



## **Transmission Parameters of Metallic Cables under Extreme Temperatures**

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**Abstract:** *This paper deals with the measurement and modeling of transmission parameters of metallic cables under extreme temperatures. Metallic cables are often used in hazardous environments and for many critical applications, in which the fire events can occur, e.g. as signaling cables for temperature and fire sensors etc. These cables usually have special fire resistant and retardant coatings and shielding to be able to resist longer during extreme temperatures (fire) compared to the standard cables with polymer (PE, PVC) coatings. However, the transmission characteristics of metallic cables, such as the attenuation and crosstalk, are significantly dependent on the surrounding temperature as well. There are already several models and simulations to describe the temperature influence on transmission characteristics of standard metallic cables, however, these models are usually valid only for a limited temperature range. That is why measurements of a fire retardant metallic cable in special laboratory with certification for fire tests were performed and are presented within this article. These results were subsequently used to estimate models and simulations of typical fire events and their influence on transmission characteristics of metallic cables.*

**Keywords:** *attenuation; FEXT; extreme temperatures; fire retardant metallic cables; modeling*

### **I. Introduction**

Today, the metallic cables are still frequently used in many applications as a cheap and reliable transmission medium [1]. There are also several specific situations, which require metallic cables with nonstandard anti-fire enhancements, such as fire resistant shielding, inner isolation with flame retardant function etc. These special cables are usually used for specific applications in hazardous and critical environments, such as in mining industry, nuclear power plants, underground subways, modern airplanes etc. These cables often connect temperature or fire sensors and other similar detectors or signaling devices, therefore they are frequently exposed to extreme conditions and temperatures usually during the fire events. However, these cables are also often used in underground public transportation (or in underground mines) for high-speed signaling devices and communication systems, so they must meet necessary transmission criteria, such as the attenuation, crosstalk characteristics, etc. There are already several models describing the temperature influence on the attenuation of metallic cables, but these models are usually valid only for a limited range of typical temperatures (usually only up to 100°C) [2]. However, during the fire event, the temperature inside the cable can easily reach 1000°C and more. Moreover, the crosstalk characteristics are also significantly influenced by the temperature of a cable or of the surrounding environment. That is why it is necessary to investigate these conditions and to derive mathematical models and description of fire events and their influence on transmission characteristics of metallic cables in a wide range of temperatures.

The first section of this article describes the measurements performed in special certified laboratory for fire tests with flame retardant metallic cable. First, it was necessary to develop the method for modeling for the fire experiment itself and the relation between the temperatures outside and inside the cable. The resulting model is based on the first-order system with specific delay necessary for simulating the heat propagation delay inside the cable. The second part of the paper contains the measured results of the attenuation and far-end crosstalk (FEXT) attenuation during the fire event. These results were also compared with proper models and several examples are included in this paper as well.

### **II. Fire Experiment and Its Modeling**

The fire experiment took place in specialized and certified laboratory FIRES s. r. o. in Slovak Republic. This workplace is able to perform fire tests of various products under internationally certified fire conditions. The main part of the laboratory consists of a large furnace and several gas burners, which work as a heating system. The temperature in a furnace during the whole test is fully controlled and it should simulate the real conditions of a fire. The measurements were performed with a sample of a star-quad type metallic cable with specification 3x4x0.8 mm with several anti-fire enhancements. This cable has special halogen-free self-extinguishable shielding with improved resistance against fire as well as the inner isolation based on the new type of halogen-

free polymers with flame retardant function. The entire cable was 35 meters long, while 4 sections of a cable with the summary length of 15.8 meters were placed inside the furnace. The main parameters measured during the fire test were resistance  $R_0$  [ $\Omega$ ], attenuation  $A$  [dB] and attenuation of FEXT crosstalk  $A_{FEXT}$  [dB]. The results were measured using Rohde&Schwarz vector network analyzer in a frequency band from 100 kHz to 100 MHz. Because the analyzer has only one pair of input/output gates, it was necessary to use four-port cross-connection high frequency Agilent switch. This switch contained proper impedance terminations of all unused pairs of a cable. The resistance was measured by calibrated ohmmeter connected to another metallic pair of a cable. The furnace also contained 6 calibrated heat sensors, therefore the accurate values of temperature inside the furnace were available during the whole fire test.

#### A. Modeling of the Temperature during Fire Experiment

The parameters of certified fire tests are specified in proper recommendations and they should simulate real fire situations. The whole fire experiment took approximately 95 minutes and the maximum temperature during that was nearly 1050°C. The temperature was continuously measured during the whole test each minute as well as the parameters of the cable – resistance  $R_0$  [ $\Omega$ ], attenuations of two pairs  $A_1$  [dB],  $A_2$  [dB] and FEXT attenuation between them,  $A_{FEXT}$  in dB.

First, it was necessary to decide the temperature inside the furnace and its relation with the internal temperature of a cable and to propose proper models of both characteristics. The temperature inside the furnace was measured with 6 sensors, while the analysis of internal temperature inside the cable can be based on the measurement of resistance. It is possible to derive the internal temperature inside the cable according to the model of the temperature influence on  $R_0$  resistance in a simplified formula [3], [4]:

$$R_0(T) = R_{20^\circ C} \cdot [1 + \sigma \cdot (T - 20)] \quad [\Omega; \Omega, ^\circ C] \quad (1)$$

where  $R_0(T)$  represents the resistance of a symmetrical pair inside the cable in case of temperature  $T$  in  $^\circ C$ ,  $R_{20^\circ C}$  is the resistance for reference temperature 20°C and  $\sigma$  is a temperature factor, in case of Cu wire  $\sigma = 0.004$ . Thanks to the application of model (1) and measured results of resistance during the fire experiment, it was possible to derive real internal temperature inside the cable. However, the model was applied only for the heated section, while the temperature as well as the resistance of the rest part of cable remained the same.

The character of a temperature in a furnace can be modeled by the first-order system [4] in combination with linear temperature growth due to the heat emitted through porous cladding of the furnace. The internal temperature in the cable follows the temperature inside the furnace with a delay given probably by the thermal gradient in both environments and also by the fact that the fire-retarding shielding of a cable is able to resist certain temperatures. However, after this shielding is destroyed by fire, the internal temperature inside the cable is rising faster and in the end of the fire experiment, its value is almost the same as the temperature inside the furnace. This delay could be therefore added to the first-order system model. The resulting model of internal temperature inside the cable can be proposed as:

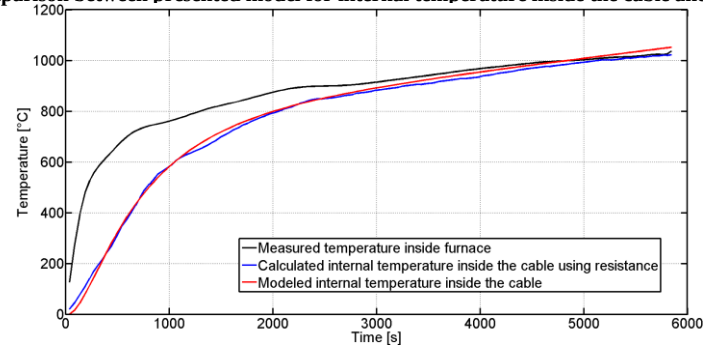
$$T(t) = \left[ k_{T1} \cdot \left( 1 - e^{-\frac{t}{k_{T2}}} \right) + k_{T3} \cdot t + T_0 \right] \cdot \left( 1 - e^{-k_{T4} \cdot t} \right) \quad (2)$$

where  $T(t)$  is the internal temperature inside the cable,  $t$  is a time and  $k_{T1}$ ,  $k_{T2}$ ,  $k_{T3}$  and  $k_{T4}$  are parameters, which were calculated using adequate approximation of measured results and their values are presented in the Tab. 1.

Table I Values of parameters used in proposed model (2).

| Parameter | $k_{T1}$ | $k_{T2}$ | $k_{T3}$ | $k_{T4}$              |
|-----------|----------|----------|----------|-----------------------|
| Value     | 629.4473 | 245.2886 | 0.0509   | $1.375 \cdot 10^{-3}$ |

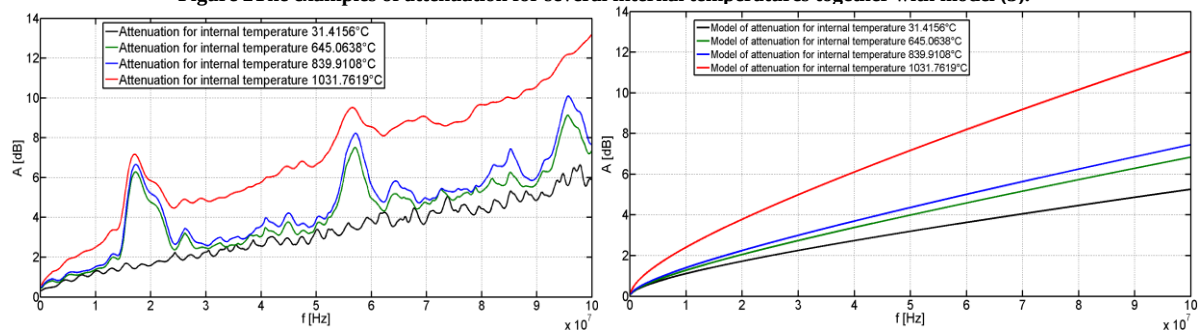
The next Fig. 1 compares the accuracy of previously presented model (2), where the black line represents measured temperature inside the furnace, blue line internal temperature inside the cable and the red line illustrates the model (2) with parameters from Tab. 1.

**Figure 1** The comparison between presented model for internal temperature inside the cable and measured results.

It is evident, that proposed model (2) provides sufficient accuracy and thanks to that can be used for following calculations and modeling of transmission parameters of the cable.

### III. Measured Results and Model of Attenuation

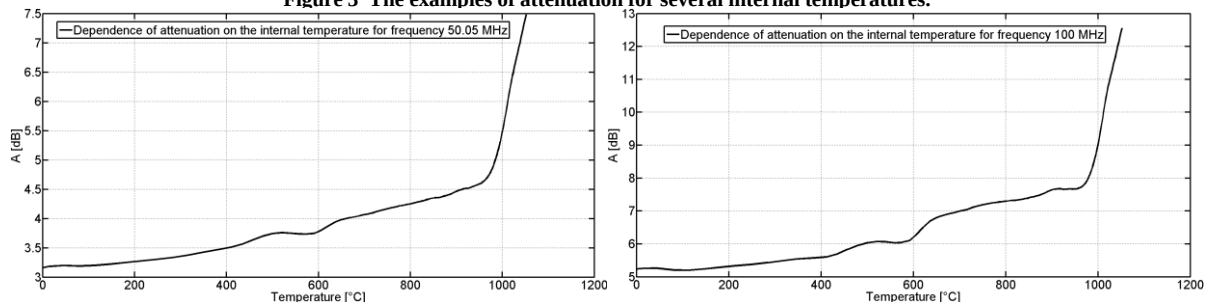
Thanks to the previously derived model of internal temperature inside the cable, it was possible to determine the dependence of attenuation on real internal temperature. The next graph in Fig. 2 presents several examples of attenuation measured for various temperatures.

**Figure 2** The examples of attenuation for several internal temperatures together with model (3).

Due to the fact that only a part of the cable was placed inside the furnace and was heated, while the rest one was outside and not heated, inhomogeneous environment occurred at the boundaries of heated/unheated parts. These inhomogeneities as well as bending of the cable caused reflections and disturbances, which are evident in the previous graph in Fig. 2 at constant frequency bands approx. 17, 57 and 95.5 MHz. These reflections started to occur during the growth of internal temperature until the melting point of copper wires, which is approx. 1080°C. It is obvious that measured results are heavily influenced by inappropriate placing of the cable inside the furnace; therefore it was necessary to apply fitting approximation together with the standard model for attenuation, which is according to [5] defined as:

$$A(f) = (k_1 \cdot \sqrt{f} + k_2 \cdot \sqrt[3]{f} + k_3 \cdot f^2) \cdot l \quad [\text{dB}; \text{Hz}, \text{km}] \quad (3)$$

where  $A(f)$  stands for the attenuation,  $f$  is a frequency,  $l$  represents the length of a cable and  $k_1, k_2, k_3$  are the parameters of the model. These parameters were calculated using appropriate approximation for measured results. An example of results obtained using model (3) for eliminating the excessive peaks from measured results is presented in the second graph in previous Fig. 2. Another important characteristic is the relation between the attenuation and temperature at constant frequency. For the purpose of detailed analysis, examples for frequencies approx. 50 and 100 MHz were prepared and are presented in the following Fig. 3.

**Figure 3** The examples of attenuation for several internal temperatures.

The first part, from the beginning of fire experiment to the temperature approx. 950-960°C in both presented graphs, has almost linear character. However, it is evident that after then there is significant (probably exponential) growth of attenuation around the temperature of 950°C. The temperature of copper melting point is approx. 1084°C, while this significant growth can be observed much earlier. Still, it is possible to assume that since the copper wires are close to their melting points, their conductivity significantly decreases. Besides, there are also probably serious changes in internal structure of the cable and various deformations and problems with geometrical arrangement of pairs can occur, which can further remove the wires from their original positions in star-quads and due to that their attenuation increases. The linear part of attenuation in the temperature range from the beginning of the test to the temperature approx. 950°C could be estimated using modified model for cabling systems [1], which was adapted and proposed for temperature range up to 950°C as:

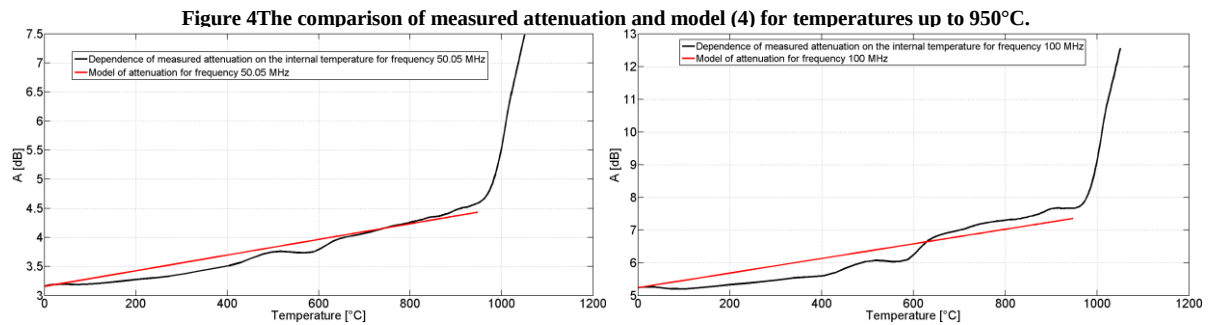
$$A(T) = A_{20^{\circ}\text{C}} \cdot \left[ 1 + l_{20^{\circ}\text{C}} \cdot k_A \cdot (T - 20) \right] \left[ \text{dB;dB,100m}, \frac{1}{100\text{m} \cdot ^{\circ}\text{C}}, ^{\circ}\text{C} \right] \quad (4)$$

where  $A(T)$  is the attenuation calculated for internal temperature inside the cable  $T$  in °C,  $A_{20^{\circ}\text{C}}$  is the reference attenuation for 20°C,  $l_{20^{\circ}\text{C}}$  is a length of a cable for reference temperature of 20°C and reference length of 100 meters,  $k_A$  is a parameter of the model and  $T$  is the internal temperature inside a cable in °C. The reference length  $l_{20^{\circ}\text{C}}$  is necessary, because the copper wires inside the cable expand due to their expandability during the fire event. The model (4) was applied on measured results, however, only for the part of the cable, which was heated in the furnace and in the temperature range up to 950°C. The parameter  $k_A$  was calculated by using proper approximation of measured results and its value for the entire cable is presented in following Tab. 2.

Table II The value of  $k_A$  parameter used in model (4).

| Parameter | $k_A$  |
|-----------|--------|
| Value     | 0.2696 |

The model (4) was applied on characteristics in Fig. 3 for 50 and 100 MHz and the resulting comparison is illustrated in Fig. 4, where the black line represents the measured result, while model (4) is presented as a red line. The results in Fig. 4 clearly illustrate that the accuracy of model (4) is sufficient for simulating the dependence of attenuation on temperature for temperatures up to 950°C.



#### IV. Modeling of Far-End Crosstalk

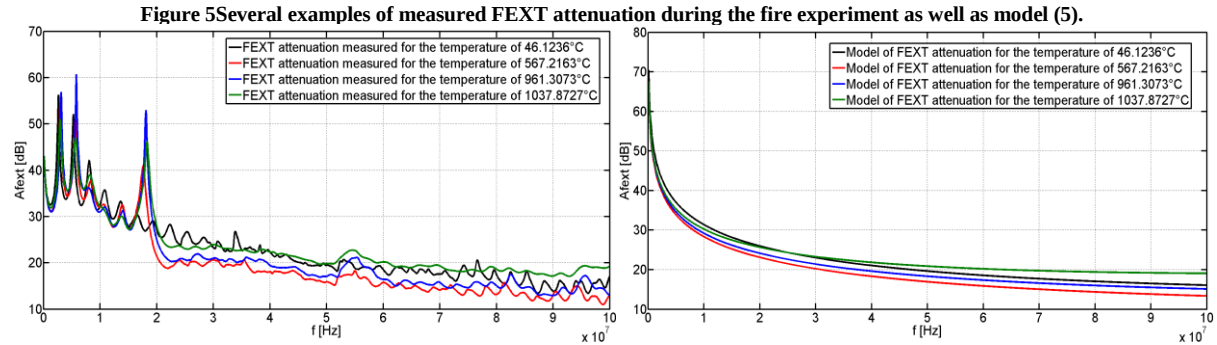
Far-end crosstalk (FEXT) was measured thanks to the Agilent four-port cross-connection high frequency switch between two pairs from the tested cable [8]. It is possible to assume, that the relation between FEXT crosstalk and temperature is given by the dependence of attenuation on temperature, by potential deformations inside the cable of symmetrical pairs and star-quads and also by the changes of the parameters of used isolation, mainly its relative permittivity  $\epsilon_r$ . Several FEXT examples measured during different temperatures are presented in Fig. 5.

The standard model for FEXT crosstalk attenuation between twisted pairs or quads in a cable comes from the derivation of capacitive and inductive unbalances between them and it can be expressed according to [2] by elementary formula as:

$$A_{\text{FEXT}}(f) = k_{\text{FEXT}} + \alpha(f) \cdot l - 20 \log f - 10 \log l \left[ \text{dB;dB,dB/km,km,MHz,km} \right] \quad (5)$$

where  $A_{\text{FEXT}}(f)$  is FEXT attenuation in dB,  $k_{\text{FEXT}}$  is a crosstalk parameter (a constant for the given combination of pairs),  $\alpha(f)$  represents the attenuation factor,  $l$  is a length and  $f$  is a frequency. The  $k_{\text{FEXT}}$  parameter represents the summary capacitive and inductive unbalances between selected pairs and its value is generally unique for all combinations of pairs inside the cable [7]. This parameter was calculated individually for all FEXT examples in

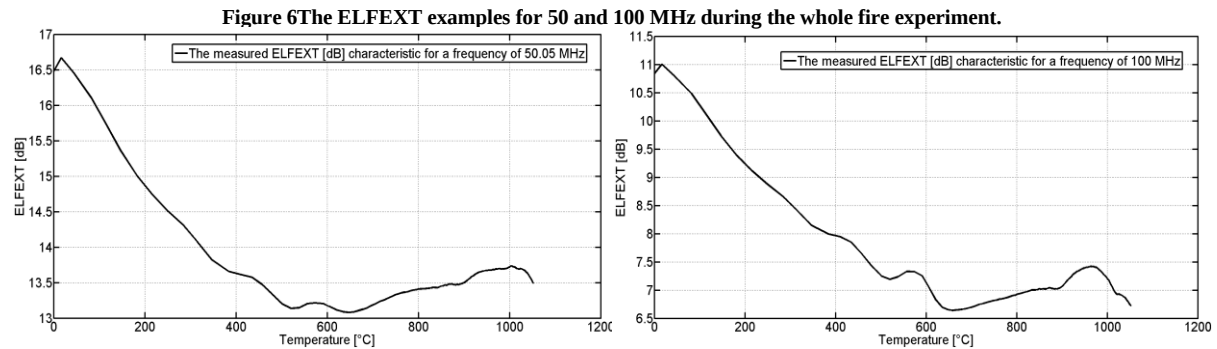
Fig. 5 and resulting FEXT models are presented in the second graph. The previous models (2) and (4) were used for modeling the attenuation and internal temperature.



It is evident, that like in the previous measurements of attenuation, narrow frequency peaks, especially in low frequency band, occur during almost whole temperature range. These peaks are again caused by inhomogeneous environment due to the fact, that only a part of the cable was inside the furnace and was heated, and also by the bending of a cable inside the furnace. It is obvious, that the FEXT attenuation decreases with increasing the internal temperature inside the cable until a specific temperature, and after that the FEXT attenuation starts to grow again and its value for temperatures above 1000°C is even greater compared with the beginning of the fire experiment. This secondary growth is caused mainly by the dependence of attenuation on internal temperature and its faster increasing for higher temperatures. Therefore, it is better to calculate the ELFEXT (Equal Level FEXT) [3] characteristic, which represents the FEXT attenuation minus the attenuation, instead the FEXT. According to [6], the ELFEXT and its model can be expressed as:

$$ELFEXT(f) = A_{FEXT}(f) - A(f) [dB; dB, dB]; ELFEXT(f) = k_{FEXT} - 20 \log f - 10 \log l \quad (6)$$

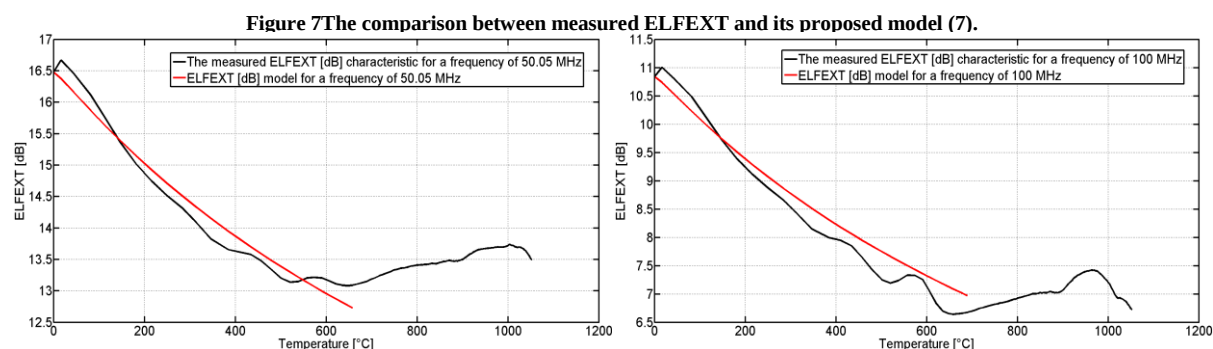
Thanks to the ELFEXT, the attenuation and its influence can be eliminated, so the resulting relation between far-end crosstalk and temperature can be observed better. The following Fig. 6 illustrates two examples of the relation between ELFEXT and internal temperature inside the cable for a constant frequency of 50 and 100 MHz.



The ELFEXT decreases almost linearly with the temperature until the temperature inside the cable reaches approx. 650°C. After that the ELFEXT slowly increases again, but this trend tends to be random. It is possible to conclude, that the external fire retardant shielding of the cable is able to resist up to the temperature of 600-650°C, because after that, the character of internal temperature quickly follows the temperature inside the furnace. Due to that, the symmetrical pairs and star-quads can expand and deform only within the cable shielding until the temperature reaches 650°C. Therefore, this first part is characterized by linear decreasing of ELFEXT, because the internal deformations of star-quads lead into increasing the capacitive and inductive unbalances between them, because the star-quads are still hold together inside the cable and these deformations greatly increase the resulting unbalances. However, after this temperature, when the external shielding of the cable is destroyed, the pairs and star-quads are released out of the cable itself and can further move and unfold almost randomly. In this part of previous graphs from Fig. 6, the ELFEXT can slightly increase, because the star-quads are no longer held and deformed together, which can result into small corrections of previous unbalances. However, since this secondary process has almost random character, the following model of ELFEXT was proposed only for the first part of the characteristics and is valid for temperatures up to 650°C. The derived model can be expressed as:

$$ELFEXT(T) = -10 \log \left( 10^{-0.1 ELFEXT_{20^\circ C}} \cdot [1 + l_{20^\circ C} \cdot k_E \cdot (T - 20)] \right) [dB; dB, 100m, \frac{1}{100m^\circ C}, ^\circ C] \quad (7)$$

where  $ELFEXT(T)$  represents the ELFEXT for a temperature  $T$  in  $^{\circ}\text{C}$ ,  $ELFEXT_{20^{\circ}\text{C}}$  stands for a reference value of ELFEXT for temperature of  $20^{\circ}\text{C}$ ,  $l_{20^{\circ}\text{C}}$  is a length of a cable for reference temperature of  $20^{\circ}\text{C}$  and reference length of 100 meters,  $k_E$  is a parameter of the model and  $T$  is the internal temperature inside a cable in  $^{\circ}\text{C}$ . The comparison between measured ELFEXT characteristic for 50 and 100 MHz and estimated model (7) is presented in following Fig. 7.



Tab. 3 contains the value of  $k_E$  parameter for all pairs in a cable and frequency range from 100 kHz to 100 MHz.

**Table III The value of  $k_E$  parameter used in model (7).**

| Parameter | $k_E$  |
|-----------|--------|
| Value     | 0.0021 |

## V. Conclusions

This paper presented measurements and modeling of transmission parameters of metallic cable during certified fire test. This cable was exposed to extremely high temperatures of approx.  $1050^{\circ}\text{C}$  during the experiment that took nearly 95 minutes. Several important transmission parameters were measured, especially resistance, attenuation and FEXT attenuation during the fire test. First, the model for the description of the temperature in the furnace itself and its relation with the internal temperature inside the cable was necessary to develop. The resulting model is based on the first-order system with specific delay in combination with linear character. This model was subsequently used to calculate the attenuation of pairs and FEXT crosstalk between them and several conclusions were deduced. Next, the results of attenuation were analyzed and method for its modeling was proposed. As it was expected, the attenuation of pairs is rising together with the temperature, but this almost linear character suddenly growth steeply at the temperature of approx.  $950^{\circ}\text{C}$ . It is possible to assume that the conductivity of copper pairs significantly decreases as their temperatures were close to the melting points. A similar analysis was performed also in case of measured results of FEXT crosstalk and the model for its estimation was derived and presented. All deduced conclusions as well as the proposed models and simulations needs to be verified for different types of metallic cables and conditions by performing more tests again, however, these fire experiments are very expensive.

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## Acknowledgments

This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS 10/275/OHK3/3T/13, and also by the grant No. VG20102015053 – GUARDSENSE. Special thanks go to the company PRAKAB c.o. for providing samples of cable and enabling the performed measurements during extreme temperature conditions.