Simple Attenuation Models of Metallic Cables Suitable for G.fast Frequencies

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Abstract. *Recently, a new xDSL successor called G.fast, which can occupy frequencies up to 106 or 212 MHz, has been introduced in ITU-T G.9700 series of recommendations. Moreover, a new model of transmission characteristics suitable for various types of metallic cables has been designed and described as well. The model is based on 9 parameters specified for each type of metallic cable and can provide accurate estimations. However, its complexity together with the number of required parameters makes its practical application questionable, since the most important metallic cable characteristic, the attenuation, can be estimated using much simpler models. Therefore, two innovative attenuation models suitable for frequencies up to 250 MHz were designed and they will be introduced in this paper. The main motivation was to achieve an accurate approximation of attenuation character for various types of metallic cables, while maintaining low mathematical complexity and a number of necessary parameters. Both models were compared with attenuation characteristics measured for variety types of real metallic cables and also with other standard attenuation models. The results are included in this article as well.*

Keywords

Attenuation, G.fast, metallic cables, modelling.

1. Introduction

It is evident that the optical access networks, such as passive optical networks and various types of FTTx solutions, will sooner or later replace the existing metallic cable systems [1]. However, since the optical components are still quite expensive and mainly the installation of optical fibers represents heavy expenses, the deployment of optical fibers in access network segment is slow, especially in Europe [2]. That is why new potentials of existing metallic cables are being intensively discovered and the higher frequency bands of metallic lines are being more and more exploited [3]. Since the transmission performance of current xDSL generation, such as ADSL2+, VDSL and VDSL2, is usually not adequate to meet the requirements of various modern services and to satisfy the demand for high transmission rates [4], the ITU-T has recently introduced a modern access system called G.fast [5], [6] in ITU-T G.9700 series of recommendation.

The G.fast was designed for short local loops of existing metallic cables not exceeding 300 meters, since it exploits high frequencies up to 106 MHz (G.fast 106a version) or 212 MHz (G.fast 212a version) [5]. Due to that various combinations with FTTx are possible to cover as many potential end-users as possible with modern hybrid optical-metallic network solutions [7]. The G.fast contains several innovative concepts [5], such as a reverse power feeding, a time-division duplex transmission (TDD) and a vectoring process of transmitted discrete-multitone symbols (DMT). In order to provide accurate estimations of G.fast transmission performance and for the purpose of vectoring process, a new model of transmission characteristics of metallic cables suitable for high frequencies has been designed and described in the ITU-T G.9701 recommendation as well [8], [9]. This model is based on modelling of longitudinal impedance and shunt admittance and it includes various high-frequency effects, such as the skin effect, proximity effect, etc. However, this model, presented in Eq. (1), requires 9 specific parameters for each type of metallic cable and this, together with its complexity, makes its practical application difficult:

$$\begin{gathered} Z_S(j\omega) = j\omega \cdot L_{S\infty} + R_{S0} \cdot \\ \cdot \left(1 - q_S q_X + \sqrt{q_S^2 q_X^2 + 2\frac{j\omega}{\omega_S}\left(\frac{q_S^2 + \frac{j\omega}{\omega_S \cdot q_Y}}{\frac{q_S^2}{q_X} + \frac{j\omega}{\omega_S \cdot q_Y}}\right)} \right), \\ Y_P(j\omega) = j\omega \cdot C_{P0} \cdot (1 - q_C) \cdot \left(1 + \frac{j\omega}{\omega_D}\right)^{\frac{-2\phi}{\pi}} + \\ + j\omega \cdot C_{P0} \cdot q_C. \end{gathered} \tag{1}$$

In Eq. (1), Z_S represents the longitudinal impedance and Y_P the shunt admittance of a metallic line and $L_{S\infty}$, R_{S0}, q_S, q_X, ω_S, q_Y, C_{P0}, q_C, ω_D and ϕ are the parameters specific for a given line. On the other hand, the most important metallic line characteristic in practice as well as in theoretical estimations is usually the attenuation [10]. Due to that, various types of attenuation models have been already proposed, with miscellaneous complexity and accuracy for different frequency bands [11]. Nevertheless, these models were usually designed only for low- or mid-frequency range and their accuracy for G.fast frequencies needs to be verified.

That is why the main motivation of this paper is to propose completely new attenuation models, which are suitable for frequencies up to 250 MHz and can be therefore applied for G.fast simulations. Moreover, the purpose of these models is to achieve good accuracy over the entire frequency range for various types of metallic cables while maintaining low complexity and low number of necessary parameters. To verify this motivation, numerous measurements of attenuation of real metallic cables at high frequencies were performed and both models were compared with these measurements as well as with other standard models and the results are presented within the following sections.

2. Attenuation Models

The attenuation of a symmetrical twisted-pair or a quad is one of the secondary coefficients describing its transmission characteristics. Following [12], the propagation constant $\gamma(f)$ is a complex function of attenuation constant $\alpha(f)$ and phase constant $\beta(f)$ defined as:

$$\gamma(f) = \alpha(f) + j\beta(f). \tag{2}$$

The attenuation constant can be further calculated using primary line coefficients Eq. (3) [12], $R(f)$, $L(f)$, $C(f)$ and $G(f)$, and it depends on many factors, including the material of a conductor and its diameter, the material of an insulation and its dimensions, the proportions of pairs (quads), a twisting length, the (non)presence of a shielding, etc:

$$\begin{gathered} \gamma(f) = j\omega \cdot \sqrt{L(f)C(f)} \cdot \sqrt{1 + \frac{R(f)}{j\omega L(f)}} \cdot \\ \cdot \sqrt{1 + \frac{G(f)}{j\omega C(f)}}. \end{gathered} \tag{3}$$

In real applications, various imperfections, manufacturing tolerances as well as cable deformations can also negatively influence its resulting attenuation [13]. Generally, there are two basic approaches for modeling of the attenuation [14]. The first type of models is based on modeling the primary coefficients, while the attenuation constant is then calculated using standard equations for homogenous lines. The second approach uses direct attenuation constant modeling based on either analytical model or best approximation fitting functions. A short review of the most used models in practice is following.

2.1. Existing Attenuation Models

1) British Telecom Models (BT)

A group of British Telecom models (referred as BT [11], [12]) is based on modeling of the primary line coefficients, therefore they do not model the attenuation constant directly. Moreover, these models can be further modified by simplifying and neglecting some of the parameters, since the full version of BT model contains 13 parameters , there are also simplified versions with 11 or 7 parameters, which provide a lower accuracy but also a less complexity. The full BT model is given as Eq. (4):

$$\begin{gathered} R(f) = \frac{1}{\frac{1}{\sqrt[4]{r_{0C}^4 + a_C \cdot f^2}} + \frac{1}{\sqrt[4]{r_{0S}^4 + a_S \cdot f^2}}}, \\ L(f) = \frac{l_0 + l_\infty \cdot \left(\frac{f}{f_m}\right)^b}{1 + \left(\frac{f}{f_m}\right)^b}, \\ C(f) = c_\infty + c_0 \cdot f^{-c_e}, \\ G(f) = g_0 \cdot f^{g_e}. \end{gathered} \tag{4}$$

The 13-prameters version of BT model is adequately accurate for G.fast frequencies [15], the 7-parameters simplification for VDSL2 (up to 30 MHz) etc.

2) G.fast ITU-T G.9701 Model (KPN)

The model presented in G.fast recommendation G.9701 is based on modified KPN model, presented e.g. in [15]. The model was already described in Eq. (1) and it contains 9 parameters. This model was selected as a reference model for G.fast transmission characteristics, since G.9701 rec. [9] also contains line testing scenarios with model parameters specified for several types of metallic cables.

3) Simple Square Root Model

The simplest attenuation constant model is based on a square root of a frequency f and can be expressed as [11]:

$$\alpha(f) = k_1 \cdot \sqrt{f}, \tag{5}$$

where k_1 is a parameter specified for selected type of metallic cable. Although the model is based only on one parameter and simple square root of a frequency, it can provide a fast attenuation approximation especially for UTP cat. 5, 6 and 7 cables at higher frequencies [11], [12]. This is due to the fact, that for frequencies above 2 MHz for modern telecommunication cable using polyethylene or pvc insulation, the following conditions can be applied [16]:

$$\begin{gathered} R(f)\square\omega L(f); R(f)\infty\sqrt{f}, \\ G(f)\square\omega C(f); G(f)\infty\sqrt{f}. \end{gathered} \tag{6}$$

Therefore, implementing Eq. (6) into Eq. (3), the dependence of an attenuation constant follows the square root of a frequency with a slope given as constant k_1, which is presented in Eq. (5). However, such simplification is not very accurate for star-quad telecommunication type cables and cables with higher dielectric constant, as will be presented in the following section.

4) Chen's Model (aka KM1 Model)

To overcome the problems with low accuracy of simple square root model for telecommunication cables using quad internal configuration or with higher dielectric constant, Chen [11] proposed a modification by adding an additional term with another parameter k_2 for simulating linear frequency dependence of attenuation Eq. (7):

$$\alpha(f) = k_1 \cdot \sqrt{f} + k_2 \cdot f. \tag{7}$$

This model Eq. (7) became one of the most used metallic line attenuation models, since it usually provides sufficient accuracy over wide frequency band for various types of telecommunication cables. The accuracy of the model was also validated by mathematical derivation presented in [17], in which the causality of Chan's model was corrected and the resulting model is called KM1.

5) KM2 and KM3 Models

Further improvements of previous KM1 model led into introducing KM2 Eq. (8) and KM3 Eq. (9) models, which were presented in [16] and also in [17]. According to mathematical derivations of a fundamental Eq. (3) and by applying the Hilbert transform, the series expansion of the square root expressions in Eq. (3) can be further modeled by adding another term(s) with additional parameters k_3, k_4 in order to increase the accuracy of attenuation modeling:

$$\alpha(f) = k_1 \cdot \sqrt{f} + k_2 \cdot f + k_3, \tag{8}$$

$$\alpha(f) = k_1 \cdot \sqrt{f} + k_2 \cdot f + k_3 + k_4 \cdot \frac{1}{\sqrt{f}}. \tag{9}$$

However, additional parameters and terms negatively increase the complexity of the resulting models, while the increase of their accuracy is only limited. There are also extra modifications based on KM models and/or similar, which were designed especially for quad-constructed telecommunication cables and for pair-constructed cables [18], [19]. Although they can provide extra accuracy for each constructional category of metallic cables, a universal attenuation model suitable for both constructional types should be designed.

2.2. Low Complexity Inverse Hyperbolic Cotangent Models

In this section, two innovative attenuation models based on different approach will be introduced. Based on numerous experience obtained during measurements of various metallic cables and lines with different constructional parameters and types, the inverse hyperbolic cotangent function could potentially fit the typical attenuation character of most metallic lines especially for higher frequencies above 10 MHz. Due to that, its combination with the appropriate root frequency function could potentially result in accurate attenuation modeling. In order to maintain low number of necessary parameters and complexity of proposed models, the cotangent function was implemented and two new models, called Inverse Hyperbolic Cotangent Models – LM1 Eq. (10) and LM2 Eq. (11), are expressed as:

$$\alpha(f) = \frac{1}{2 \cdot \operatorname{arccotgh}(f^{0.1})} + k_1 \cdot f^{0.61}, \tag{10}$$

$$\alpha(f) = \frac{k_2 \cdot f}{\operatorname{arccotgh}(f^{4 \cdot \sqrt{k_1}})} + k_1 \cdot \sqrt{f}. \tag{11}$$

The LM1 Eq. (10) model is based only on one parameter, k_1, while LM2 model uses two parameters, k_1 and k_2. Although the cotangent function is used, the complexity of both models is very low and the number of required parameters is also low, equal to the number of parameters used in simple square root model

Eq. (5) and Chen's (KM1) model Eq. (7). The verification of presented models through comparisons with various measured characteristics as well as other models is presented in the following section.

3. Experimental Results and Comparisons

First, the k-parameters for all models presented in previous Section 2 need to be calculated for each type of metallic cable. This can be simply performed by using least-squares fitting method, which can be implemented in Matlab environment by using Nelder-Mead algorithm [13]. Therefore, each k-parameter is found through finding a minimum of its partial derivatives with respect to each parameter to be zero [17].

Next, in order to compare the accuracy of attenuation modeling, the squared error between the attenuation constant, approximated by using each model, and real attenuation constant measured for a specific metallic cable should be calculated. The frequency character of this squared error $E(f)$ is simply given as Eq. (12) [17]:

$$\begin{aligned} E(f) &= (\alpha_M(f) - \alpha(f))^2, \\ E_S &= \textstyle\sum_f E(f), \end{aligned} \tag{12}$$

where $\alpha(f)$ represents a measured attenuation constant for a real metallic cable, $\alpha_M(f)$ is an attenuation constant obtained by a model and summary squared error, E_S, is then calculated as a sum of squared errors for all frequency points (frequency range), used in measurement and simulation.

In order to cover as many different types of metallic cables as possible, the following samples of metallic cables were measured with their lengths: UTP cat. 5 (50 meters), UTP cat. 6 (50 meters), STP cat. 7 (97 meters), SYKFY 4×2×0.5 (25 meters) – a typical cable for indoor and last network segments installations, SXKFY 4×2×0.5 (47 meters) – similar to SYKFY cable with different insulation material and shielding, TCEPKPFLE 75×4×0.4 (100 meters) – a typical buried distribution cable with quad-star construction, PE insulation and gel filling, TCEKFLES 3×4×0.6 (251 meters) – a burial cable with star-quad construction often used in access networks for VDSL2 frequencies. All measurements were performed by using calibrated Rohde&Schwarz vector network analyzer together with NorthHills baluns in a frequency range between 2 MHz and 250 MHz for UTP cat. 5, 6 and STP cat. 7, between 2 MHz and 150 MHz for SXKFY, SYKFY and TCEPKPFLE cables and finally, TCEKFLES cable was measured in a frequency band from 0.1 MHz to 30 MHz in order to compare all models also in VDSL2 frequencies.

To illustrate the potential of presented models and to provide adequate comparison, the following models were selected – simple square root model Eq. (5), Chen's model (KM1) Eq. (7), KM3 model Eq. (9), LM1 model Eq. (10) and LM2 model Eq. (11). The k-parameters for each model were calculated individually for each metallic cable as well as the frequency characteristic of a squared error $E(f)$ and its summary value E_S.

3.1. Results of Modeling

The first results were obtained for structured cabling systems, therefore Fig. 1 contains measured attenuation constants for UTP cat. 5, while the squared error between each model and real measured characteristic is illustrated in Fig. 2 with a summary squared error in Tab. 1. The same graphs were also prepared for UTP cat. 6 (Fig. 3 and Fig. 4, Tab. 2) and STP cat. 7 (Fig. 5 and Fig. 6, Tab. 3).

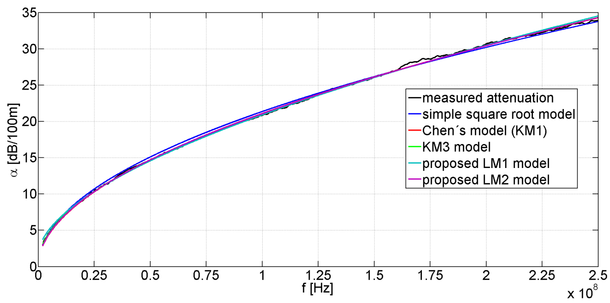

Fig. 1: Measured and modeled attenuation constants for UTP cat. 5.

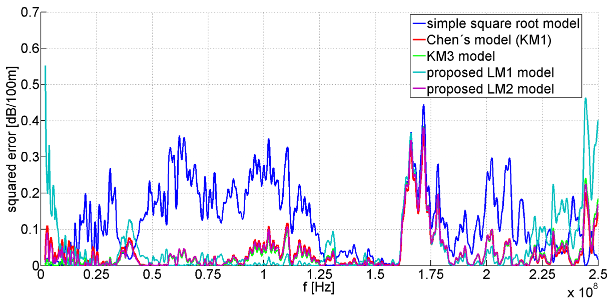

Fig. 2: Squared error characteristic for each model for UTP cat. 5.

Obviously, the proposed LM1 model with one single parameter is more accurate for UTP cat. 5 and 6 cables than simple square root model. The only situation, in which the attenuation constant estimated by LM1 model is worse, is for STP cat. 7 cable. The accuracy of LM2 model, which uses two parameters, is approximately the same as the accuracy of Chen's (KM1) model, since there are only minor differences between summary squared errors, as can be concluded by comparing results in Tab. 1, Tab. 2 and

Tab. 1: Summary squared error for each model for UTP cat. 5 cable.

Model	Square root	Chen's (KM1)	KM3	LM1	LM2
Summary squared error, E_S [dB/100m]	199.355	59.155	56.008	96.780	58.922

Tab. 2: Summary squared error for each model for UTP cat. 6 cable.

Model	Square root	Chen's (KM1)	KM3	LM1	LM2
Summary squared error, E_S [dB/100m]	865.666	49.637	47.791	264.827	50.073

Tab. 3: Summary squared error for each model for STP cat. 7 cable.

Model	Square root	Chen's (KM1)	KM3	LM1	LM2
Summary squared error, E_S [dB/100m]	11.929	10.885	10.021	81.822	10.625

Tab. 4: Summary squared errors for SXKFY cable.

Model	Square root	Chen's (KM1)	KM3	LM1	LM2
Summary squared error, E_S [dB/100m]	11.929	10.885	10.021	81.822	10.625

Tab. 5: Summary squared errors for SYKFY cable.

Model	Square root	Chen's (KM1)	KM3	LM1	LM2
Summary squared error, E_S [dB/100m]	11.929	10.885	10.021	81.822	10.625

Tab. 6: Summary squared errors for TCEPKPFLE cable.

Model	Square root	Chen's (KM1)	KM3	LM1	LM2
Summary squared error, E_S [dB/100m]	199.355	59.155	56.008	96.780	58.922

Tab. 7: Summary squared error for each model for TCEKFLES cable.

Model	Square root	Chen's (KM1)	KM3	LM1	LM2
Summary squared error, E_S [dB/100m]	199.355	59.155	56.008	96.780	58.922

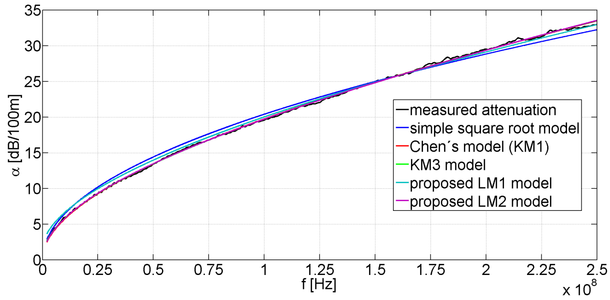

Fig. 3: Measured and modeled attenuation constants for UTP cat. 6.

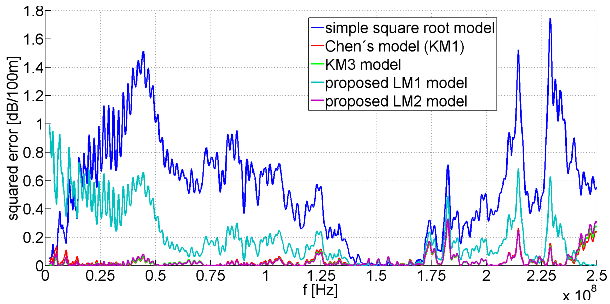

Fig. 4: Squared error characteristic for each model for UTP cat. 6.

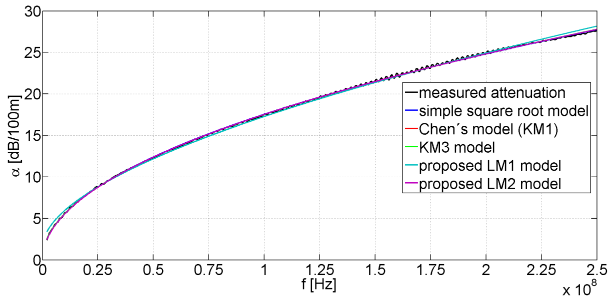

Fig. 5: Measured and modeled attenuation constants for STP cat. 7.

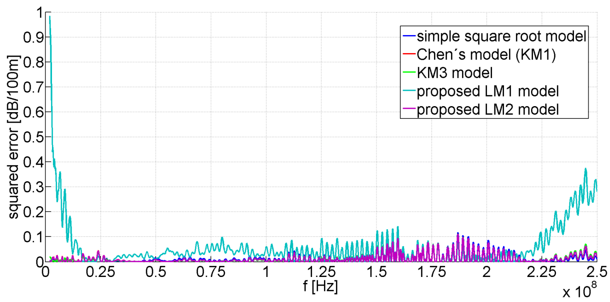

Fig. 6: Squared error characteristic for each model for STP cat. 7.

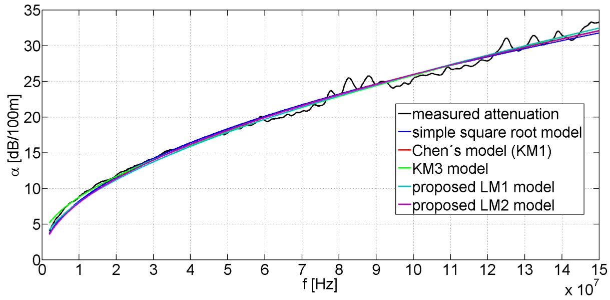

Fig. 7: Results of attenuation constant for SXKFY cable.

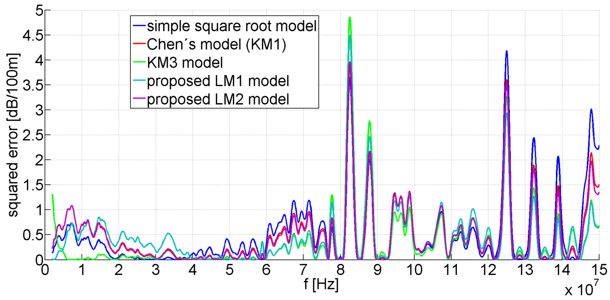

Fig. 8: SXKFY cable squared error characteristics.

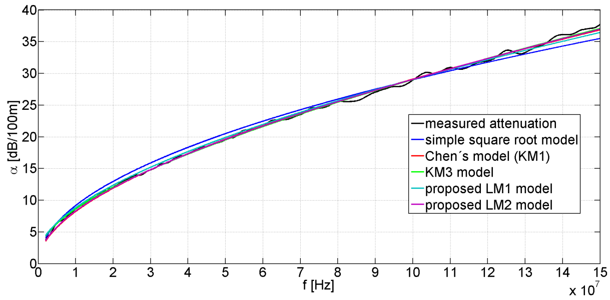

Fig. 9: Results of attenuation constant for SYKFY cable.

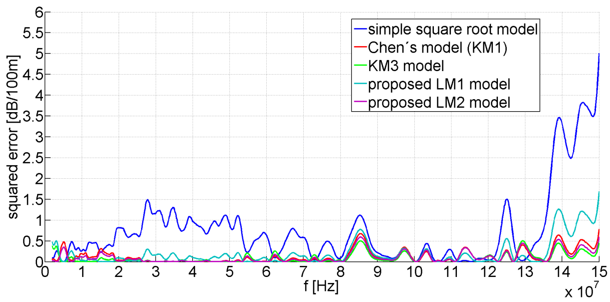

Fig. 10: SYKFY cable squared error characteristics.

Tab. 3. The most accurate attenuation approximation is provided by KM3 model, however, it uses four k-parameters, moreover, the improvement is not that significant. Next, the same comparisons of all models are presented for SXKFY (Fig. 7 and Fig. 8, Tab. 4), SYKFY (Fig. 9 and Fig. 10, Tab. 5), TCEPKPFLE (Fig. 11 and Fig. 12, Tab. 6) and TCEKFLES (Fig. 13 and Fig. 14, Tab. 7) telecommunication cables.

As can be concluded from previous Fig. 7, Fig. 8, Fig. 9, Fig. 10 and results in Tab. 4 and Tab. 5, the LM1 model is more accurate than simple square root model, while both uses only one parameter. The similar conclusions can be provided for LM2 model, which is again more accurate than Chen's (KM1) model with the same number of necessary parameters. The results for the last two cables are presented within Fig. 11 and Fig. 12 and Tab. 6 for TCEPKPFLE cable and in Fig. 13 and Fig. 14 and Tab. 7 for TCEKFLES telecommunication cable.

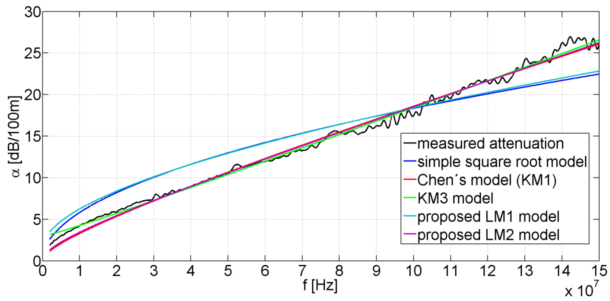

Fig. 11: Results of attenuation constant for TCEPKPFLE cable.

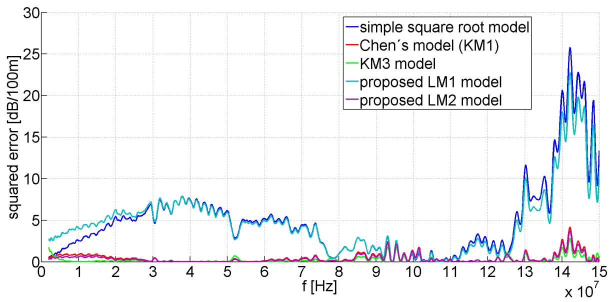

Fig. 12: TCEPKPFLE cable squared error characteristics.

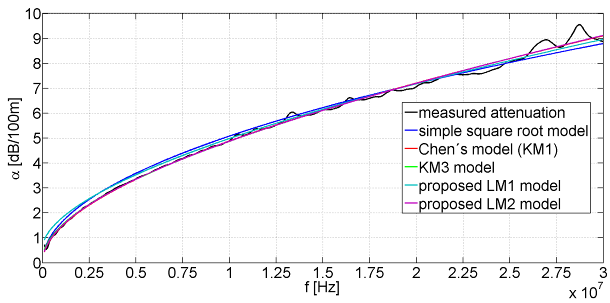

Fig. 13: Attenuation constants for TCEKFLES cable.

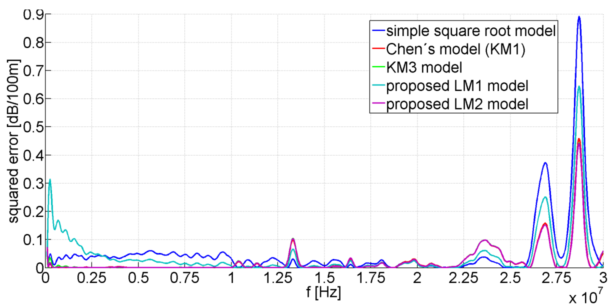

Fig. 14: Squared error characteristic for TCEKFLES cable.

It is evident that simple square root model Eq. (5) is not very suitable for quad-star telecommunication cables, since its accuracy, especially for TCEPKPFLE cable is very limited. Nevertheless, the similar (in)accuracy for TCEPKPFLE cable is provided by presented LM1 model as well, therefore none from these simplest single k-parameter models can be recommended for modeling attenuation of 0.4 quad-star telecommunication cables with foamed PE insulation. On the other hand, the proposed LM2 model provides more accurate attenuation estimation for both TCEPKPFLE and TCEKFLES cables compared to Chen's (KM1) model, moreover in case of TCEKFLES cable the LM2 model is even more accurate than KM3 model even with half number of required k-parameters.

Generally, both LM1 and LM2 models proved their suitability and accuracy for different types of metallic cables over wide frequency range. The LM1 model always provided more accurate attenuation approximation than the square root model (except for STP cat. 7 cable), while both models are based on only one k-parameter. The accuracy of LM2 model for structured cabling (UTP cat. 5, 6 and STP cat. 7) is nearly the same as the Chen's (KM1) model, however, the LM2 is more accurate for typical indoor telecommunication cables (SXKFY and SYKFY) and is significantly more accurate for buried quad-star telecommunication cables (TCEPKPFLE and TCEKFLES) used in comparisons. Since both models use again the same number of necessary k-parameters (two), a general conclusion is that the proposed LM2 model is more suitable and accurate than Chen's (KM1) model for G.fast frequencies and variety types of metallic cables and lines.

4. Conclusion

This article presented two innovative attenuation models, which are suitable for G.fast frequencies up to 250 MHz. Both models are based on inverse hyperbolic cotangent function and low numbers of used k-parameters. The accuracy of proposed LM1 and LM2 models was further examined and compared with other typical attenuation models used for telecommunication systems (simple square root model, Chen's (KM1) model and KM3 model) together with variety types of telecommunication cables in typical G.fast frequencies (up to 250, 150 and 30 MHz).

The main advantage of both proposed models, LM1 and LM2, is a very low number of necessary k-parameters and both models also proved to be more accurate than typical attenuation models with the same number of k-parameters. The LM1 model is more accurate than simple square root attenuation approximation and its accuracy is good for structured cabling systems and sufficient for attenuation estimations of most types of star-quad telecommunication cables for G.fast frequencies. The LM2 model provides approximately the same results for structured cabling as the Chen's

(KM1) model, however, the LM2 is more suitable for variety types of quad-star telecommunication cables, since it provides their better attenuation approximation in given G.fast frequencies. Further improvements and modifications of presented LM1 and LM2 models are possible to improve their accuracy or versatility for different types of metallic cables and lines.

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