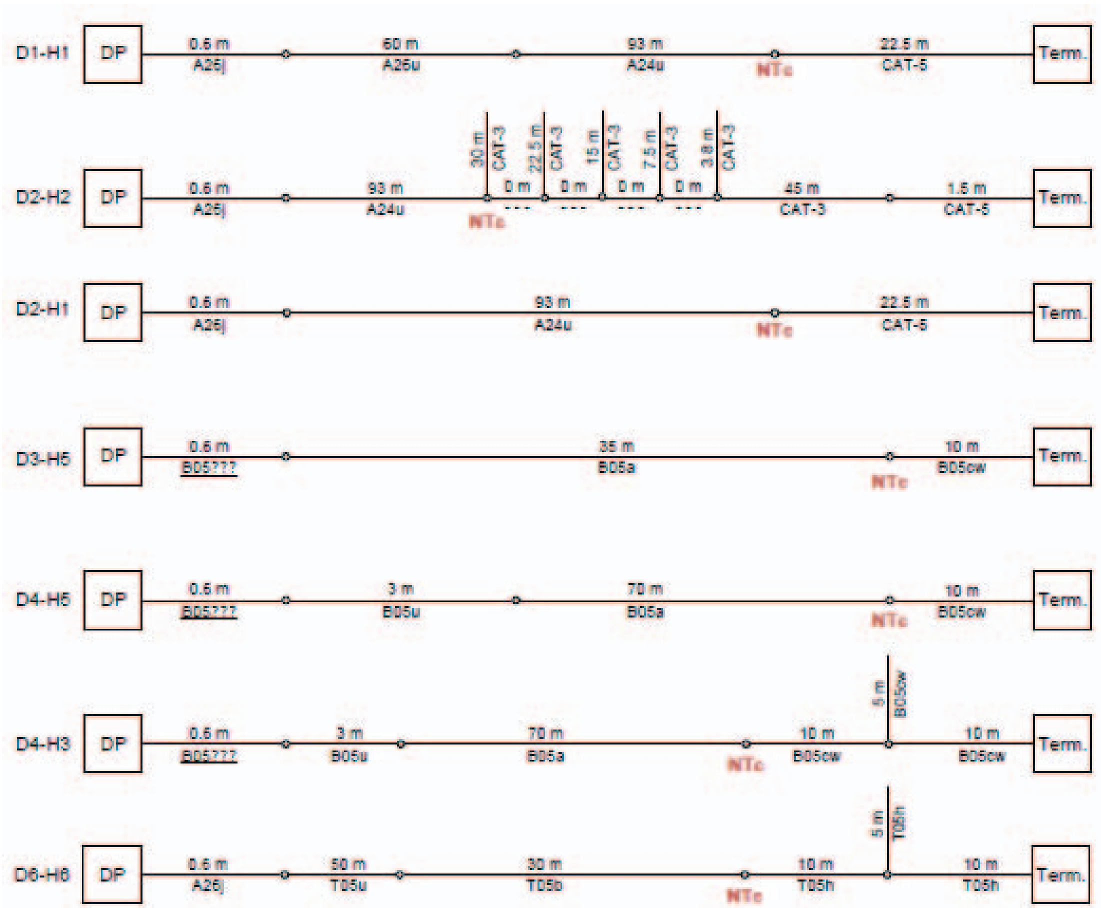

Fig. 2. G.fast reference loops as defined in [2].

Definition 2 (KHM)**.** *The propagation constant, $\gamma(f) = \alpha(f) + j\beta(f)$, is modeled by*

$$\alpha(f) = k_1\sqrt{f} + k_2 f, \tag{8}$$

$$\beta(f) = k_1\sqrt{f} - k_2\frac{2}{\pi} f \ln f + k_3 f. \tag{9}$$

The characteristic impedance, $Z_0(f) = \Re\{Z_0(f)\} + j\Im\{Z_0(f)\}$, is modeled by

$$\Re\{Z_0(f)\} = h_1 + h_2\frac{1}{\sqrt{f}}, \tag{10}$$

$$\Im\{Z_0(f)\} = -h_2\frac{1}{\sqrt{f}}. \tag{11}$$

□

The 5 empirical parameters composing the model are: $\boldsymbol{\Theta} = \{k_1, k_2, k_3, h_1, h_2\}$, where k_1 is the parameter that controls the attenuation factor from the skin effect, k_2 is the parameter

TABLE I
BRIEF DESCRIPTION OF THE REAL LINES ASSOCIATED WITH THE CABLE TYPES CAT5, B05A, T05B, T05H AND T05U.

Cable type	Description
CAT5	Typical Category 5 cable commonly used in structured cabling for computer networks, such as Ethernet [9]
B05a	Cable Aerial Drop-wire No 55 (CAD55), a typical copper line used in the UK [15]
T05b	Medium quality multi-quad cable used in buildings [9]
T05h	Low quality cable used for in-house telephony wiring [9]
T05u	KPN cable, a typical access line used in the Netherlands [9]

TABLE II
PARAMETER VALUES DEFINED IN [2] FOR MODELING THE CABLE TYPES: CAT5, B05A, T05B, T05H AND T05U.

Parameter (per m) / Cable type	CAT5	B05a	T05b	T05h	T05u
$Z_{0\infty}$	98.000000	105.0694	132.348256	98.369783	125.636455
η_{VF}	0.690464	0.6976	0.675449	0.681182	0.729623
R_{s0}	165.900000e-3	0.1871	170.500000e-3	170.800000e-3	180.000000e-3
q_L	2.150000	1.5315	1.789725	1.700000	1.666050
q_H	0.859450	0.7415	0.725776	0.650000	0.740000
q_x	0.500000	1	0.799306	0.777307	0.848761
q_y	0.722636	0	1.030832	1.500000	1.207166
q_c	0	1.0016	0	0	0
ϕ	0.973846e-3	-0.2356	0.005222e-3	3.023930e-3	1.762056e-3
f_d	1.000000	1.000000	1.000000	1.000000	1.000000

that controls the attenuation factor from the dielectric loss, k_3 is the parameter that controls the linear phase constant, h_1 is a zero order approximation of $Z_0(f)$ and h_2 is the parameter that controls the transition from the low-frequency region (that is, the region below the skin effect mode onset) to the region where the characteristic impedance tends to be constant. The theoretical background behind the derivation of the synthesis equations described in Definition 2, as well as the meaning of each one of its parameters can be found in [11] and [12].

Continuing, we discuss the technique adopted in this work for fitting the values of the KHM model parameters to the cable types CAT5, B05a, T05b, T05h and T05u.

V. ANALYSIS PROCEDURE

The analysis procedure consists of obtaining an estimate $\hat{\mathbf{\Theta}}$ of the cable model parameter values from given data Ξ (that is, fitting the model parameters to Ξ), which is generically denoted here by $\hat{\mathbf{\Theta}} = \mathcal{A}\{\Xi\}$.

The data Ξ can be obtained from measurements using specialized equipments, such as vector network analyzers and impedance analyzers, or from simulations (which is the case in this work). The associated analysis can be done either via closed-form expressions of the type $\hat{\Theta}_i = f(\Xi)$ or iterative optimization in the fitting procedures such as Levenberg-Marquardt and genetic algorithms.

An interesting feature of a cable model is its easiness of the associated analysis procedure. Depending on the application, the computational cost of the analysis may be taken into account. For example, when the analysis has to be executed in real time by a limited-power embedded system or repeatedly invoked as part of an optimization process. Besides the advantage with respect to the computational cost, if a cable model allows the analysis to be done with closed-form expressions, it also facilitates user interaction. When dealing with iterative optimization procedures, defining the search space and initial conditions may not be a trivial task [16]. A related aspect is that many iterative procedures can get stuck in a local maximum (or minimum) and do not guarantee convergence.

Fig. 3 illustrates the sequential steps composing the analysis procedure performed in this work. First, we used the reference model, synthesis equations and set $\mathbf{\Theta}$ of parameters defined by the ITU in the G.9701 recommendation in order to obtain by simulation the primary and secondary coefficients of the cable types CAT5, B05a, T05b, T05h and T05u. The simulations were conducted using a frequency range from 100 kHz up to 500 MHz. Using the data Ξ from these simulations, the analysis procedure was invoked in order to obtain estimates $\hat{\mathbf{\Theta}}$ of the values for the KHM model parameters that best fit the cable types under test. For performing the numerical calculations, the same least-squares fitting techniques based on closed-form expressions described in [11] and [12] were employed. Note that the reference length adopt by the TNO/EAB model parameters is meter (see Table II), while the KHM uses kilometer.

VI. RESULTS

Table III presents the parameter values estimated for modeling the cable types CAT5, B05a, T05b, T05h and T05u, using the KHM model.

Assuming that the lines are perfectly terminated, and using the estimated set $\hat{\mathbf{\Theta}}$ of parameters presented in Table III as well as the synthesis equations of the KHM model, the transfer functions corresponding to 50 m long cables were derived for each cable type under test. Fig. 4 shows the results.

Similarly, Fig. 5 shows the results (absolute values) for the characteristic impedances.

The accuracy of the modeling approach proposed in this work is illustrated in Figs. 6 and 7 that show the transfer function absolute error in dB, and the characteristic impedance absolute error in Ω, derived when modeling the cable types

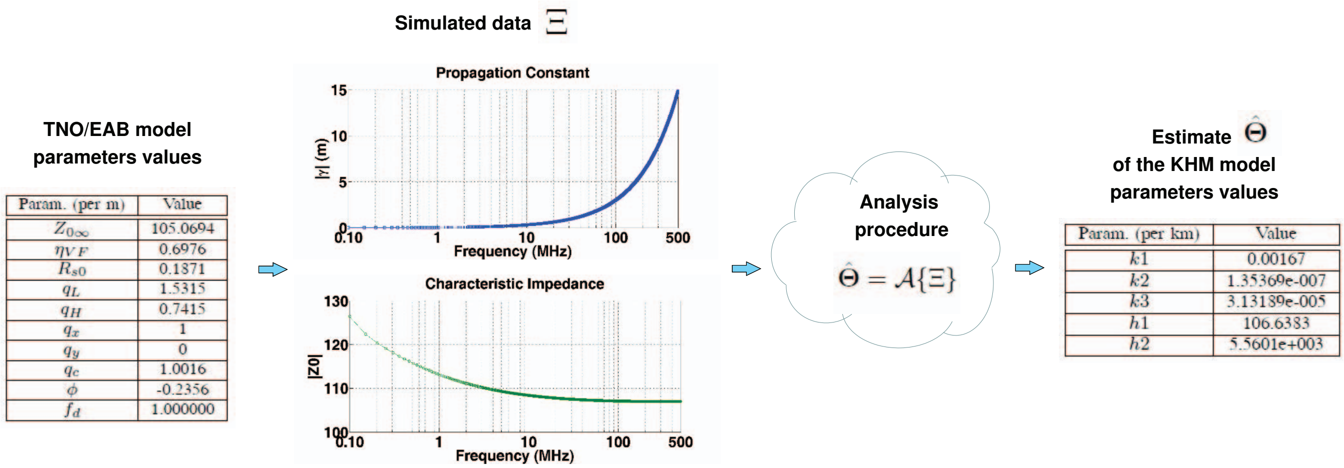

Fig. 3. Sequential steps composing the analysis procedure performed in this work. In this example, the cable type B05a (CAD55) was under test.

TABLE III
PARAMETER VALUES PROPOSED IN THIS WORK FOR MODELING THE CABLE TYPES: CAT5, B05A, T05B, T05H AND T05U.

Parameter (per km) / Cable type	CAT5	B05a	T05b	T05h	T05u
k_1	1.97311e-003	1.67334e-003	1.70454e-003	2.48426e-003	1.78466e-003
k_2	1.24206e-008	1.35369e-007	4.98183e-011	4.65719e-008	2.51367e-008
k_3	3.03005e-005	3.13189e-005	3.10070e-005	3.07543e-005	2.87051e-005
h_1	98.5944	106.6383	132.3825	100.3102	127.0785
h_2	6.0876e+003	5.5601e+003	6.9128e+003	6.9374e+003	6.9114e+003

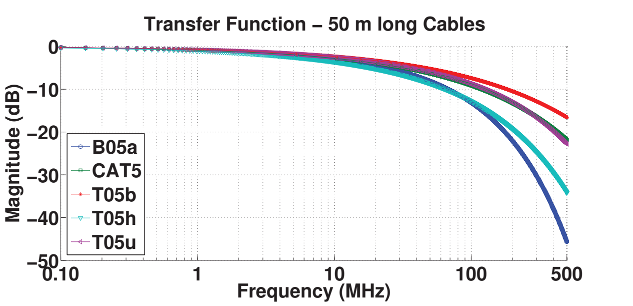

Fig. 4. Transfer functions for the cable types CAT5, B05a, T05b, T05h and T05u as modeled by the KHM model up to 500 MHz. The curves are for 50 m long cables.

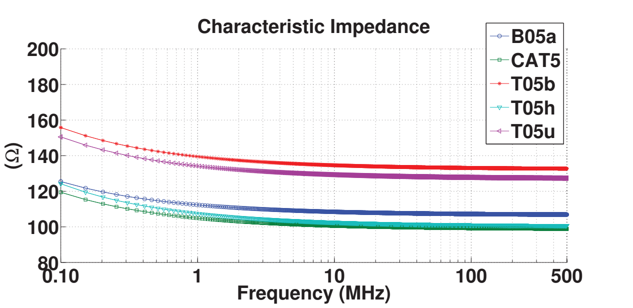

Fig. 5. Characteristic impedances for the cable types CAT5, B05u, T05b, T05h and T05u as modeled by the KHM model up to 500 MHz.

under test using the KHM model and the cable model currently adopted by the ITU.

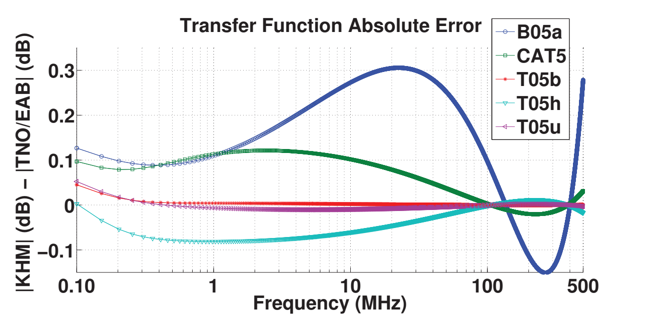

Fig. 6. Transfer functions absolute error.

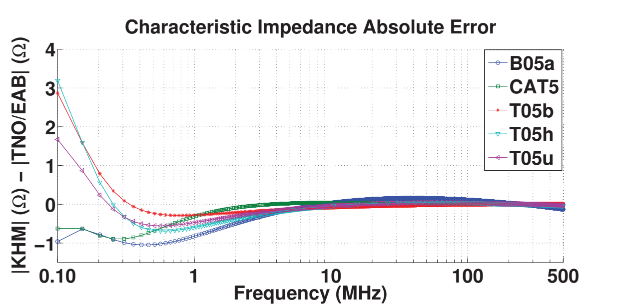

Fig. 7. Characteristic impedances absolute error.

In terms of the transfer function, it can be observed that except for the wire type B05a, the error is within ± 0.15 dB in all the frequency range (from 100 kHz up to 500 MHz). For the wire type B05a we observed a maximum error of up to 0.3 dB, which is reasonable for many applications. For example, equivalent channel capacity simulation results can be achieved using both models when the discrepancy is within this range, as discussed in [12]. An interesting alternative for reducing these errors even more is to adopt the synthesis equation of the KM2 model, presented in [11], for characterizing the propagation constant in the KHM model. This includes a new parameter $k4$, which can potentially improve the model accuracy. Regarding the characteristic impedance, it can be observed a maximum error of up to 3.5 Ω at 100 kHz for the wire type T05h. However, it is important to highlight that the start frequency standardized to be used in G.fast is 2.2 MHz [2]. In this case, the error is within $\pm$ 1 Ω for all cases, confirming the accuracy of the proposed modeling approach.

VII. Conclusion

This work presented a set of parameter values for modeling five types of copper lines adopted in the G.fast reference loops, by means of the KHM cable model. The results indicated that the KHM model can accurately characterize the electrical characteristics of such lines, leading to equivalent results with respect to the ones derived by the model standardized by the ITU, with the benefit of low computational cost and closed-form expressions for fitting the values of its parameters to measured or simulated data.

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