Analysis of Channel Transfer Functions in Power Line Communication System for Smart Metering and Home Area Network

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***Abstract*—The paper deals with simulations of power line channel transfer functions in Network Simulator version 3. Firstly, an empirical model and calculation of the channel transfer function are given to reflect the necessity of channel transfer function for Power Line Communication system design. The framework for Power Line Communication in Network Simulator version 3 and then the necessary extension implementation are introduced. Other simulators are also mentioned. Secondly, various scenarios were implemented for the analysis and simulation of power line channel transfer functions. New scenarios for large topologies and for different approaches to calculate primary parameters were created. In the simulations, various kinds of topologies are considered for an analysis of the power line transfer function. The simulation part also focuses on the simulation of channel transfer function where the time- and frequency-selective impedances are considered. Finally, the last part focuses on measurements and a comparison of the simulation results with real measurements are given.**

***Index Terms*—measurement, power distribution lines, simulation, smart grids, transfer function.**

I. Introduction

Communication over power lines is referred to as Power Line Communication (PLC). PLC is a wired communication technology, however PLC systems do not require any specific cabling because the terminal equipment is connected via couplers directly to the power network.

PLC is a technology that has matured to a level of high performance and worldwide deployment [1], however, particular PLC technologies are not compatible and do not deliver the same level of performance for Smart Metering or the Home Area Network issue.

PLC technologies fall into three areas [2], [3]:

- Ultra Narrow Band (UNB) PLC operates at a very low data rate (100 bps) in the low frequency band (0.3–3 kHz). UNB is mostly based on proprietary solution and uses one-way communication, used in particular for load control. UNB has a very large operational range (hundreds of kilometers).
- Narrowband (NB) PLC operates in the 3–500 kHz band (3–148.5 kHz band in Europe). Single-carrier NB technologies achieve data rates of a few kbps for operational ranges of kilometers. Multicarrier technologies are capable of data rates of hundred kbps. Multicarrier technologies have adopted the Orthogonal Frequency Division Multiplexing (OFDM) modulation technology [4].
- Broadband PLC operates in the high frequency band 1.8–250 MHz and has data rates of several megabits per second up to hundreds of Mbps, however, the operational range is only hundreds of meters. Most of the BB-PLC standards have adopted the OFDM modulation technology [5].

Broadband PLC was initially intended for Internet access applications. Nowadays, it is successfully used for Home Area Networking (HAN) [6]. NB-PLC can be used for automatic meter reading (AMR) [7]. Standards in the multicarrier NB-PLC technology are targeted directly at Smart Grids requirements.

The article focuses on analysis and comparison of the available simulation tools for evaluation of the PLC technology. The significant influence of calculation of power cable primary parameters will be shown based on this comparison. The main contribution of this article is to provide an extension of the PLC simulator in Network Simulator version 3 (NS-3) in order to investigate parameters which significantly influence the transfer function of the power line channel. The results are also verified by measurements and compared with other simulators.

The article is divided as follows: In the first part, we analyze the channel transfer function calculation and the importance of estimating and evaluating the channel transfer function. Simulators for obtaining the power line channel transfer function are also presented. In the second part, a comparison of the NS-3 PLC simulator with the MATLAB simulators is introduced. Finally, the simulation results and measurement tests are presented.

II. Channel Transfer Function

In order to develop efficient PLC systems and propose improvements to the existing technology, it is necessary to accurately characterize the electrical infrastructure. The characteristics of the Channel Transfer Function (CTF) and the stationary noise give an indication of the PLC channel capacity, and allow evaluating the PLC system performance.

A. Channel Transfer Function Calculation

The transfer function of the power line channel can be

Research described in this paper was financed by the National Sustainability Program under grant LO1401 and by the Czech Science Foundation under grant no. GP14-29084P. For the research, the infrastructure of the SIX Center was used.

Digital Object Identifier 10.4316/AECE.2016.04008

calculated via three possible approaches:

First, according to the description in [8], it is possible to calculate the transfer function as a ratio of the load voltage to the source voltage, using the equation (see Fig. 1):

$$H = \frac{V_L}{V_S} = \left| \frac{Z_C}{AZ_C + B + CZ_C Z_S + DZ_S} \right| \quad (1)$$

A, B, C and D are frequency-dependent coefficients, which are calculated from the secondary parameters: characteristic impedance Z_C and propagation constant γ.

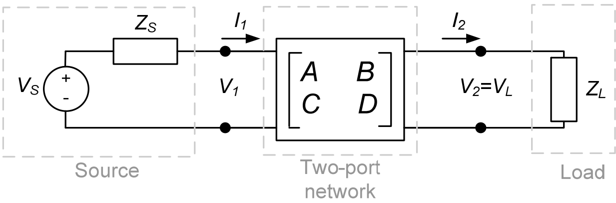

Figure 1. Two-port network model

Second, based on [9] it is possible to calculate the insertion loss (IL) defined in dB as a ratio between power across the load Z_L before (P_{bef}) and after (P_{aft}) the insertion of the channel, using the equation:

$$IL = 10\log_{10}\frac{P_{bef}}{P_{aft}} = 20\log_{10}\left|\frac{V_{L1}}{V_{L2}}\right| = \left|\frac{Z_L + Z_S}{AZ_L + B + CZ_L Z_S + DZ_S}\right|, \quad (2)$$

where V_{L1} is the voltage across the load before insertion of the line and V_{L2} is the voltage across the load after insertion of the line.

Third, if we consider only the voltage ratio between the output and the input of a two-port network, the transfer function can be calculated using the equation:

$$H_{loop} = \frac{V_2}{V_1} = 20\log_{10}\left|\frac{Z_L \cdot C + D}{Z_L \cdot A \cdot C + B \cdot C + A \cdot D + \dfrac{B \cdot D}{Z_L}}\right| \quad (3)$$

The knowledge of CTF allows understanding the intrinsic impairments of the PLC channel and developing efficient protection methods or adaptive communication approaches.

B. Estimation and Evaluation of Channel Transfer Function - Adaptive Communication Approaches

A fixed communication set-up often fails due to the varying conditions, therefore adaptive approaches are required. Consequently, the CTFs have to be known to avoid transmitting data on subcarriers with poor quality.

Several adaptive approaches have been presented in the last decade, we point out the most prominent ones:

- Matching the bit loading of a carrier to the conditions on the channel attenuation and noise (especially load fluctuations) was published in [10].
- A tool called "Power Line Analyzing Tool" (iPLATO) introduced for the first time in ISPLC'99 [11] provides an estimate of the channel transfer function and noise ratios, and can be implemented as a real-time system.
- In the Digital Subscriber Line (DSL) system, methods for estimating the transfer function based on the second derivative of the transfer function are designed [12].

The G3-PLC standard uses the adaptive tone mapping, which adaptively selects the optimum modulation. In [13] the adaptive tone mapping (ATM) mode was described, which adaptively selects the usable tones and the optimum modulation and coding type.

III. Simulators of PLC Channel Transfer Function

The simulator enables free configuration of the PLC network topology and is flexible enough to capture the time and frequency selective behavior of PLC channels.

The main representatives of simulators in MATLAB, can include the Cañete et al. simulator [14] (hereinafter Cañete PLC Simulator), Telecommunications Research Center Vienna (FTW) simulator [15], [16] (hereinafter FTW PLC Simulator) and linear time-invariant (LTI) power line generator (hereinafter LTI power line generator).

Cañete PLC Simulator is based on a deterministic model, i.e. it uses detailed knowledge of the topology and is designed for low-voltage networks. An advantage of this simulator is that it considers both the LTI system [17] and the Linear and Periodically Time Varying (LPTV) system [18-20].

FTW PLC Simulator is based on a model of cascaded two-port networks. An advantage over the Cañete PLC Simulator is the freely available source codes that can be arbitrarily edited.

The LTI power line generator and an analysis using this generator were introduced in [21]. In comparison with the Cañete and the FTW PLC Simulators, the LTI power line generator provides similar configurations. An LPTV approach was also considered [18]. The LTI power line generator enable to opt for a different calculation of primary parameters, terminal load analysis from measurements, simulations with frequencies of up to 100 MHz, input impedance analysis, and evaluation of limit values.

Due to the lack of simulation tools, a framework for PLC simulations in NS-3 environment (hereinafter referred to as NS-3 Simulator) was developed [22].

Like the above-mentioned simulators, the NS-3 Simulator focuses on the behaviour of power line transfer channel and it is possible to simulate both narrowband and broadband communication. The simulator enables to define a variety of topologies and includes time- and frequency-variable behaviour of the PLC channel in the simulations.

Based on this simulator, the G.hn (ITU standard for a PLC) Network Simulator was design [23]. In [24], this NS-3 Simulator is used for medium access control scheduler simulation in a realistic in-home scenario.

A. Evaluation of available simulators

In comparison to MATLAB, the advantage of NS-3 is that libraries for a large number of communication technologies are implemented in NS-3. This allows the user to combine multiple technologies and simulate applications for the Smart Grid or heterogeneous/hybrid networks.

The above-mentioned simulators focus mainly on simulations of the broadband PLC for in-home scenarios. Therefore, the article focuses on the PLC channel simulator in NS-3 and on simulations of broadband PLC for HAN but also simulations of narrowband PLC for Smart Metering.

IV. Comparison of NS-3 PLC Simulator with Other Simulators

The NS-3 Simulator was compared with available simulators: FTW PLC Simulator and Cañete PLC Simulator.

For the simulators to be compared, it was necessary to implement in the NS-3 Simulator cables with properties as described in [14] and cables used in the Czech Republic and Europe. Together with cables, it was also necessary to extend the simulator by different approaches to calculate the primary parameters.

In practice, different calculations are used to obtain a primary parameter:

- One type of calculation is the calculation according to the equations described in [26], which are derived from the physical parameters of the line (hereinafter referred to as derived calculation). More information about this primary parameters R', L', C' and G' calculation can be found in [25-27].
- A different procedure for calculating primary parameters is used in [15] (hereinafter referred to as provided calculation) is derived from the data provided by typical electrical cable manufacturers. This provided calculation is used in [14-15]. In [14], there are values for different types of cable with cross-sections from 1.5 to 10 mm^2, which have been implemented in the NS-3 Simulator.

For comparison with the other simulators, the cable with two-conductor and reference wire with the cross-section of 2.5 mm^2 was used. A comparison of CTF waveforms between the NS-3 Simulator with derived calculation and the Cañete and also FTW PLC simulators with provided calculation is shown in Fig. 2.

The comparison of CTF waveforms between the NS-3 Simulator, FTW and Cañete PLC Simulators for provided calculation is shown in Fig. 3. These results show the big influences of primary parameter calculation on the CTF.

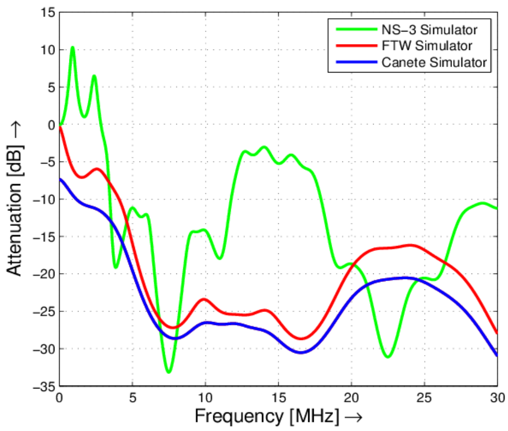

Figure 2. The CTF waveforms for NS-3 (derived calculation), Cañete PLC Simulator and FTW PLC Simulator (provided calculation)

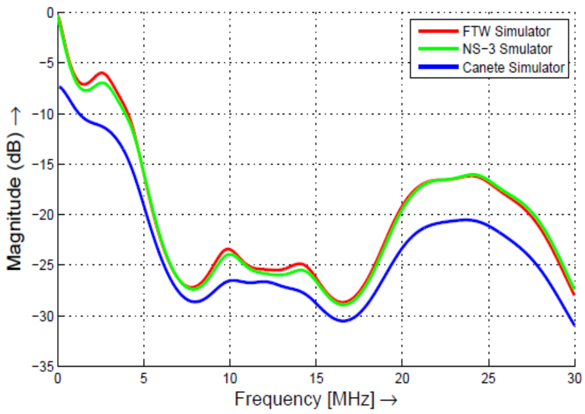

Figure 3. Comparison of all simulators with the same calculation of primary parametres (provided calculation)

V. SIMULATIONS

In the simulations, three topologies were considered: first, a small topology with three branches (Broadband PLC for HAN), second, an extensive topology with many branches (NB-PLC for Smart Metering) and third, a topology with time and frequency selective impedance (Broadband PLC).

A. Topology with three branches

Fig. 4 shows a topology with three branches, which was used for the following simulations:

1) The impact of a change in terminal branch impedance on CTF.
2) The impact of the branch length on the CTF.
3) The impact of a change in the direct path between nodes on the CTF.

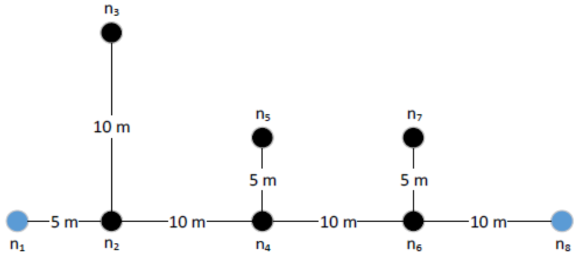

Figure 4. Topology with three branches based on [3]

1) Change of terminating branch impedance

The aim of the scenarios was to determine the influence of the change in terminal branch impedance on the CTF. The results of a change in n_3 node impedance are represented in Fig. 5. The impedance was gradually changed from the original value of 1000 Ω to values of 10 Ω and 10^{15} Ω. The difference in the form of CTF can be seen here. For lower impedance values (the red waveform) we can see a change in attenuation, which grows at most frequencies. For high impedances (the blue waveform), there is a change in attenuation on the notches of channel transfer function. At frequencies of 6 MHz and 17 MHz, there is a significant increase in attenuation: at a frequency of 6 MHz by 9 dB and at a frequency of 17 MHz by 4 dB.

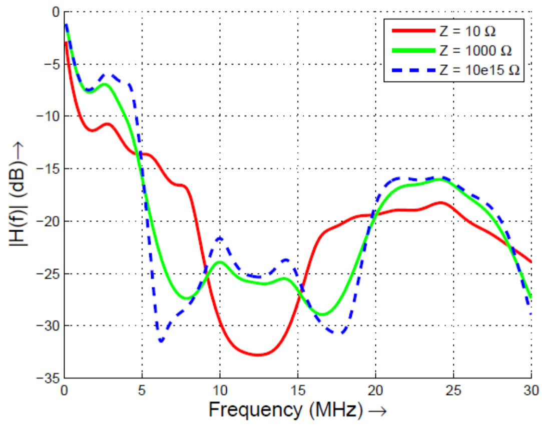

Figure 5. Change in impedance on n_3 node

The influence of impedance change on the n_5 node is shown in Fig. 6. Mainly the influence of low impedance has manifested itself (the red waveform). There was a change in attenuation over the whole range of frequency characteristics of the channel transfer function. In the first part (0 to 4 MHz) the attenuation increased considerably (by 10 dB) on the notch at a frequency of 1.7 MHz. On the contrary, in the range from 6 to 18 MHz the attenuation decreased, on average by 6.5 dB. In the range from 18 to 30 MHz the attenuation rose again, on average by 5 dB. For high impedance (the blue waveform) the difference was not so marked. Between the notches at frequencies of 10 to 14.5 MHz there was a significant growth in attenuation. The attenuation increased by up to 7 dB.

The results of the influence of a change in impedance on the n_7 node are similar to those for the n_5 node.

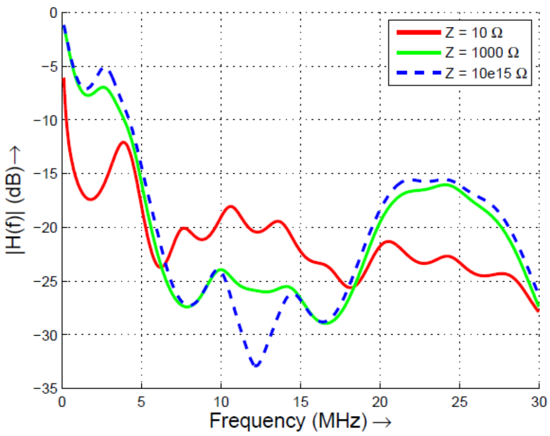

Figure 6. Change of impedance on n_5 node

2) Change of branch length

The simulation focused on the impact of the change in branch length on the CTF. The results for the change of branch length of node n_5 are shown in Fig. 7. For a lower distance (1 m – the red waveform) the form of CTF frequency characteristics is almost identical to the initial distance (5 m – the green waveform) except for the frequencies ranging from 5 to 19 MHz. In this section, the attenuation decreased on average by 5.5 dB. The increase in branch length (1000 m – the blue waveform) was reflected by a change in attenuation. The notch attenuation at a frequency of 4 MHz rose by 4 dB. In the middle part (6 to 17 MHz), the attenuation decreased by 3 dB on average and in the range of 17 to 30 MHz, the attenuation increased by only 1.5 dB on average.

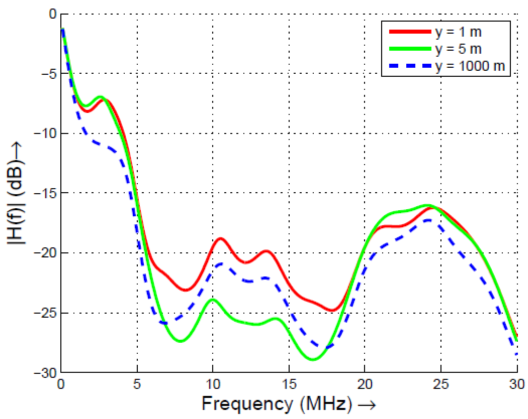

Figure 7. Change of branch length of n_5 node

3) Change in the direct path between nodes

The simulation focused on the impact of a change in the direct path between the nodes n_1 and n_8. The resulting form of channel transfer functions when changing the distance between the nodes n_2 and n_4 is shown in Fig. 8.

It follows from this graph that a change in the direct path between communicating nodes has a greater effect on the shape of CTF than a change in the branch length or a change in load impedance on the branch end.

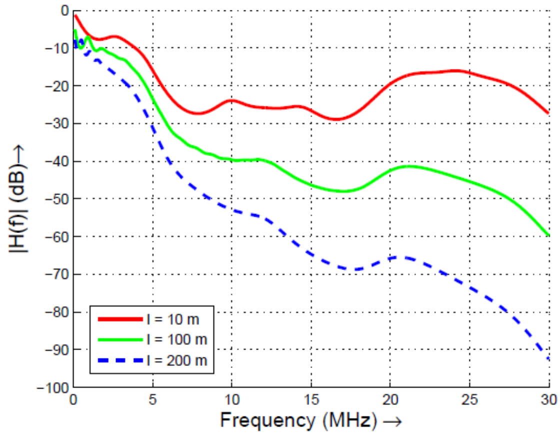

Figure 8. Change of distance between nodes n_2 and n_4

B. Extensive topology

The topology in Fig. 9 represents a real PLC network for Smart Metering, consisting of 30 nodes with fixed impedances. The magnitude of impedances was chosen from the range of the values corresponding to a real environment (50 to 700 Ω).

Figure 9. Extensive topology

Fig. 10 shows the CTF between the nodes Z_S and Z_{29}. In this scenario, the load impedance values of the Z_{15} node was gradually varied from 638 Ω to values of 10 Ω and 10^{15} Ω.

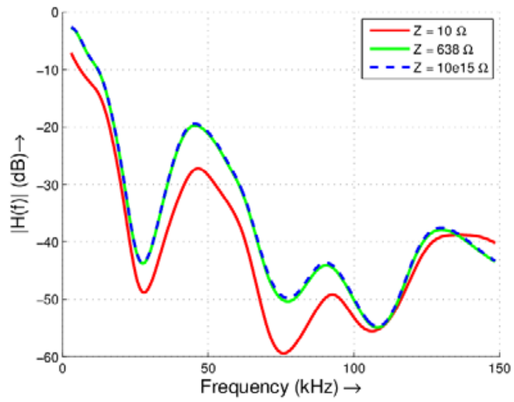

Figure 10. Change of impedance on Z_{15} node

We can see in Fig. 10 that when using a lower impedance than the characteristic impedance, the attenuation increases. When using a higher impedance, the attenuation acquires almost identical values.

To determine the effect of branch length on the CTF, the initial branch length (137 m) was shortened to 10 m and then extended by 10 km. The effect of this change is shown in Fig. 11. The graph demonstrates that when the distance is increased, the attenuation increases as well.

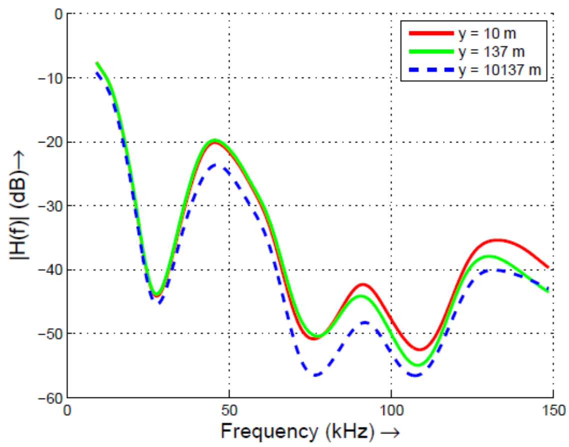

Figure. 11. CTF between nodes Z_S and Z_{29} - change of branch length of Z_{15} node

C. *Topology with time and frequency selective impedance*

A simulation for small topology using fixed, time and frequency selective impedance was also carried out. The topology is shown in Fig. 12.

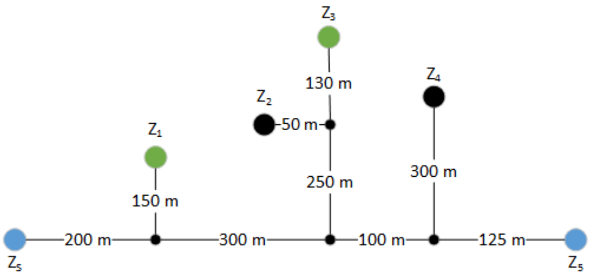

Figure 12. Topology with time (Z_1) and frequency (Z_3) selective impedance

The node Z_1 was completed with a frequency selective impedance and the node Z_3 with a time selective impedance. Fixed impedance was considered in the remaining nodes. A frequency band up to 500 kHz was considered. The aim of the simulation was to display the channel transfer function between the nodes Z_s and Z_5 (see Fig. 13).

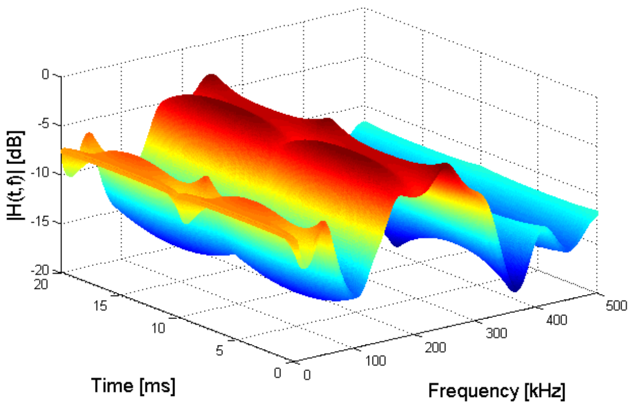

Figure 13. Channel transfer function between Z_s a Z_5 nodes

VI. Measurements

The measurements were carried out in laboratory environment with isolated power line. The Signal-to-Noise ratio (SNR) and channel frequency response (CFR) were measured using the SNR Scope tool. The SNR Scope tool measures CFR and SNR between two PLC modems Corinex (Head End modem and Slave modem). For the LTI system, we can consider the characteristics (notches, attenuation) of transfer functions and frequency response to be similar.

Fig. 14 shows the measurements of the impact of the direct path between modems on the CFR in point-to-point connection. In comparison with the simulation (see Fig. 8), we can see a similar characteristic: with increasing length the attenuation decreases significantly.

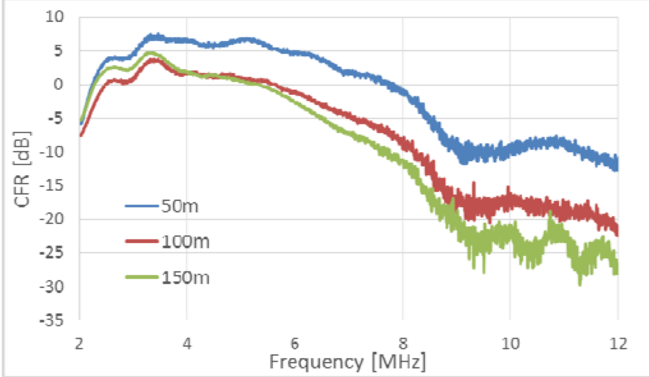

Figure 14. Channel frequency response for different lengths between modems

The impact of branches on CFR was measured with a direct line of 50 meters and one no-load branch of 30 meters in length (the branch is located 50 meters from the transmitter). This branch caused notches in CFR (see Fig. 15). Therefore only one branch caused a decrease in transmission parameters (e.g. data rate). The extensive topology with many branches caused a higher decrease in transmission parameters.

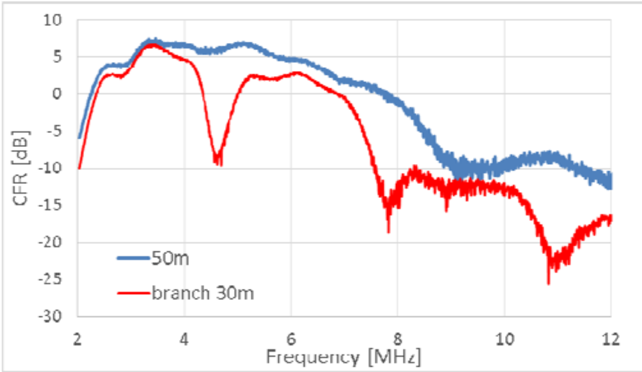

Figure 15. Comparison of CFR for direct line and topology with one branch

VII. Simulations and Measurements Outcomes

The outcomes of the simulations and measurements are the following:

- The calculations approaches of primary parameters of power cables have significant influence on CTF. The resulting CTF had different peaks and notches and therefore different frequency bands or unusable tones (adaptive tone mapping) will be omitted from transmission.
- The terminal branch impedance influences the position of peak and notches and the attenuation of notches significantly decrease with impedance larger or lower than characteristic impedance of power line.
- The length of the branches influence only slightly the attenuation, attenuation decreases by only about 1 dB per 100 m longer branch.
- The length of the direct path influences significantly the attenuation, especially on the higher frequencies attenuation decreases by about 10 dB per 50 m longer path.

VIII. Conclusion

The paper analyzed available simulation tools for evaluation of the PLC technology and described an extension of the framework for PLC communication simulations in NS-3 environment. The extension was an implementation of other cables and related calculations of primary parameters of power cables that have a big influence on the shape of the transfer function. Thanks to this extension it was also possible to compare the NS-3 Simulator with other available simulators, namely the Cañete and FTW PLC Simulators.

The disadvantage of the PLC framework in NS-3 in comparison with other communication technologies already implemented in NS-3, is that it still requires more and more extensions and implementations for full functionality. This disadvantage, one of possible extensions, was described in this paper.

In the paper a series of simulations was presented with the aim to change the impedance of branches, change the length of branches and change the direct path between communicating nodes for a small topology, large topology and topology with frequency- and time-varying impedances.

The final part of the paper considered the measurements of frequency channel response. The results of measurements show similar characteristics between simulation and measurement.

The framework for a simulation of the PLC technology in NS-3 is completely unique. The results show that there is a great potential and the extension of these simulators should continue and other functionalities should be implemented in order to adequately include the PLC technology in the NS-3 simulation tool or other network simulators.

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