Artificial Intelligence, Machine Learning and Neural Networks for Tomography in Smart Grid – Performance Comparison between Topology Identification Methodology and Neural Network Identification Methodology for the Distribution Line and Branch Line Length Approximation of Overhead Low-Voltage Broadband over Power Lines Network Topologies

Athanasios G. Lazaropoulos[1,2,*] and Helen C. Leligou[2]

1: School of Electrical and Computer Engineering / National Technical University of Athens / 9 Iroon Polytechniou Street / Zografou, GR 15780
2: Department of Industrial Design and Production Engineering / School of Engineering / University of West Attica / 250 Thivon & P. Ralli / Athens, GR 12244

Received December 8, 2022; Accepted January 5, 2023; Published January 9, 2023

Until now, the neural network identification methodology for the branch number identification (NNIM-BNI) has identified the number of branches for a given overhead low-voltage broadband over powerlines (OV LV BPL) topology channel attenuation behavior [1]. In this extension paper, NNIM-BNI is extended so that the lengths of the distribution lines and branch lines for a given OV LV BPL topology channel attenuation behavior can be approximated; say, the tomography of the OV LV BPL topology. NNIM exploits the Deterministic Hybrid Model (DHM) and the OV LV BPL topology database of Topology Identification Methodology (TIM). By following the same methodology of the original paper, the results of the neural network identification methodology for the distribution line and branch line length approximation (NNIM-LLA) are compared against the ones of the newly proposed TIM-based methodology, denoted as TIM-LLA.

Keywords: Smart Grid; Broadband over Power Lines (BPL) networks; Power Line Communications (PLC); Distribution and Transmission Power Grids; Neural Networks; Machine Learning; IT; Modeling; Artificial Intelligence

1. Introduction

The evolution of the today's traditional power grid to a modern power grid that is upgraded with an intelligent IP-based communications network may support a myriad of broadband applications [1-5]. Among the communications solutions that may allow this smart grid transformation, Broadband over Power Lines (BPL) technology exploits the available wired power grid infrastructure while permitting the coexistence with other communications solutions through their BPL wireline/wireless interfaces [5-8]. However, the wired power grid infrastructure remains a hostile propagation and transmission

**Corresponding author:* AGLazaropoulos@gmail.com

medium for BPL signals that suffer in these communications channels from high and frequency-selective channel attenuation and noise [9-15].

Until now, a plethora of channel models has been proposed or properly adjusted from other communications technologies in the literature for characterizing BPL channels; say, deterministic, statistical, bottom-up, top-down BPL channel models or appropriate syntheses of the aforementioned ones [9], [11], [16-28]. Similarly to [1], the deterministic hybrid model (DHM) is here applied in the overhead low voltage (OV LV) BPL networks for modeling BPL signal propagation and transmission across them and thus providing critical broadband performance metrics, which further act as the big data feed for the broadband applications. In this extension paper, Topology Identification Methodology (TIM), which has been proposed in [29, 30] and is one of the broadband applications supported by BPL technology in the smart grid, stores in its TIM BPL topology database, analyzes and reports with the DHM the channel attenuation measurements of various BPL topologies. In [29, 30], TIM approximates the exact topological characteristics (*i.e.*, number of branches, length of branches, length of main lines and branch terminations) of an examined BPL topology by comparing its channel attenuation measurements with the theoretical channel attenuation results stored in the TIM BPL topology database. In [1], TIM has been extended to TIM-based Branch Number Identification methodology (TIM-BNI) so that the number of branches of an OV LV BPL topology whose theoretical channel attenuation results are known can be approximated when this examined OV LV BPL topology is not among the OV LV BPL topologies of the TIM BPL topology database. In this extension paper, TIM and TIM-BNI are further extended to the new TIM-based methodology for approximating the distribution line and branch line lengths (TIM-LLA) of an examined OV LV BPL topology when the examined topology is not among the OV LV BPL ones of the TIM BPL topology database.

In [1], the set of the supported broadband applications by the smart grid has been enriched by experimenting with artificial intelligence (AI) and machine learning (ML) capabilities. By exploiting the available big data of the TIM BPL topology database for the OV LV BPL topologies and the neural network architectures / training, the neural network identification methodology for the branch number identification (NNIM-BNI) of OV LV BPL topologies has been proposed in [1]. Alternatively to TIM-LLA, NNIM-BNI is upgraded in this extension paper so as to approximate the distribution line and branch line lengths (NNIM-LLA) of an examined OV LV BPL topology when this topology is not included in the TIM BPL topology database. By following the same methodology of [1] and exploiting its findings and conclusions for better approximation performances of the family products of TIM and NNIM, new default operation settings are applied in this extension paper. Finally, the performance results of NNIM-LLA are going to be compared against the ones of TIM-LLA for different operation scenarios and OV LV BPL topologies.

The rest of this paper is organized as follows: Section 2 briefly presents DHM, TIM-BNI and NNIM-BNI. Certain aspects that have been highlighted in the original paper and concern the operation of TIM-BNI and NNIM-BNI are demonstrated in this Section. Section 3 focuses on the proposal of TIM-LLA and NNIM-LLA as well as the corresponding performance metrics. Section 4 introduces the new default operation settings while the performance metric results for TIM-LLA and NNIM-LLA are presented for the indicative OV LV BPL topologies of the original paper. Section 5 concludes this extension paper.

2. DHM, TIM-BNI and NNIM-BNI

In this Section, a brief synopsis of the basic elements that have been presented in [1] and are going to influence the operation and performance of TIM-LLA and NNIM-LLA is given. More specifically, DHM is presented by focusing on its output of channel attenuation that is appropriately included into TIM OV LV BPL topology database. Then, TIM-BNI and NNIM-BNI, which have been proposed in [1], are briefly discussed as well as the corresponding useful conclusions of [1] that are going to be used in this extension paper and may further affect the operation and performance of TIM-LLA and NNIM-LLA.

2.1 DHM and TIM OV LV BPL Topology Database

In accordance with [1], DHM is a synthetic BPL channel model where a bottom-up, a top-down, a coupling scheme and other performance metric computation modules may be concatenated [9-12], [16], [31], [32]. With reference to eq. (2) of [1], the coupling scheme channel transfer function, which is the system output of the first three DHM modules, relates the output BPL signals with the input ones through:

$$H^{\mathrm{OVLV},C}\{\cdot\} = \left[\mathbf{C}^{\mathrm{out}}\right]^{\mathrm{OVLV},C} \cdot \mathbf{H}^{\mathrm{OVLV}}\{\cdot\} \cdot \left[\mathbf{C}^{\mathrm{in}}\right]^{\mathrm{OVLV},C} \tag{1}$$

where $[\cdot]^{\mathrm{c}}$ denotes the applied coupling scheme, $\mathbf{C}^{\mathrm{in}}$ and $\mathbf{C}^{\mathrm{out}}$ are the input and output coupling matrices and $\mathbf{H}^{\mathrm{OVLV}}\{\cdot\}$ is the channel transfer function matrix. From eq. (1), it is clear that the channel attenuation is a frequency dependent DHM output that depends on the applied coupling scheme, the OV LV multiconductor transmission line (MTL) configuration and the examined OV LV BPL topology [33, 34]. Therefore, a correspondence between the topological characteristics of an OV LV BPL topology and its channel attenuation is established from eq. (1) when the applied coupling scheme and the OV LV MTL configuration are given. When a great number of OV LV BPL topologies are assumed, respective topological characteristics and channel attenuation data can be available from eq. (1) thus acting as the big data feed of the TIM OV LV BPL topology database.

TIM OV LV BPL topology database, which acts as the big data pool for both TIM- and NNIM-based methodologies of the original paper and this extension one, is in fact the core part of TIM [29]. In this extension paper and with reference to Figure 1b of [1], the following data are maintained for each OV LV BPL topology of the TIM OV LV BPL topology database of this extension paper, namely: (i) its ID number p in the TIM OV LV BPL topology database when P is the number of all OV LV BPL topologies in the TIM OV LV BPL topology database; (ii) the actual number of branches N; (iii) the actual lengths of the distribution lines $\mathbf{L} = [L_1 \quad L_2 \quad \cdots \quad L_{N+1}]$; (iv) the actual lengths of the branch lines $\mathbf{L_b} = [L_{\mathrm{b}1} \quad L_{\mathrm{b}2} \quad \cdots \quad L_{\mathrm{b}N}]$; and (v) the coupling scheme channel transfer function values with respect to the frequency. According to [1], [29], the size of the TIM OV LV BPL topology database depends on the TIM OV LV BPL topology database specifications, which are part of the default operation settings of this extension paper, havinh to do with the topological characteristics of the OV LV BPL topologies stored in the database such as the maximum number of branches $N_{\max}$, the length spacing L_{s} for both branch distance and branch length, the maximum branch length $L_{\mathrm{b,max}}$ and the operation frequency range. Here, it should be reminded that TIM is a BPL broadband application that aims at identifying an OV LV BPL topology with respect to its topological characteristics when its theoretical or actual coupling scheme transfer function behavior is known even if measurement differences may occur [29], [35], [36].

2.2 TIM-BNI and NNIM-BNI

TIM-BNI has been proposed and assessed in [1]. TIM-BNI has aimed at approximating the branch number of an examined OV LV BPL topology by comparing its coupling scheme channel transfer function values of eq. (1) against the respective ones of all the OV LV BPL topologies of the TIM OV LV BPL topology database. Note that the indicative OV LV BPL topologies, which have been reported in Table 1 of [1], have not been included in the TIM OV LV BPL topology database except for the OV LV BPL Line-of-Sight (LOS) topology case. In order to approximate the branch number, TIM-BNI has identified the R OV LV BPL topologies of the TIM OV LV BPL topology database that have better approximated the channel attenuation behavior of the examined indicative OV LV BPL topology. To identify the R closest approximations, TIM-BNI has applied the performance metric of the root-mean-square deviation (RMSD) of the amplitude of the coupling scheme channel transfer function in dB, as shown in eqs (3) and (4) of [1]. The average value of the branch numbers of the R OV LV BPL topologies of the TIM OV LV BPL topology database that have presented the R lowest RMSDs among the P computed ones has defined the TIM-BNI approximation of the branch number of the examined indicative OV LV BPL topology $N_{\mathrm{TIM-BNI}}$ [1]. Factors that affect the accuracy performance of the TIM-BNI approximations are the required accuracy degree of the TIM OV LV BPL topology database, the number R of the OV LV BPL topologies of the TIM OV LV BPL topology database with the lowest RMSDs and the representativeness of the TIM OV LV BPL topology database.

Similarly to TIM-BNI, NNIM-BNI has been proposed and assessed in [1] while its operation philosophy lies in the areas of AI, ML and neural networks [37-40]. The operation of NNIM-BNI has been based on: (i) the TIM OV LV BPL topology database; and (ii) the MATLAB neural network program of [38], [41] that implements the fully connected neural network architecture of Figure 2 of [1] through the training, validation and testing phases. Since NNIM-BNI may train neural networks of variable numbers of hidden layers, NNIM-BNI has exploited the performance metric of RMSD of the amplitude of the coupling scheme channel transfer function in dB, as shown in eq (5) of [1]. In fact, NNIM-BNI has approximated the branch numbers $N_{\mathrm{NNIM-BNI}}$ of the examined indicative OV LV BPL topology per hl hidden layer but also reports RMSD of each approximation. In a similar way, factors that affect the accuracy performance of the NNIM-BNI approximations are the required accuracy degree of the TIM OV LV BPL topology database, the number HL of the hidden layers assumed, the participation percentage of the three phases and the representativeness of the TIM OV LV BPL topology database.

3. TIM-LLA and NNIM-LLA

In this Section, TIM-LLA and NNIM-LLA are proposed. Prior to this proposal, additional specifications that affect the definition of the TIM OV LV BPL topology database for its operation with TIM-LLA and NNIM-LLA are required to be given. After the proposal, similarly to [1], suitable performance metrics, which allow the approximation assessment of the distribution line and branch line lengths of the examined indicative OV LV BPL topologies in each methodology are reported. Note that the number of branches of the examined indicative OV LV BPL topologies is assumed to be known prior to apply both methodologies.

3.1 Additional Specifications for TIM OV LV BPL Topology Database

With reference to Sec.2.2, the number of OV LV BPL topologies vary in the TIM OV LV BPL topology depending on the assumed TIM OV LV BPL topology database specifications [1], [29], [30]. By considering the assumption of the known number of branches of the examined indicative OV LV BPL topologies and the conclusion of [1] regarding the need for database representativeness, only the OV LV BPL topologies of the TIM OV LV BPL topology database with the same number of branches with the examined indicative OV LV BPL topology are going to be examined during the operation of TIM-LLA and NNIM-LLA. In addition, so as not to disrupt the approximations due to the symmetry of BPL topologies (*e.g.*, the OV LV BPL topology with lengths of its distribution lines $\mathbf{L} = [100m \quad 900m]$ and of its branch lines $\mathbf{L_b} = [20m]$ is symmetrical to the OV LV BPL topology with respective lengths $\mathbf{L} = [900m \quad 100m]$ and $\mathbf{L_b} = [20m]$) [42], [43], only one of the symmetrical OV LV BPL topologies is stored in the OV LV BPL topology database.

3.2 TIM-LLA

Similarly to [1], each indicative OV LV BPL topology that is going to be examined in this extension paper is not included in the TIM OV LV BPL topology database by definition. Hence, TIM-LLA is going to approximate the distribution and branch line lengths of the examined indicative OV LV BPL topology by comparing its coupling scheme channel transfer function values against the respective ones of all the OV LV BPL topologies of the TIM OV LV BPL topology database with the same number of branches. The performance metric of RMSD of the amplitude of coupling scheme transfer functions in dB that is expressed by eqs. (3) and (4) of [1] is also here applied in order to identify the OV LV BPL topologies of the TIM OV LV BPL topology database that achieve the best approximations of the channel attenuation behavior of the examined indicative OV LV BPL topology. The average value for each of the lengths of the R OV LV BPL topologies of the TIM OV LV BPL topology database that present the R lowest RMSDs among the P computed ones defines the TIM-LLA approximation of the respective lengths of the examined indicative OV LV BPL topology (i.e., the TIM-LLA approximation lengths of the distribution and branch lines are $\mathbf{L}_{\text{TIM-LLA}} = [L_{1,\text{TIM-LLA}} \quad L_{2,\text{TIM-LLA}} \quad \cdots \quad L_{N+1,\text{TIM-LLA}}]$ and $\mathbf{L}_{\text{b,TIM-LLA}} = [L_{\text{b1,TIM-LLA}} \quad L_{\text{b2,TIM-LLA}} \quad \cdots \quad L_{\text{b}N,\text{TIM-LLA}}]$, respectively). Similarly to TIM-BNI, it is clear that TIM-LLA performance towards the distribution and branch line length identification of OV LV BPL topologies, that is numerically assessed in Section 4, is affected by the required accuracy degree of the TIM OV LV BPL topology database and the number R of the lowest RMSDs.

3.3 NNIM-LLA

With reference to Figure 2 of [1], NNIM-LLA is going to adopt a similar neural network architecture with NNIM-BNI; say, a fully connected neural network with *HL* hidden layers of neurons where its input is P column vectors; the p, p=1,…,P column vector consists of the differences between the amplitude of the coupling scheme channel transfer functions of the arbitrary p OV LV BPL topology of the TIM OV LV BPL topology database in dB and the amplitude of the coupling scheme channel transfer functions of LOS case in dB at each frequency of the operating frequency range. After the input layer, *HL* hidden layers occur; each *hl* of the *HL* hidden layers receives as input a column vector from the previous one while it gives as output a column vector for the following one where the activation function, the array of weights and array of biases of the *hl* hidden layer are taken into consideration. The output of the fully connected neural network that coincides with the output of the *HL* hidden layer defines the NNIM-LLA approximation of the respective lengths of the examined indicative OV LV BPL topology (i.e., the NNIM-LLA approximation lengths of the distribution and branch lines are $\mathbf{L}_{\mathrm{NNIM-LLA}} = [L_{1,\mathrm{NNIM-LLA}} \quad L_{2,\mathrm{NNIM-LLA}} \quad \cdots \quad L_{N+1,\mathrm{NNIM-LLA}}]$ and $\mathbf{L}_{\mathrm{b,NNIM-LLA}} = [L_{\mathrm{b1,NNIM-LLA}} \quad L_{\mathrm{b2,NNIM-LLA}} \quad \cdots \quad L_{\mathrm{b}N,\mathrm{NNIM-LLA}}]$, respectively). Similarly to [1], NNIM-LLA exploits the MATLAB neural network training program of [38], [41] while the big data handling of the TIM OV LV BPL topology database is divided into three phases; say, training, validation and testing phase. As in the case of TIM-LLA, NNIM-LLA applies the RMSD performance metric of the examined indicative OV LV BPL topologies for different numbers of the hidden layers during all its three phases. Therefore, TIM-LLA may give as output its approximation for the lengths of the distribution and branch lines as well as their approximation RMSDs per hidden layer. Similarly to NNIM-BNI, it is clear that NNIM-LLA performance, which is numerically assessed in Section 4 in comparison with the TIM-LLA performance, is affected by the required accuracy degree of the TIM OV LV BPL topology database and the participation percentage of the three phases of the MATLAB neural network training program.

4. Numerical Results and Discussion

In this Section, numerical results concerning the performance of TIM-LLA and NNIM-LLA are presented as well as their evaluation. Actually, this extension paper follows the same structure regarding the demonstration of the numerical results with [1]. First, the default operation settings for the base scenario are given in Sec. 4.1 by also taking under consideration the findings and conclusions of [1]. Second, the effect of the *R* value of the OV LV BPL topologies of the TIM OV LV BPL topology database with the lowest RMSDs that is considered during the computation of the average values of the lengths of the distribution and branch lines is examined during the operation of TIM-LLA in Sec. 4.2. Third, the role of the participation percentages of the three phases of NNIM-LLA during its operation is assessed in Sec. 4.3. Finally, an overall numerical performance comparison between TIM-LLA and NNIM-LLA is attempted in Sec. 4.4.

4.1 Base Scenario and Default Operation Settings B

As the base scenario of the operation of TIM-LLA and NNIM-LLA is concerned, certain default operation settings should be assumed. Actually, the default operation settings of [1], denoted as default operation settings A in the rest of this extension paper, are here enriched so as to exploit the experience from the operation of TIM-BNI and NNIM-BNI, that act as the predecessor family products of the TIM-LLA and NNIM-LLA, respectively, and boost the accuracy for the challenging issue of OV LV BPL topology tomography. More specifically, the following default operation settings B are assumed:

- The applied OV LV MTL configuration and the typical OV LV BPL topology that are used in this extension paper are shown in Figures 1(a) and 1(b) of [1], respectively. With reference to Figure 1(b), three indicative OV LV BPL topologies, which are shown in green background color, are reported in terms of their topological characteristics in Table 1. The three indicative OV LV BPL topologies of interest (i.e., urban case A, suburban case and rural case), which have already been used for the evaluation of TIM-BNI and NNIM-BNI, are going to be further adopted in this extension paper so that the approximation performances of TIM-LLA and NNIM-LLA can also be evaluated. In accordance with [1], the branch terminations are assumed to be open-circuit while the transmitting and receiving ends are assumed to be matched [9]-[12], [16]. WtG[1] coupling scheme is applied across the indicative and TIM OV LV BPL topologies of this extension paper.
- As the preparation of the TIM OV LV BPL topology database is concerned for the evaluation of TIM-LLA and NNIM-LLA, the indicative urban case A, suburban case and rural case will be excluded from the TIM OV LV BPL topology database so that TIM-LLA and NNIM-LLA blindly perform their approximations. As already been mentioned, depending on the examined indicative OV LV BPL topology, the number of branches is known thus influencing the segmentation and the accuracy of the TIM OV LV BPL topology database in each case (i.e., only the OV LV BPL topologies with the same number of branches with the examined one are considered from the TIM OV LV BPL topology database in each approximation execution by TIM-LLA and NNIM-LLA).
- During the preparation of the TIM OV LV BPL topology database [29], [30], the length spacings for branch distance and branch length are assumed to be equal to 100m and 100m, respectively, while the branch line length may range from 0m to 300m. In accordance with [1], the distribution line length and, thus, the length between the transmitting and receiving ends of all the OV LV BPL topologies of this paper is assumed to be equal to 1000m. Despite the higher maximum branch line length of 300m in comparison with the 100m of [1], the high length spacings of 100m in comparison with the 25m of [1] imply that: (i) better execution times during the TIM OV LV BPL topology database and the simulation process occur; and (ii) the branch line lengths of rural OV LV BPL topologies (the maximum one is equal to 300m in this extension paper) can range from 0m to 300m. In accordance with [1], there is a trade-off relationship between the accuracy of the TIM OV LV BPL topology database and the length spacings. Therefore, high RMSDs due to high differences between the actual and approximated branch lengths are expected in this paper due to the combination of high branch line length spacing and maximum branch line length.

Table 1
Indicative OV LV BPL Topologies [1]

OV LV BPL Topology Name	Number of Branches (N)	Length of Distribution Lines	Length of Branch Lines
Urban case A (Typical urban case)	3	L_1=500m, L_2=200m, L_3=100m, L_4=200m	L_{b1}=8m, L_{b2}=13m, L_{b3}=10m
Urban case B (Aggravated urban case)	5	L_1=200m, L_2=50m, L_3=100m, L_4=200m, L_5=300m, L_6=150m	L_{b1}=12m, L_{b2}=5m, L_{b3}=28m, L_{b4}=41m, L_{b5}=17m
Suburban case	2	L_1=500m, L_2=400m, L_3=100m	L_{b1}=50m, L_{b2}=10m
Rural case	1	L_1=600m, L_2=400m	L_{b1}=300m
Line-of-Sight (LOS) case	0	L_1=1000m	-

- In accordance with Sec. 3.1, symmetrical OV LV BPL topologies are excluded from the TIM OV LV BPL topology database. This implies that TIM-LLA and NNIM-LLA are going to give as output original approximated OV LV BPL topologies that is the first of the two parts of the full answer; the second and last part of the full answer is the symmetrical approximated OV LV BPL topology to the original one. For example, if NNIM-LLA gives as output the approximation lengths of the distribution and branch lines $\mathbf{L}_{\mathrm{NNIM-LLA}} = [100\mathrm{m} \quad 500\mathrm{m} \quad 400\mathrm{m}]$ and $\mathbf{L}_{\mathrm{b,NNIM-LLA}} = [50\mathrm{m} \quad 75\mathrm{m}]$ of the original approximated OV LV BPL topology, the symmetrical approximated OV LV BPL topology has lengths of the distribution and branch lines that are equal to $\mathbf{L}_{\mathrm{NNIM-LLA}} = [400\mathrm{m} \quad 500\mathrm{m} \quad 100\mathrm{m}]$ and $\mathbf{L}_{\mathrm{b,NNIM-LLA}} = [75\mathrm{m} \quad 50\mathrm{m}]$, respectively. Similarly to the urban case A, suburban case and rural case, it should be noted that the symmetrical OV LV BPL topologies of the aforementioned three indicative OV LV BPL topologies are also excluded from the TIM OV LV BPL topology database so that TIM-LLA and NNIM-LLA blindly perform their approximations.
- Due to the improved results presented in Sec. 4.2 of [1] concerning the assumption of wide and dense frequency ranges, the frequency range and the flat-fading subchannel frequency spacing are assumed to be equal to 3-88MHz and 1MHz, respectively, in this extension paper.
- Similarly to [1], the performance metric of RMSD is going to be used by TIM-LLA; say, the RMSD of the amplitudes of coupling scheme channel transfer functions in dB of the OV LV BPL topologies from the TIM OV LV BPL topology database with respect to the ones of each of the indicative OV LV BPL topologies of Table 1 as described in eq. (3) of [1]. For the base scenario where the default operation settings B are assumed, the average value for each of the lengths of the five OV LV BPL topologies of the TIM OV LV BPL topology database (i.e., R=5) that present the five lowest RMSDs among the P computed ones defines the TIM-LLA approximation of the respective length of each of the examined indicative OV LV BPL topologies of Table 1 (i.e., the TIM-LLA approximation lengths of the distribution and branch lines are $\mathbf{L}_{\mathrm{TIM-LLA}} = [L_{1,\mathrm{TIM-LLA}} \quad L_{2,\mathrm{TIM-LLA}} \quad \cdots \quad L_{N+1,\mathrm{TIM-LLA}}]$ and $\mathbf{L}_{\mathrm{b,TIM-LLA}} = [L_{\mathrm{b1,TIM-LLA}} \quad L_{\mathrm{b2,TIM-LLA}} \quad \cdots \quad L_{\mathrm{b}N,\mathrm{TIM-LLA}}]$, respectively). The TIM-LLA

performance assessment is going to be fulfilled through the comparison between the TIM-LLA distribution and branch line lengths and the real ones while the performance metric of RMSD again assesses the overall TIM-LLA approximation for the three examined indicative OV LV BPL topologies of Table 1.

- With reference to [1], the default participation percentages of the three phases of the MATLAB neural network training program of [38], [41], say, training, validation and testing phase, during the operation of NNIM-LLA are assumed to be equal to 70%, 15% and 15%, respectively. Similarly to [1], the output of NNIM-LLA is going to be the NNIM-LLA approximation lengths of the distribution lines $\mathbf{L}_{\mathrm{NNIM-LLA}} = [L_{1,\mathrm{NNIM-LLA}} \quad L_{2,\mathrm{NNIM-LLA}} \quad \cdots \quad L_{N+1,\mathrm{NNIM-LLA}}]$ and of the branch lines $\mathbf{L}_{\mathrm{b,NNIM-LLA}} = [L_{\mathrm{b1,NNIM-LLA}} \quad L_{\mathrm{b2,NNIM-LLA}} \quad \cdots \quad L_{\mathrm{b}N,\mathrm{NNIM-LLA}}]$ per hidden layer when the maximum number of hidden layers HL is assumed to be equal to 5. In addition, three executions of NNIM-LLA are going to be reported in each examined case when the participation percentages of the three phases are given. The results of NNIM-LLA are going to be compared with the real ones in each case while the performance metric of RMSD is going to assess the overall NNIM-LLA approximation.

In Table 2, the length approximations of the distribution and branch lines of TIM-LLA and NNIM-LLA are reported when the aforementioned default operation settings B are assumed and the urban case A of Table 1 is examined. Apart from the original approximations that are given in black font color, the symmetrical approximations of TIM-LLA and NNIM-LLA for the urban case A are also given in blue font color. In addition, the real lengths of the distribution and branch lines of the urban case A are presented for comparison reasons while the RMSDs of TIM-LLA and NNIM-LLA approximations for the urban case are also computed. Similarly to [1], the three executions of NNIM-LLA are reported for the urban case A per hidden layer. Tables 3 and 4 are same with Table 2 but for the suburban and rural case of Table 1, respectively. Note that RMSD is computed in Tables 2-4 when 4 distribution line segments and 3 branches are assumed for all the three examined indicative OV LV BPL topologies for comparison reasons. RMSD is marked with X and is not computed when at least one of the approximated distribution and branch line lengths is below zero during the NNIM-LLA approximations (i.e., unacceptable approximations for the rest of this paper).

To permit an easier and graphical comparison of TIM-LLA and NNIM-LLA among the three indicative OV LV BPL topologies of Table 1, the RMSD results of Table 2 are presented in Figure 1. More specifically, with reference to the RMSD of the original and symmetrical approximations, TIM-LLA and NNIM-LLA are plotted with respect to the number of hidden layers for the urban case A. The best approximations between the original and symmetrical approximations are shown for TIM-LLA and NNIM-LLA given the number of the hidden layers. For NNIM-LLA, the RMSD values concerning all the 3 executions of NNIM-LLA are separately demonstrated. In Figures 2 and 3, similar curves are given with Figure 1 but for the suburban and rural case with reference to Table 3 and 4, respectively.

Table 2
Distribution and Branch Line Length Approximations of TIM-LLA and NNIM-LLA for the Urban Case A and Default Operation Settings B (the symmetrical approximations are reported in blue font color)

Indicative OV LV BPL Topologies of Table 1		**Urban case A (Typical urban case)**	**RMSD**	**Notes**
Distribution Line Length L = $[L_1 \quad L_2 \quad L_3 \quad L_4]$ **Branch Line Length** $\mathbf{L}_b = [L_{b1} \quad L_{b2} \quad L_{b3}]$		[500m 200m 100m 200m] [8m 13m 10m]	-	-
TIM-LLA **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{TIM-LLA}} = [L_{1,\mathrm{TIM-LLA}} \quad L_{2,\mathrm{TIM-LLA}} \quad L_{3,\mathrm{TIM-LLA}} \quad L_{4,\mathrm{TIM-LLA}}]$ **(Approximated Branch Line Length)** $\mathbf{L}_{\mathrm{b,TIM-LLA}} = [L_{\mathrm{b1,TIM-LLA}} \quad L_{\mathrm{b2,TIM-LLA}} \quad L_{\mathrm{b3,TIM-LLA}}]$		[200m 80m 80m 640m] [80m 0 160m] [640m 80m 80m 200m] [160m 0m 80m]	215.89m 94.55m	Default Operation Settings B
NNIM-LLA **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{NNIM-LLA}} = [L_{1,\mathrm{NNIM-LLA}} \quad L_{2,\mathrm{NNIM-LLA}} \quad L_{3,\mathrm{NNIM-LLA}} \quad L_{4,\mathrm{NNIM-LLA}}]$ **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,NNIM-LLA}} = [L_{\mathrm{b1,NNIM-LLA}} \quad L_{\mathrm{b2,NNIM-LLA}} \quad L_{\mathrm{b3,NNIM-LLA}}]$	1st execution	[115.25m 241.32m 240.29m 403.15m] [149.09m 150.59m 151.83m] [403.14m 240.29m 241.32m 115.25m] [151.83m 150.59m 149.09m]	196.26m 117.79m	Default Operation Settings B + 1 hidden layer
	2nd execution	[57.79m 303.94m 345.78m 292.49m] [158.60m 151.65m 157.30m] [292.49m 345.78m 303.94m 57.79m] [157.30m 151.65m 158.60m]	220.04m 164.63m	
	3nd execution	[115.94m 241.76m 237.44m 404.86m] [149.16m 148.34m 151.15m [404.86m 237.44m 241.76m 115.94m] [151.15m 148.34m 149.16m]	195.77m 116.98m	
	1st execution	[159.16m 206.79m 109.35m 524.70m] [152.25m 166.69m 155.59m] [524.70m 109.35m 206.79m 159.61m] [155.59m 166.69m 152.25m]	202.61m 111.83m	Default Operation Settings B + 2 hidden layers
	2nd execution	[117.63m 36.03m 388.25m 458.10m] [148.52m 151.64m 143.13m] [458.10m 388.25m 36.03m 117.63m] [143.13m 151.64m 148.52m]	232.84m 122.32m	
	3nd execution	[114.03m 254.92m 243.90m 387.73m] [148.62m 149.89m 152.30m] [387.73m 243.90m 254.92m 114.03m] [152.30m 149.89m 148.62m]	195.19m 122.30m	
	1st execution	[1,138.6m -1,148.3m -1,526.4m 2,467.4m] [92.93m 199.43m 33.93m] [2,467.4m -1,526.4m -1,148.3m 1,138.6m] [33.93m 199.43m 92.93m]	X X	Default Operation Settings B + 3 hidden layers
	2nd execution	[226.51m 29.39m 184.02m 559.97m] [131.44m 137.30m 126.66m] [559.97m 184.02m 29.39m 226.51m] [126.66m 137.30m 131.44m]	201.72m 87.68m	
	3nd execution	[1,942.86m -4,384.77m -1,045.92m 4,421.53m] [198.84m 449.87m 80.76m] [4,421.523m -1045.92m -4384.77m 1942.86m]	X X	

		[80.76m 449.87m 198.84m]		
	1st execution	[2,418.6m -3,347.0m -3,311.1m 5,169.2m] [-34.68m 164.43m -245.33m] [5,169.2m -3,311.1m -3,347.0m 2,418.6m] [-245.33m 164.43m -34.68m]	X X	Default Operation Settings B + 4 hidden layers
	2nd execution	[-98.26m 503.72m 473.95m 122.57m] [70.64m 83.27m 45.29m] [122.57m 473.95m 503.72m -98.26m] [45.29m 83.27m 70.64m]	X X	
	3rd execution	[-23.78m 636.36m 85.31m 302.10m] [163.17m 141.32m 148.92m] [302.10m 85.31m 636.36m -23.78m] [148.92m 141.32m 163.17m]	X X	
	1st execution	[2,147.6m -2,267.3m -2,547.8m 3,359.6m] [-572.73m -445.75m -594.49m] [3,359.6m -2,547.8m -2,267.3m 2,147.6m] [-594.49m -445.75m -572.73m]	X X	Default Operation Settings B + 5 hidden layers
	2nd execution	[298.26m -43.39m -95.89m 830.53m] [-407.63m -413.91m -464.40m] [830.53m -95.89m -43.39m 298.26m] [-464.40m -413.91m -407.63m]	X X	
	3rd execution	[575.63m -563.26m -771.69m 1,701.78m] [-123.70m -172.83m -236.46m] [1,701.78m -771.69m -563.26m 575.63m] [-236.46m -172.83m -123.70m]	X X	

Table 3
Distribution and Branch Line Length Approximations of TIM-LLA and NNIM-LLA for the Suburban Case and Default Operation Settings B (the symmetrical approximations are reported in blue font color)

Indicative OV LV BPL Topologies of Table 1		Suburban case	RMSD	Notes
Distribution Line Length L =[L_1 L_2 L_3 0] **Branch Line Length** $\mathbf{L}_b$ =[L_{b1} L_{b2} 0]		[500m 400m 100m 0m] [50m 10m 0m]	-	-
TIM-LLA **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{TIM-LLA}}$ = [$L_{1,\mathrm{TIM-LLA}}$ $L_{2,\mathrm{TIM-LLA}}$ $L_{3,\mathrm{TIM-LLA}}$ 0] **(Approximated Branch Line Length)** $\mathbf{L}_{\mathrm{b,TIM-LLA}}$ = [$L_{\mathrm{b1,TIM-LLA}}$ $L_{\mathrm{b2,TIM-LLA}}$ 0]		[120m 100m 780m 0m] [160m 140m 0m] [780m 100m 120m 0m] [140m 160m 0m]	322.00m 168.78m	Default Operation Settings B
NNIM-LLA **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{NNIM-LLA}}$ = [$L_{1,\mathrm{NNIM-LLA}}$ $L_{2,\mathrm{NNIM-LLA}}$ $L_{3,\mathrm{NNIM-LLA}}$ 0] **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,NNIM-LLA}}$ = [$L_{\mathrm{b1,NNIM-LLA}}$ $L_{\mathrm{b2,NNIM-LLA}}$ 0]	1st execution	[55.07m 711.81m 233.12m 0m] [140.71m 159.39m 0m] [233.12m 711.81m 55.07m 0m] [159.39m 140.71m 0m]	221.51m 168.83m	Default Operation Settings B + 1 hidden layer
	2nd execution	[76.83m 665.77m 257.40m 0m] [144.41m 155.37m 0m] [257.40m 665.77m 76.83m 0m] [155.37m 144.41m 0m]	208.57m 150.81m	
	3rd execution	[49.86m 714.25m 235.89m 0m] [146.61m 163.70m 0m] [235.89m 714.25m 49.86m 0m]	224.50m 170.13m	

		[163.70m 146.61m 0m]		
	1st execution	[203.43m 164.18m 632.36m 0m] [57.94m 68.58m 0m] [632.36m 164.18m 203.43m 0m] [68.58m 57.94m 0m]	247.98m 111.14m	Default Operation Settings B + 2 hidden layers
	2nd execution	[60.75m 734.65m 204.60m 0m] [47.50m 71.93m 0m] [204.60m 734.65m 60.75m 0m] [71.93m 47.50m 0m]	213.71m 170.16m	
	3rd execution	[37.72m 762.84m 199.44m 0m] [134.24m 159.11m 0m] [199.44m 762.84m 37.72m 0m] [159.11m 134.24m 0m]	234.39m 190.19m	
	1st execution	[148.53m 385.22m 466.25m 0m] [0.04m -2.27m 0m] [466.25m 385.22m 148.53m 0m] [-2.27m 0.04m 0m]	X X	Default Operation Settings B + 3 hidden layers
	2nd execution	[843.26m -2,699.02m 2,852.79m 0m] [-334.88m -386.90m 0m] [2,852.79m -2699.02m 843.26m 0m] [-386.90m -334.88m 0m]	X X	
	3rd execution	[-48.50m 963.42m 85.48m 0m] [133.83m 215.75m 0m] [85.48m 963.42m -48.50m 0m] [215.75m 133.83m 0m]	X X	
	1st execution	[1,555.7m -5,874.3m 5,315.6m 0m] [-169.42m -186.57m 0m] [5,315.6m -5,874.3m 1,555.7m 0m] [-186.57m -169.42m 0m]	X X	Default Operation Settings B + 4 hidden layers
	2nd execution	[-840.97m 4,001.01m -2150.27m 0m] [-106.82m 106.07m 0m] [-2,150.27 4,001.01m -840.97m 0m] [106.07m -106.82m 0m]	X X	
	3rd execution	[-2,116.01m 9,237.87m -6,116.30m 0m] [-154.24m -2.59m 0m] [-6,116.30m 9,237.87m -2,116.01m 0m] [-2.59m -154.24m 0m]	X X	
	1st execution	[2,288.5m -8,430.0m 7,135.0m 0m] [565.12m 578.81m 0m] [7,135.0m -8,430.0m 2,288.5m 0m] [578.81m 565.12m 0m]	X X	Default Operation Settings B + 5 hidden layers
	2nd execution	[500.56m -774.33m 1,267.43m 0m] [130.94m 37.00m 0m] [1,267.43m -774.33m 500.56m 0m] [37.09m 130.94m 0m]	X X	

	3rd execution	[1,582.31m -5,718.78m 5,131.67m 0m] [-770.69m -853.92m 0m] [5,131.67m -5,718.78m 1,582.31m 0m] [-853.92m -770.69m 0m]	X X	

Table 4
Distribution and Branch Line Length Approximations of TIM-LLA and NNIM-LLA for the Rural Case and Default Operation Settings B (the symmetrical approximations are reported in blue font color)

Indicative OV LV BPL Topologies of Table 1		**Rural case**	**RMSD**	**Notes**
Distribution Line Length $\mathbf{L}=[L_1 \quad L_2 \quad 0 \quad 0]$ **Branch Line Length** $\mathbf{L}_b=[L_{b1} \quad 0 \quad 0]$		[600m 400m 0m 0m] [300m 0m 0m]	-	-
TIM-LLA **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{TIM-LLA}}=[L_{1,\mathrm{TIM-LLA}} \quad L_{2,\mathrm{TIM-LLA}} \quad 0 \quad 0]$ **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,TIM-LLA}}=[L_{\mathrm{b1,TIM-LLA}} \quad 0 \quad 0]$		[220m 780m 0m 0m] [300m 0m 0m] [780m 220m 0m 0m] [300m 0m 0m]	203.12m 96.21m	Default Operation Settings B
NNIM-LLA **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{NNIM-LLA}}=[L_{1,\mathrm{NNIM-LLA}} \quad L_{2,\mathrm{NNIM-LLA}} \quad 0 \quad 0]$ **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,NNIM-LLA}}=[L_{\mathrm{b1,NNIM-LLA}} \quad 0 \quad 0]$	1st execution	[265.66m 866.04m 0m 0m] [156.07m 0m 0m] [866.04m 265.66m 0m 0m] [156.07m 0m 0m]	223.51m 125.09m	Default Operation Settings B + 1 hidden layer
	2nd execution	[266.67m 733.33m 0m 0m] [233.33m 0m 0m] [733.33m 266.67m 0m 0m] [233.33m 0m 0m]	179.94m 75.59m	
	3rd execution	[264.20m 790.81m 0m 0m] [167.59m 0m 0m] [790.81m 264.20m 0m 0m] [167.59m 0m 0m]	201.08m 101.69m	
	1st execution	[247.53m 772.84m 0m 0m] [215.07m 0m 0m] [772.84m 247.53m 0m 0m] [215.07m 0m 0m]	196.56m 92.84m	Default Operation Settings B + 2 hidden layers
	2nd execution	[154.74m 839.50m 0m 0m] [198.02m 0m 0m] [839.50m 154.74m 0m 0m] [198.02m 0m 0m]	239.59m 135.18m	
	3rd execution	[204.86m 789.55m 0m 0m] [156.79m 0m 0m] [789.55m 204.86m 0m 0m] [156.79m 0m 0m]	216.59m 116.20m	
	1st execution	[216.21m 784.78m 0m 0m] [160.92m 0m 0m] [784.78m 216.21m 0m 0m] [160.92m 0m 0m]	212.03m 111.65m	Default Operation Settings B + 3 hidden layers
	2nd execution	[168.69m 817.75m 0m 0m] [159.63m 0m 0m]	233.07m	

		[817.75m 168.69m 0m 0m] [159.63m 0m 0m]	131.27m	
	3rd execution	[200.262m 799.74m 0m 0m] [300.01m 0m 0m] [799.74m 200.26m 0m 0m] [300.01m 0m 0m]	213.67m 106.76m	
	1st execution	[233.58m 728.75m 0m 0m] [274.36m 0m 0m] [728.75m 233.58m 0m 0m] [274.36m 0m 0m]	186.32m 80.11m	Default Operation Settings B + 4 hidden layers
	2nd execution	[244.33m 781.10m 0m 0m] [162.38m 0m 0m] [781.10m 244.33m 0m 0m] [162.38m 0m 0m]	203.78m 104.18m	
	3rd execution	[100.00m 900.00m 0m 0m] [300m 0m 0m] [900.00m 100.00m 0m 0m] [300.00m 0m 0m]	267.26m 160.36m	
	1st execution	[50m 950m 0m 0m] [300m 0m 0m] [950m 50m 0m 0m] [300m 0m 0m]	293.99m 187.08m	Default Operation Settings B + 5 hidden layers
	2nd execution	[209.52m 817.46m 0m 0m] [291.02m 0m 0m] [817.46m 209.52m 0m 0m] [291.02m 0m 0m]	216.08m 109.32m	
	3rd execution	[220.07m 779.93m 0m 0m] [300.00m 0m 0m] [779.93m 220.07m 0m 0m] [300.00m 0m 0m]	203.08m 96.18m	

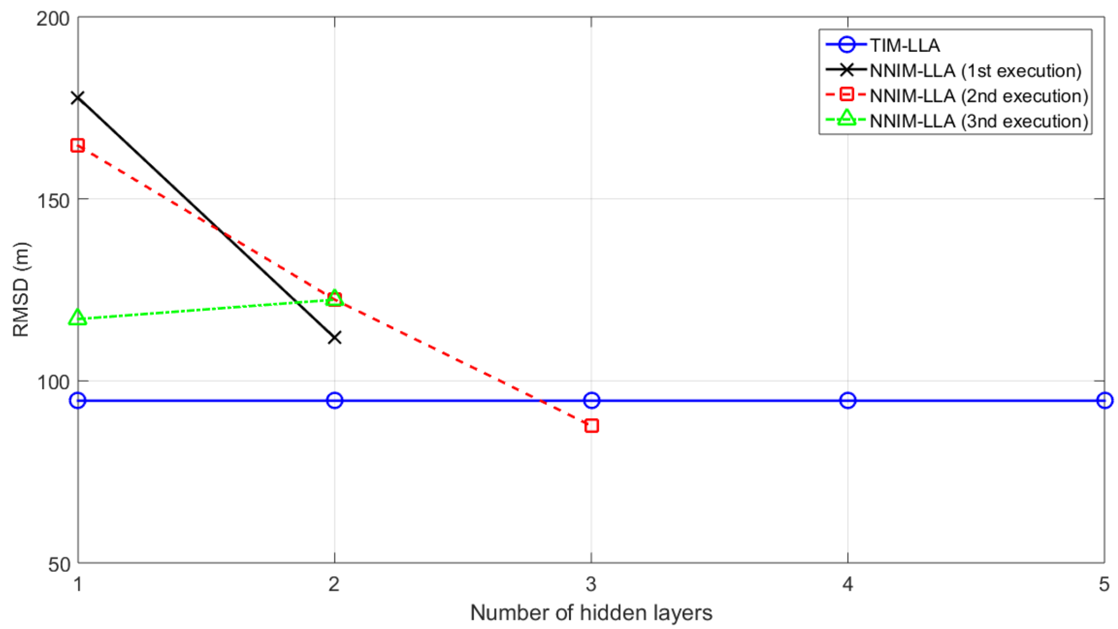

Figure 1. The best approximation RMSD of TIM-LLA and NNIM-LLA for the urban case A for different number of hidden layers when the default operation settings B are assumed.

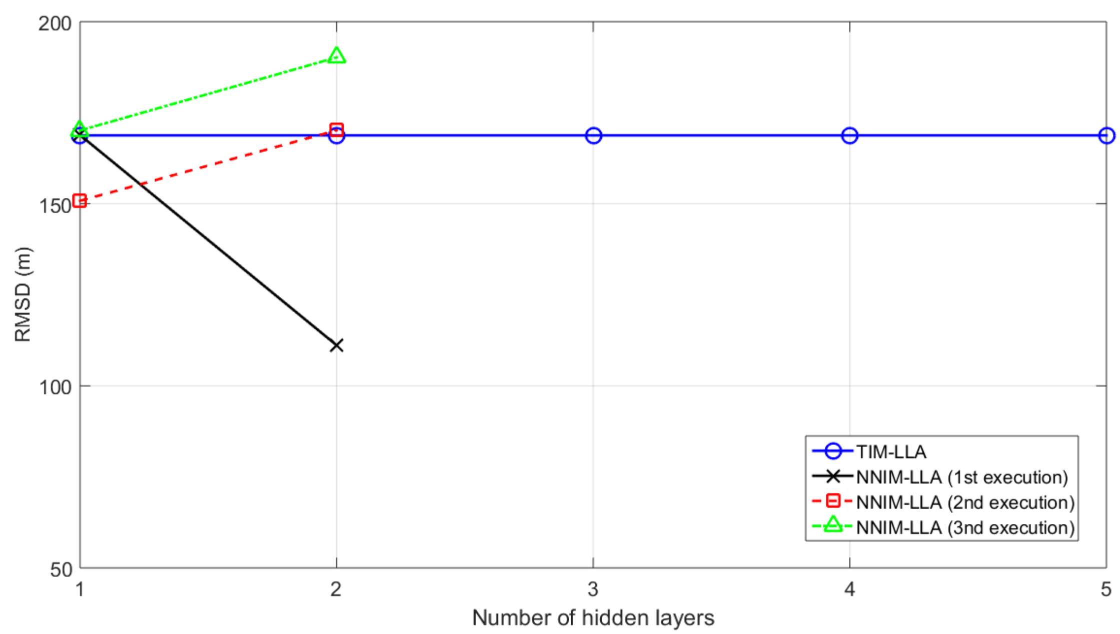

Figure 2. The best approximation RMSD of TIM-LLA and NNIM-LLA for the suburban case for different number of hidden layers when the default operation settings B are assumed.

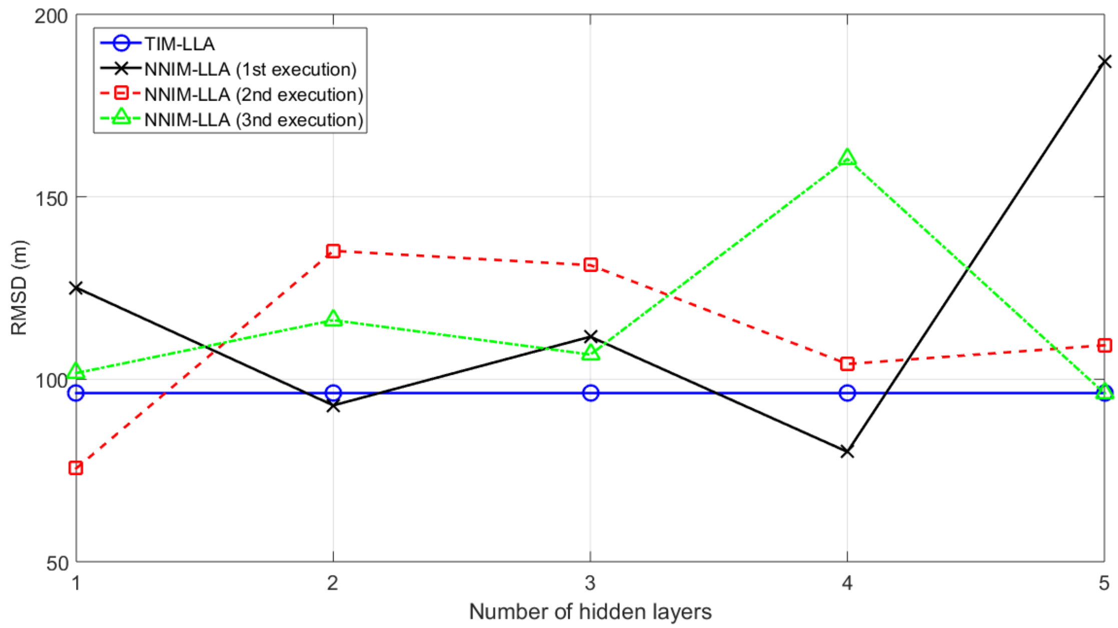

Figure 3. The best approximation RMSD of TIM-LLA and NNIM-LLA for the rural case for different number of hidden layers when the default operation settings B are assumed.

From Tables 2-4 and Figures 1-3, several interesting observations concerning the general approximation performance of TIM-LLA and NNIM-LLA can be discussed during the base scenario where the default settings B are applied, namely:

- With reference to the performance metric of RMSD, TIM-LLA better approximates the distribution and branch line lengths when the number of branches of the examined OV LV BPL topology remains high (*i.e.,* urban case A). For the suburban and rural case, there are at least two executions that the NNIM-LLA approximations present lower RMSDs in comparison with the TIM-LLA approximation, namely: (i) For the suburban case, the TIM-LLA best approximation RMSD is equal to 168.78m whereas the two NNIM-LLA approximations that present the lowest RMSD approximations are equal to 111.14m and 150.81m for 2 hidden layers (1^{st} execution) and 1 hidden layer (2^{nd} execution), respectively; and (ii) For the rural case, the TIM-LLA best approximation RMSD is equal to 96.21m whereas the three NNIM-LLA approximations that present the lowest approximation RMSDs are equal to 75.59m, 80.11m and 92.81m for 1 hidden layer (2^{nd} execution), 4 hidden layers (1^{st} execution) and 2 hidden layers (1^{st} execution), respectively.
- TIM-LLA does not depend on the number of the hidden layers thus presenting a stable approximation behavior in Figures 1-3 for given OV LV BPL topology. In contrast, NNIM-LLA depends on the number of the hidden layers and the execution and it presents fluctuations when different numbers of hidden layers are applied for the different executions. In addition, unacceptable NNIM-LLA approximations may occur when high numbers of hidden layers are assumed; in the urban case A and suburban case, unacceptable approximations occur for numbers of hidden layers that are greater than 3 and 2, respectively. Anyway, as

the number of hidden layers rises, the differences among the executions of the NNIM-LLA approximations become considerable.

- By assuming up to 5 hidden layers and up to 3 executions per hidden layer, stochastic nature of NNIM-LLA is unveiled. In [1], the preparation of the TIM OV LV BPL topology database significantly has affected the branch number approximations of NNIM-BNI when the default operation settings A had been assumed; since the number of OV LV BPL topologies with 3 branches is significantly higher than the number of OV LV BPL topologies with 2 branches that is again significantly higher than the number of OV LV BPL topologies with 1 branch, NNIM-BNI seemed to favor approximations close to 3 branches since greater number of OV LV BPL topologies of 3 branches are initially present in the TIM OV LV BPL topology database due to its preparation process. The representative sets of the TIM OV LV BPL topology database improved the performance of NNIM-BNI. In this paper, the concept of the representative sets of the TIM OV LV BPL topology database of [1] has been adopted by default during the preparation of the default operation settings B; only the OV LV BPL topologies with the same number of branches with the examined one are considered from the TIM OV LV BPL topology database in each approximation of the TIM-LLA and NNIM-LLA. Hence, the preparation of the TIM OV LV BPL topology database with the default operation settings B appears to equally treat with the OV LV BPL topologies in terms of RMSDS and the relative position of the TIM-LLA and NNIM-LLA approximations.
- Although RMSD differences among the different NNIM-LLA executions may occur for given number of hidden layer and examined indicative OV LV BPL topology, these differences remain relatively small when the number of the hidden layers is also low so that only one execution is going to be applied for the following NNIM-LLA simulations, as already done in [1]. Numerically, the greatest RMSD differences between the best approximations of NNIM-LLA executions for given number of hidden layers and indicative OV LV BPL topology are: (i) *Urban case A*: 60.81m and 10.49m for 1 and 2 hidden layers, respectively. Note that there is no difference computation for the case of 3 layers where only one successful approximation occurs; (ii) *Suburban case*: 19.32m and 79.05m for 1 and 2 hidden layers, respectively; and (iii) *Rural case*: 49.50m, 42.32m, 24.51m, 80.25m and 90.90m for 1, 2, 3, 4 and 5 hidden layers, respectively.
- High length spacings of the TIM OV LV BPL topology database imply high RMSD values both in TIM-LLA and NNIM-LLA approximations. Lower length spacings during the preparation of TIM OV LV BPL topology database may allow more accurate approximations regarding the approximated branch lengths and lower RMSDs for both approximations.

After the application of the default operation settings B, TIM-LLA and NNIM-LLA appear almost equivalent approximation performances for the OV LV BPL topologies of 1, 2 and 3 branches. Wanting to further investigate the approximation performance and discover possible improvements of the two methods, TIM-LLA approximations slightly prevail for the OV LV BPL topologies of 3 branches whereas NNIM-LLA approximations are more accurate for the OV LV BPL topologies of 1 and 2 branches. With reference to Sec. 4.3 and 4.4 of [1], the impact of *R* on TIM-LLA performance and the impact of participation percentages on NNIM-LLA performance are examined in Secs. 4.2 and 4.3, respectively, so as to explore any scope for improving the TIM-LLA and NNIM-LLA approximation performances with reference to the base scenario of the default operation settings B.

4.2 The Impact of *R* on TIM-LLA Performance

In accordance with [1], the TIM-BNI branch number approximation $N_{\mathrm{TIM-BNI}}$ has come from the average value of the branch numbers of the *R* OV LV BPL topologies of the TIM OV LV BPL topology database that present the *R* lowest RMSDs among the computed ones. In the default operation settings A, the default value of *R* was equal to 5. In the default operation settings B of this paper, the same default value of *R*=5 is assumed for the TIM-LLA while the procedure for approximating the distribution and branch line lengths remains almost the same; say, for each of the line length approximations, the mean value of the *R* lowest TIM-LLA RMSDs is applied. In Table 5, the distribution and branch line length approximations of TIM-LLA are reported for the urban case A when the default operation settings B are assumed but for six different values of *R* (i.e., 1, 2, 3, 5, 7 and 10). Apart from the distribution and branch line length approximations, the actual distribution and branch line lengths of the urban case A are presented. Also, RMSDs of TIM-LLA approximations for the urban case A are reported when the previous six different values of *R* are applied. Tables 6 and 7 are same with Table 5 but for the suburban and rural case of Table 1, respectively. Similarly to the Tables 2-4, the original approximations are given in black font color whereas the symmetrical approximations of TIM-LLA are given in blue font color in Tables 5-7.

To facilitate the benchmark of TIM-LLA among the three indicative OV LV BPL topologies of Table 1 when different values of *R* are examined, the RMSD results of Tables 5-7 are presented in Figure 4. More analytically, with reference to the RMSD of the original and symmetrical approximations, best TIM-LLA approximations are plotted with respect to the value of *R* for the urban case A, suburban case and rural case. Similarly to Figures 1-3, the best approximation between the original and symmetrical approximations are shown for TIM-LLA given the value of *R*.

Table 5
Distribution and Branch Line Length Approximations of TIM-LLA for the Urban Case A, Default Operation Settings B and Different *R* Values (the symmetrical approximations are reported in blue font color)

Indicative OV LV BPL Topologies of Table 1	***R* Value**	**Urban case A (Typical urban case)**	**RMSD**	**Notes**
Distribution Line Length L =[L_1 L_2 L_3 L_4] **Branch Line Length L**$_b$ =[L_{b1} L_{b2} L_{b3}]		[500m 200m 100m 200m] [8m 13m 10m]	-	-
TIM-LLA **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{TIM-LLA}}$ = [$L_{1,\mathrm{TIM-LLA}}$ $L_{2,\mathrm{TIM-LLA}}$ $L_{3,\mathrm{TIM-LLA}}$ $L_{4,\mathrm{TIM-LLA}}$] **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,TIM-LLA}}$ = [$L_{\mathrm{b1,TIM-LLA}}$ $L_{\mathrm{b2,TIM-LLA}}$ $L_{\mathrm{b3,TIM-LLA}}$]	1	[0m 0m 0m 1000m] [0m 0m 0m] [1,000m 0m 0m 0m] [0m 0m 0m]	366.52m 220.50m	Default Operation Settings B except for *R* value
	2	[200m 50m 50m 700m] [50m 0m 100m] [700m 50m 50m 200m] [100m 0m 50m]	231.47m 103.67m	Default Operation Settings B except for *R* value
	3	[233.33m 66.67m 66.67m 633.33m] [66.67 0m 133.33m] [633.33m 66.67m 66.67m 233.33m] [133.33m 0m 66.67m]	205.84m 90.13m	Default Operation Settings B except for *R* value
	5	[200m 80m 80m 640m] [80m 0 160m] [640m 80m 80m 200m] [160m 0m 80m]	215.89m 94.55m	Default Operation Settings B
	7	[185.71m 58.71m 58.71m 642.86m] [100m 0m 157.14m] [642.86m 85.71m 85.71m 185.71m] [157.14m 0m 100m]	219.89m 95.91m	Default Operation Settings B except for *R* value
	10	[160m 180m 90m 570m] [100m 0m 170m] [570m 90m 180m 160m] [170m 0m 100m]	202.57m 92.21m	Default Operation Settings B except for *R* value

Table 6
Distribution and Branch Line Length Approximations of TIM-LLA for the Suburban Case, Default Operation Settings B and Different *R* Values (the symmetrical approximations are reported in blue font color)

Indicative OV LV BPL Topologies of Table 1	***R* Value**	**Suburban case**	**RMSD**	**Notes**
Distribution Line Length L =[L_1 L_2 L_3 0] **Branch Line Length L**$_b$ =[L_{b1} L_{b2} 0]		[500m 400m 100m 0m] [50m 10m 0m]	-	-
TIM-LLA **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{TIM-LLA}}$ = [$L_{1,\mathrm{TIM-LLA}}$ $L_{2,\mathrm{TIM-LLA}}$ $L_{3,\mathrm{TIM-LLA}}$ 0] **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,TIM-LLA}}$ = [$L_{\mathrm{b1,TIM-LLA}}$ $L_{\mathrm{b2,TIM-LLA}}$ 0]	1	[0m 100m 900m 0m] [100m 200m 0m] [900m 100m 0m] [200m 100m]	381.46m 203.75m	Default Operation Settings B except for *R* value
	2	[0m 100m 900m 0] [150m 150m 0m]	379.77m	Default Operation Settings B except

		[900m 100m 0m 0m] [150m 150m 0m]	203.40m	for R value
	3	[66.67m 100m 833.33m 0m] [166.67m 133.33m 0m] [833.33m 100m 66.67m 0m] [133.33m 166.67m]	347.31m 182.72m	Default Operation Settings B except for R value
	5	[120m 100m 780m 0m] [160m 140m 0m] [780m 100m 120m] [140m 160m 0m]	322.00m 168.78m	Default Operation Settings B
	7	[128.57m 100m 771.43m 0m] [157.14m 142.86m 0m] [771.43m 100m 128.57m 0m] [142.86m 157.14m 0m]	318.01m 166.80m	Default Operation Settings B except for R value
	10	[200m 100m 700m 0m] [150m 150m 0m] [700m 100m 200m 0m] [150m 150m 0m]	282.26m 155.66m	Default Operation Settings B except for R value

Table 7
Distribution and Branch Line Length Approximations of TIM-LLA for the Rural Case, Default Operation Settings B and Different R Values (the symmetrical approximations are reported in blue font color)

Indicative OV LV BPL Topologies of Table 1	R Value	Rural case	RMSD	Notes
Distribution Line Length $\mathbf{L} = [L_1 \quad L_2 \quad 0 \quad 0]$ **Branch Line Length** $\mathbf{L}_b = [L_{b1} \quad 0 \quad 0]$		[600m 400m 0m 0m] [300m 0m 0m]	-	-
TIM-LLA **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{TIM-LLA}} = [L_{1,\mathrm{TIM-LLA}} \quad L_{2,\mathrm{TIM-LLA}} \quad 0 \quad 0]$ **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,TIM-LLA}} = [L_{\mathrm{b1,TIM-LLA}} \quad 0 \quad 0]$	1	[200m 800m 0m 0m] [300m 0m 0m] [800m 200m 0m 0m] [300m]	213.81m 106.90m	Default Operation Settings B except for R value
	2	[150m 850m 0m 0m] [300m 0m 0m] [850m 150m 0m 0m] [300m 0m 0m]	240.54m 133.63m	Default Operation Settings B except for R value
	3	[200m 800m 0m 0m] [300m 0m 0m] [800m 200m 0m 0m] [300m 0m 0m]	213.81m 106.90m	Default Operation Settings B except for R value
	5	[220m 780m 0m 0m] [300m 0m 0m] [780m 220m 0m 0m] [300m 0m 0m]	203.12m 96.21m	Default Operation Settings B
	7	[171.43m 828.57m 0m 0m] [214.29m 0m 0m] [828.57m 171.43m 0m 0m] [214.29m 0m 0m]	231.36m 126.40m	Default Operation Settings B except for R value

	10	[210m 790m 0m 0m] [150m 0m 0m] [790m 210m 0m 0m] [150m 0m 0m]	216.04m 116.31m	Default Operation Settings B except for R value

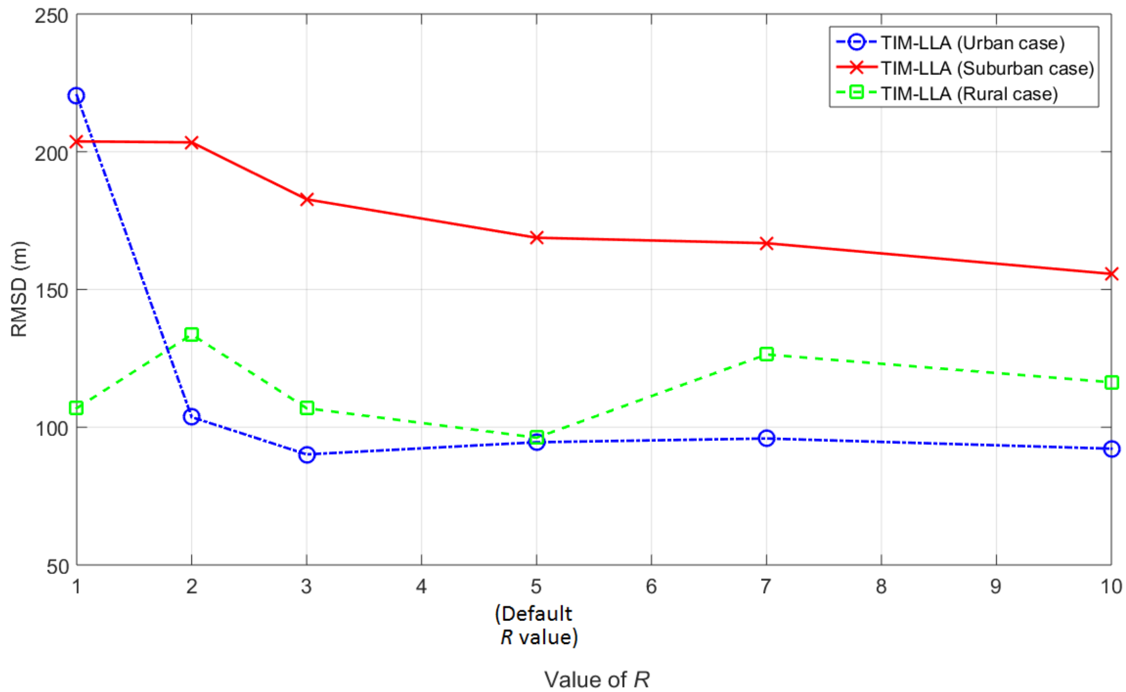

Figure 4. The best approximation RMSD of TIM-LLA for the urban case A, suburban case and rural case for different values of R when the default operation settings B are assumed.

From Tables 5-7 and Figure 4, the following remarks concerning the RMSD dependence on the value of R can be pointed out, namely:

- When R is equal to 1, only one OV LV BPL topology from the TIM OV LV BPL topology database is chosen by the TIM-LLA for approximating each of the examined indicative OV LV BPL topologies. More specifically:
  - When the urban case A is examined, TIM-LLA gives as its best approximation an OV LV BPL topology where its first distribution line length $L_{1,\mathrm{TIM-LLA}}$ is equal to 1000m and the other three ones are equal to 0m. As the approximated branch line lengths of the best TIM-LLA approximation are concerned, these are all equal to 0. Examining the aforementioned best OV LV BPL topology approximation of TIM-LLA, this approximation seems to the LOS case of Table 1. Actually, the short branch line lengths of the urban case A cannot be accurately approximated by TIM-LLA due to the assumed high spacing of branch lengths (i.e., 100m). Hence, the best OV LV BPL topology approximation of TIM-LLA is characterized by the shortest possible branch line lengths that are close to the actual ones anyway inferring their multipath character (i.e., 0m).

Note that the RMSD of this *R* value is the worst one among the RMSDs of all the *R* values.
    - When the suburban and rural cases are examined, the approximated OV LV BPL topologies by the TIM-LLA are characterized by RMSD values that are close to their respective best ones thus offering decent approximations.

  In total, TIM-LLA approximations of *R*=1 value are considered to be decent for the OV LV BPL topologies of lower number of branches (*i.e.*, 1 or 2 branches) whereas they become inaccurate when high number of branches occur (*i.e.,* 3 branches).
- When *R* is greater than 1, mean values among the chosen OV LV BPL topologies occur for the approximated distribution and branch line lengths thus allowing better approximations of the real distribution and branch line lengths. Indeed, the RMSDs of the best and the worst approximations for each of the examined indicative OV LV BPL topologies decrease as the value of *R* increases until the *R* becomes equal to 5 (*i.e.*, default value of the operation settings B). For *R* values that are greater than 5, RMSDs of the TIM-LLA approximations: (i) remain stable for the urban case A; (ii) slowly decrease for the suburban case; and (iii) increase for the rural case.
- Strictly numerically and with reference to Figure 4, the best of the best approximations of TIM-LLA for the three indicative OV LV BPL topologies are: (i) *Urban case A*: when the *R* value is equal to 3, its minimum RMSD of all TIM-LLA approximations is equal to 90.13m; (ii) *Suburban case*: when *R* is equal to 10, its minimum RMSD of all TIM-LLA approximations is equal to 155.66m; and (iii) *Rural case*: when the *R* value is equal to 5, its minimum RMSD of all TIM-LLA approximations is equal to 96.21m.

From the previous analysis, the assumption of the *R* value that is equal to 5 in the operation settings B allows TIM-LLA to decently approximate the distribution and branch line lengths of all the indicative OV LV BPL topologies of Table 1. Anyway, the *R* value of 5 came from the findings of [1] where this *R* value also helped towards satisfactory approximations concerning the number of branches of the indicative OV LV BPL topologies of Table 1. In order to examine whether further performance improvement is feasible for NNIM-LLA beyond the operation settings B, the impact of participation percentages on NNIM-LLA performance is examined in Sec. 4.3.

4.3 The Impact of Participation Percentages on NNIM-LLA Performance

Until now, the *R* value that affects the operation of TIM-LLA has been studied in the case that TIM-LLA performance can further be improved with respect to the performance after applying default operation settings B. In this subsection, the factor that affects the approximation performance of NNIM-LLA is analyzed; say, the participation percentages of the three phases of the NNIM-LLA operation; training, validation and testing phases. In Table 8, the distribution and branch line length approximations of NNIM-LLA are reported for the urban case A when the default operation settings B are assumed but for seven different combinations of the training, validation and testing participation percentages – *i.e.*, (10%, 45%, 45%), (30%, 35%, 35%), (50%, 25%, 25%), (70%, 15%, 15% default), (80%, 10%, 10%), (90%, 5%, 5%) and (98%, 1%, 1%)–. Apart from the distribution and branch line length approximations, the actual distribution and branch line lengths of the urban case A are presented. Also, RMSDs of

NNIM-LLA approximations for the urban case A, when the previous seven combinations of the training, validation and testing participation percentages are applied, are reported. Tables 9 and 10 are same with Table 8 but for the suburban and rural case of Table 1, respectively. Similarly to Tables 2-7, the original approximations are given in black font color whereas the symmetrical approximations of NNIM-LLA are given in blue font color in Tables 8-10.

To visualize the information of Tables 8-10, the RMSD results of Table 8 concerning the different participation percentages of the three phases of NNIM-LLA are presented in Figure 5 when the urban case A is approximated. More specifically, with reference to the RMSD of the original and symmetrical approximations, NNIM-LLA is plotted with respect to the number of hidden layers for the urban case A. The best approximations between the original and symmetrical approximations are shown for NNIM-LLA given the number of the hidden layers and the participation percentages of the three phases. Note that only one execution of NNIM-LLA is here demonstrated for each set of the participation percentages of the three phases. In Figures 6 and 7, similar curves are given with Figure 8 but for the suburban and rural case with reference to Table 9 and 10, respectively.

From Figures 5-7, the significance of the participation percentages of the three phases of NNIM-LLA is highlighted. In contrast with [1] where high participation percentages of the validation and testing phases favored low RMSDs, a more balanced ratio among the participation percentages is here promoted for achieving lower RMSDs. Strictly numerically and with reference to Figures 5-7, the best of the best approximations of NNIM-LLA for the three indicative OV LV BPL topologies are:

- *Urban case A*: when the participation percentages for training, validation and testing are equal to 50%, 25% and 25%, respectively, and 3 hidden layers are assumed, the minimum RMSD of all NNIM-LLA best approximations is equal to 103.31m. Anyway, the best RMSDs of all sets of participation percentages except for (10%, 45%, 45%) and (30%, 35%, 35%) remain very close to the minimum RMSD of 103.31m when hidden layers from 1 to 3 are assumed.
- *Suburban case*: when the participation percentages for training, validation and testing are equal to 80%, 10% and 10%, respectively, and 2 hidden layers are assumed, the minimum RMSD of all NNIM-LLA best approximations is equal to 72.58m. Anyway, the RMSDs of the sets (90%, 5%, 5%), (10%, 45%, 45%) and (98%, 1%, 1%) remain close to the aforementioned minimum one.
- *Rural case*: when the participation percentages for training, validation and testing are equal to 30%, 35% and 35%, respectively, and 4 hidden layers are assumed, the minimum RMSD of all NNIM-LLA best approximations is equal to 68.33m. Anyway, the RMSD of the sets (10%, 45%, 45%), (80%, 10%, 10%), (50%, 25%, 25%) and (70%, 15%, 15%) remain close to the aforementioned minimum one.

Table 8
Distribution and Branch Line Length Approximations of NNIM-LLA for the Urban Case A, Default Operation Settings B and Different Participation Percentage Values and Hidden Layers (the symmetrical approximations are reported in blue font color)

Indicative OV LV BPL Topologies of Table 1	**Participation Percentages for Training, Validation and Testing (%,%,%)**	**Urban case A (Typical urban case)**	**RMSD**	**Notes**
Distribution Line Length L =[L_1 L_2 L_3 L_4] **Branch Line Length** $\mathbf{L_b}$ =[L_{b1} L_{b2} L_{b3}]		[500m 200m 100m 200m] [8m 13m 10m]	-	-
NNIM-LLA **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{NNIM-LLA}}$ = [$L_{1,\mathrm{NNIM-LLA}}$ $L_{2,\mathrm{NNIM-LLA}}$ $L_{3,\mathrm{NNIM-LLA}}$ $L_{4,\mathrm{NNIM-LLA}}$] **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,NNIM-LLA}}$ = [$L_{b1,\mathrm{NNIM-LLA}}$ $L_{b2,\mathrm{NNIM-LLA}}$ $L_{b3,\mathrm{NNIM-LLA}}$]	(10%,45%,45%)	[152.03m 75.72m 395.36m 373.71m] [150.18m 155.66m 163.99m] [373.71m 395.33m 75.72m 152.03m] [163.99m 155.66m 150.18m]	213.21m 131.65m	Default Operation Settings B + 1 hidden layer
	(30%,35%,35%)	[114.06m 230.89m 251.05m 403.99m] [148.62m 150.11m 152.63m] [403.99m 251.05m 230.89m 114.06m] [152.63m 150.11m 148.62m]	197.57m 116.66m	
	(50%,25%,25%)	[104.83m 239.65m 256.25m 398.64m] [146.47m 151.34m 149.72m] [398.64m 256.25m 239.65m 104.83m] [149.72m 151.34m 146.47m]	199.80m 119.43m	
	(70%,15%,15%) Default	[115.25m 241.32m 240.29m 403.14m] [149.09m 150.59m 151.83m] [403.14m 240.29m 241.32m 115.25m] [151.83m 150.59m 149.09m]	196.26m 117.79m	
	(80%,10%,10%)	[109.94m 202.13m 271.94m 415.98m] [149.63m 150.41m 151.07m] [415.98m 271.94m 202.13m 109.94m] [151.07m 150.41m 149.63m]	202.56m 113.15m	
	(90%,5%,5%)	[115.50m 240.79m 239.61m 404.10m] [149.30m 150.40m 152.04m] [404.10m 239.61m 240.79m 115.50m] [152.04m 150.40m 149.30m]	196.28m 117.57m	
	(98%,1%,1%)	[128.16m 74.86m 335.59m 461.38m] [152.87m 154.03m 153.24m] [461.38m 335.59m 74.86m 128.16m] [153.24m 154.03m 152.87m]	220.11m 111.52m	
	(10%,45%,45%)	[81.01m 281.34m 362.84m 269.12m] [123.07m 118.41m 101.52m] [269.12m 362.84m 281.34m 81.01m] [101.52m 118.41m 123.07m]	203.10m 150.95m	Default Operation Settings B + 2 hidden layers
	(30%,35%,35%)	[110.31m 319.60m 77.59m 494.45m] [147.84m 147.20m 158.14m] [494.45m 77.59m 319.60m 110.31m] [158.14m 147.20m 147.84m]	211.42m 136.71m	
	(50%,25%,25%)	[2,638.42m -3,780.68m -5,118.86m 7,205.92m] [-684.51m -723.02m -1,567.15m]	X	

		[7,205.92 -5,118.86m -3,780.68m 2,638.42m] [-1,567.15m -723.02m -684.51m]	X	
	(70%,15%,15%) Default	[159.16m 206.79m 109.35m 524.70m] [152.25m 166.69m 155.59m] [524.70m 109.35m 206.79m 159.16m] [155.59m 166.69m 152.25m]	202.61m 111.83m	
	(80%,10%,10%)	[115.07m 232.10m 267.55m 385.28m] [151.25m 150.15m 152.05m] [385.28m 267.55m 232.10m 115.07m] [152.05m 150.15m 151.25m]	196.80m 120.65m	
	(90%,5%,5%)	[111.40m 237.59m 270.54m 380.47m] [149.35m 150.32m 151.75m] [380.47m 270.54m 237.59m 111.40m] [151.75m 150.32m 149.35m]	197.49m 122.46m	
	(98%,1%,1%)	[122.05m 12.36m 365.42m 500.15m] [151.15m 151.52m 144.57m] [500.15m 365.42m 12.36m 122.05m] [144.57m 151.52m 151.15m]	237.96m 118.85m	
	(10%,45%,45%)	[130.75m 35.15m 384.33m 518.12m] [155.19m 171.88m 166.20m] [518.12m 384.33m -35.15m 130.75m] [166.20m 171.88m 155.19m]	252.13m X	Default Operation Settings B + 3 hidden layers
	(30%,35%,35%)	[48.76m 383.16m 313.44m 254.19m] [135.21m 151.39m 140.66m] [254.19m 313.44m 383.16m 48.76m] [140.66m 151.39m 135.21m]	219.76m 180.78m	
	(50%,25%,25%)	[194.67m 51.72m 85.22m 668.38m] [111.15m 121.44m 102.01m] [668.38m 85.22m 51.72m 194.67m] [102.01m 121.44m 111.15m]	228.56m 103.31m	
	(70%,15%,15%) Default	[1,138.55m -1,148.34m -1,526.45m 2,467.43m] [92.93m 199.43m 33.93m] [2,467.43m -1,526.45m -1,148.34m 1,138.55m] [33.93m 199.43m 92.93m]	X X	
	(80%,10%,10%)	[139.43m 163.65m 265.94m 430.50m] [148.44m 148.81m 150.59m] [430.50m 265.94m 163.65m 139.43m] [150.59m 148.81m 148.44m]	196.37m 103.39m	
	(90%,5%,5%)	[1,758.12m -1,863.26m -2,534.78m 3,494.16m] [-6.63m -66.63m 33.56m] [3,494.16m -2,534.78m -1,863.26m 1,758.12m] [33.56m -66.63m -6.63m]	X X	
	(98%,1%,1%)	[1,691.61m -1,781.63m -2,535.55m 3,422.96m] [134.46m 70.35m 113.19m] [3,422.96m -2,535.55m -1,781.63m 1,691.61m] [113.19m 70.35m 134.46m]	X X	
	(10%,45%,45%)	[59.73m 342.82m 342.04m 279.28m]	224.42m	Default

		[168.37m 175.88m 155.58m] [279.28m 342.04m 342.82m 59.73m] [155.58m 175.88m 168.37m]	 177.65m	Operation Settings B + 4 hidden layers
	(30%,35%,35%)	[767.69m -744.19m -1,099.11m 2,058.23m] [426.92m 57.38m 131.21m] [2,058.23m -1,099.11m -744.19m 767.69m] [131.21m 57.38m 426.92m]	X X	
	(50%,25%,25%)	[1,213.45m -1,805.84m -1,945.48m 3,314.22m] [361.26m 53.03m 161.95m] [3,314.22m -1,945.48m -1,805.84m 1,213.45m] [161.95m 53.03m 361.26m]	X X	
	(70%,15%,15%) Default	[2418.57m -3346.98m -3311.13m 5169.19m] [-34.68m 164.43m -245.33m] [5169.19m -3311.13m -3346.98m 2418.57m] [-245.33m 164.43m -34.68m]	X X	
	(80%,10%,10%)	[1,476.12m -1,638.64m -2,102.72m 3,167.57m] [63.59m 156.05m 44.39m] [3,167.57m -2,102.72m -1,638.64m 1,476.12m] [44.39m 156.05m 63.59m]	X X	
	(90%,5%,5%)	[260.03m 70.47m -37.75m 704.40m] [-5.44m 0.78m 33.33m] [704.40m -37.75m 70.47m 260.03m] [33.33m 0.78m -5.44m]	X X	
	(98%,1%,1%)	[1,220.62m -1,354.31m -1,636.03m 2,742.52m] [-159.19m 2.78m -230.15m] [2,742.52m -1,636.03m -1,354.31m 1,220.62m] [-230.15m 2.78m -159.19m]	X X	
	(10%,45%,45%)	[86.68m 223.46m 285.89m 384.12m] [151.28m 149.58m 146.44m] [384.12m 285.89m 223.46m 86.68m] [146.44m 149.58m 151.28m]	206.20m 123.44m	Default Operation Settings B + 5 hidden layers
	(30%,35%,35%)	[1,329.10m -1,637.87m -2,422.43m 3,527.58m] [-268.04m -189.39m -182.65m] [3,527.58m -2,422.43m -1,637.87m 1,329.10m] [-182.65m -189.39m -268.04m]	X X	
	(50%,25%,25%)	[1,229.08m -1,748.39m -1,926.08m 3,299.86m] [-98.19m -193.91m -161.55m] [3,299.86m -1,926.08m -1,748.39m 1,229.08m] [-161.55m -193.91m -98.19m]	X X	
	(70%,15%,15%) Default	[2,147.65m -2,267.28m -2,547.68m 3,359.61m] [-572.72m -445.75m -594.49m] [3,359.61m -2,547.68m -2,267.28m 2,147.65m] [-594.49m -445.75m -572.72m]	X X	
	(80%,10%,10%)	[924.90m -1,041.43m -1,701.15m 2,614.81m] [6.23m -130.81m -117.23m] [2,614.81m -1,701.15m -1,041.43m 924.90m] [-117.23m -130.81m 6.23m]	X X	
	(90%,5%,5%)	[-2,978.36m 4,909.27m 6,219.73m -7,120.47m] [185.18m -395.09m 1,032.06m]	X	

		[-7,120.47m 6,219.73m 4,909.27m -2,978.36m] [1,032.06m -395.09m 185.18m]	X	
	(98%,1%,1%)	[-0.29m 435.05m 558.04m 11.29m] [164.40m 174.86m 216.50m]	X	
		[11.29m 558.04m 435.05m -0.29m] [216.50m 174.86m 164.40m]	X	

Table 9
Distribution and Branch Line Length Approximations of NNIM-LLA for the Suburban Case, Default Operation Settings B and Different Participation Percentage Values and Hidden Layers (the symmetrical approximations are reported in blue font color)

Indicative OV LV BPL Topologies of Table 1	Participation Percentages for Training, Validation and Testing (%,%,%)	Suburban case	RMSD	Notes
Distribution Line Length L =[L_1 L_2 L_3 0] **Branch Line Length** $\mathbf{L_b}$ =[L_{b1} L_{b2} 0]		[500m 400m 100m 0m] [50m 10m 0m]	-	-
NNIM-LLA **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{NNIM-LLA}}$ = [$L_{1,\mathrm{NNIM-LLA}}$ $L_{2,\mathrm{NNIM-LLA}}$ $L_{3,\mathrm{NNIM-LLA}}$ 0] **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,NNIM-LLA}}$ = [$L_{\mathrm{b1,NNIM-LLA}}$ $L_{\mathrm{b2,NNIM-LLA}}$ 0]	(10%,45%,45%)	[103.36m 699.47m 197.18m 0m] [100.47m 158.92m 0m]	200.42m	Default Operation Settings B + 1 hidden layer
		[197.18m 699.47m 103.36m 0m] [158.92m 100.47m 0m]	169.64m	
	(30%,35%,35%)	[43.07m 755.35m 201.58m 0m] [135.74m 158.83m 0m]	231.42m	
		[201.58m 755.35m 43.07m 0m] [158.83m 135.74m 0m]	187.55m	
	(50%,25%,25%)	[73.90m 691.65m 234.46m 0m] [146.66m 151.93m 0m]	211.86m	
		[234.46m 691.65m 73.90m 0m] [151.93m 146.66m 0m]	162.71m	
	(70%,15%,15%) Default	[55.07m 711.81m 233.12m 0m] [140.71m 159.39m 0m]	221.51m	
		[233.12m 711.81m 55.07m 0m] [159.39m 140.71m 0m]	168.83m	
	(80%,10%,10%)	[59.01m 711.03m 229.97m 0m] [142.19m 162.93m 0m]	220.39m	
		[229.97m 711.03m 59.01m 0m] [162.93m 142.19m 0m]	169.69m	
	(90%,5%,5%)	[146.19m 325.48m 528.55m 0m] [146.03m 156.65m 0m]	222.04m	
		[528.55m 325.48m 146.19m 0m] [156.65m 146.03m 0m]	74.05m	
	(98%,1%,1%)	[-1,347.51m 5,757.91m -3,349.96m 0m] [-79.40m 234.97m 0m]	X	
		[-3349.956m 5,757.91m -1,347.51m 0m] [234.97m -79.40m 0m]	X	
	(10%,45%,45%)	[-208.09m 1537.21m -369.88m 0m]	X	Default

		[-422.42m -344.21m 0m] [-369.88m 1537.21m -208.09m 0m] [-344.21m -422.42m 0m]	 X	Operation Settings B + 2 hidden layers
	(30%,35%,35%)	[-931.03m 4272.94m -2333.96m 0m] [20.68m 265.88m 0m] [-2333.96m 4272.94m -931.03m 0m] [265.88m 20.68m 0m]	X X	
	(50%,25%,25%)	[-49.73m 1,068.10m -18.35m 0m] [33.96m 48.92m 0m] [-18.36m 1,068.10m -49.73m 0m] [48.92m 33.96m 0m]	X X	
	(70%,15%,15%) Default	[203.43m 164.18m 632.36m 0m] [57.94m 68.56m 0m] [632.36m 164.18m 203.43m 0m] [68.58m 57.94m 0m]	247.98m 111.14m	
	(80%,10%,10%)	[141.86m 341.28m 516.86m 0m] [150.07m 158.49m 0m] [516.86m 341.28m 141.86m 0m] [158.49m 150.07m 0m]	219.59m 72.58m	
	(90%,5%,5%)	[230.75m -42.17m 811.37m 0m] [274.11m 296.98m 0m] [811.37m 42.17m 230.75m 0m] [296.98m 274.11m 0m]	359.89m 250.80m	
	(98%,1%,1%)	[103.72m 576.04m 320.23m 0m] [-5.61m -2.81m 0m] [320.23m 576.04m 103.72m 0m] [-2.81m -5.61m 0m]	X X	
	(10%,45%,45%)	[170.90m 236.32m 595.01m 0m] [109.46m 66.63m 0m] [595.01m 236.32m 170.90m 0m] [66.63m 109.46m 0m]	235.09m 85.37m	Default Operation Settings B + 3 hidden layers
	(30%,35%,35%)	[139.00m 418.08m 442.87m 0m] [249.27m 267.46m 0m] [442.87m 418.08m 139.00m 0m] [267.46m 249.27m 0m]	224.94m 125.16m	
	(50%,25%,25%)	[158.62m 351.08m 491.39m 0m] [2.35m -30.28m 0m] [491.39m 351.08m 158.62m 0m] [-30.28m 2.35m 0m]	X X	
	(70%,15%,15%) Default	[148.53m 385.22m 466.25m 0m] [0.04m -2.27m 0m] [466.25m 385.22m 148.53m 0m] [-2.27m 0.04m 0m]	192.92m X	
	(80%,10%,10%)	[56.77m 785.41m 198.24m 0m] [141.69m 166.25m 0m]	235.27m	

		[198.24m 785.41m 56.77m 0m] [166.25m 141.69m 0m]	197.24m	
	(90%,5%,5%)	[-166.96m 1,787.74m -620.55m 0m] [-45.93m -75.84m 0m] [-620.55m 1,787.74m -166.96m 0m] [-75.84m -45.93m 0m]	X X	
	(98%,1%,1%)	[-33.60m 1,048.41m -16.66m 0m] [67.84m 120.55m 0m] [-16.66m 1,048.41m -33.60m 0m] [120.55m 67.84m 0m]	X X	
	(10%,45%,45%)	[143.64m 1,242.46m 953.47m 0m] [409.94m 157.46m 0m] [953.47m 1,242.46m 143.64m 0m] [157.46m 409.94m 0m]	495.18m 394.39m	Default Operation Settings B + 4 hidden layers
	(30%,35%,35%)	[-756.93m 3,263.07m -1,415.99m 0m] [191.40m 102.91m 0m] [-1,415.99m 3,263.07m -756.93m 0m] [102.91m 191.40m 0m]	X X	
	(50%,25%,25%)	[-219.37m 1,876.11m -564.73m 0m] [10.04m 16.53m 0m] [-564.73m 1,876.11m -219.37m 0m] [16.53m 10.04m 0m]	X X	
	(70%,15%,15%) Default	[1,555.73m -5,874.29m 5,315.56m 0m] [-169.42m -186.57m 0m] [5,315.55m 5,874.29m 1,555.73m 0m] [-186.57m -169.42m 0m]	X X	
	(80%,10%,10%)	[116.03m 580.39m 304.44m 0m] [-5.09m -5.56m 0m] [304.44m 580.39m 116.03m 0m] [-5.56m -5.09m 0m]	X X	
	(90%,5%,5%)	[5,533.40m -23,793.42m 19,254.14m 0m] [-1,097.74m -1,112.27m 0m] [19,254.14m -23,793.42m 5,533.40m 0m] [-1,112.27m -1,097.74m 0m]	X X	
	(98%,1%,1%)	[227.72m 381.73m 409.35m 0m] [113.07m 117.73m 0m] [409.35m 381.73m 227.72m 0m] [117.73m 113.07m 0m]	162.90m 75.66m	
	(10%,45%,45%)	[8.37m 220.28m 400.72m 0m] [134.44m 206.89m 0m] [400.72m 220.28m 8.37m 0m] [206.89m 134.44m 0m]	242.11m 113.80m	Default Operation Settings B + 5 hidden layers
	(30%,35%,35%)	[1,126.70m -5,642.68m 5,510.10m 0m] [170.50m -282.24m 0m] [5,510.10m -5,642.68m 1,126.70m 0m] [-282.24m 170.50m 0m]	X X	

	(50%,25%,25%)	[418.23m -581.91m 1,160.68m 0m] [85.18m 26.28m 0m] [1,160.68m -581.91m 418.23m 0m] [26.28m 85.18m 0m]	X X	
	(70%,15%,15%) Default	[2,288.45m 8,429.98m 7,134.97m 0m] [565.12m 578.81m 0m] [7,134.97m -8,429.98m 2,288.45m 0m] [578.81m 565.12m 0m]	X X	
	(80%,10%,10%)	[1,469.42m -6,012.17m 5,547.10m 0m] [138.33m 269.54m 0m] [5,547.10m -6,012.17m 1,469.42m 0m] [269.54m 138.33m 0m]	X X	
	(90%,5%,5%)	[99.39m 1,255.15m -354.41m 0m] [240.46m -91.46m 0m] [-354.41m 1,255.15m 99.39m 0m] [-91.46m 240.46m 0m]	X X	
	(98%,1%,1%)	[-560.38m 2,964.91m -1,265.14m 0m] [134.73m 358.45m 0m] [-1,265.14m 2,964.91m -560.38m 0m] [358.45m 134.73m 0m]	X X	

Table 10
Distribution and Branch Line Length Approximations of NNIM-LLA for the Rural Case, Default Operation Settings B and Different Participation Percentage Values and Hidden Layers (the symmetrical approximations are reported in blue font color)

Indicative OV LV BPL Topologies of Table 1	**Participation Percentages for Training, Validation and Testing (%,%,%)**	**Rural case**	**RMSD**	**Notes**
Distribution Line Length L $=[L_1 \quad L_2 \quad 0 \quad 0]$ **Branch Line Length** $\mathbf{L}_{\mathrm{b}}=[L_{\mathrm{b1}} \quad 0 \quad 0]$		[600m 400m 0m 0m] [300m 0m 0m]	-	-
NNIM-LLA **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{NNIM-LLA}}=[L_{1,\mathrm{NNIM-LLA}} \quad L_{2,\mathrm{NNIM-LLA}} \quad 0 \quad 0]$ **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,NNIM-LLA}}=[L_{\mathrm{b1,NNIM-LLA}} \quad 0 \quad 0]$	(10%,45%,45%)	[311.08m 696.43m 0m 0m] [175.45m 0m 0m] [696.43m 311.08m 0m 0m] [175.45m 0m 0m]	163.38m 68.37m	Default Operation Settings B + 1 hidden layer
	(30%,35%,35%)	[119.77m 904.53m 0m 0m] [44.00m 0m 0m] [904.53m 119.77m 0m 0m] [44.00m 0m 0m]	280.48m 183.92m	
	(50%,25%,25%)	[194.44m 806.07m 0m 0m] [93.66m 0m 0m] [806.07m 194.44m 0m 0m] [93.66m 0m 0m]	230.51m 134.85m	
	(70%,15%,15%) Default	[265.66m 866.04m 0m 0m] [156.07m 0m 0m] [866.04m 265.66m 0m 0m]	223.51m 125.09m	

		[156.07m 0m 0m]		
	(80%,10%,10%)	[257.40m 742.60m 0m 0m] [200.81m 0m 0m] [742.60m 257.40m 0m 0m] [200.81m 0m 0m]	186.92m 84.94m	
	(90%,5%,5%)	[220.80m 824.57m 0m 0m] [170.62m 0m 0m] [824.57m 220.80m 0m 0m] [170.62m 0m 0m]	220.65m 119.09m	
	(98%,1%,1%)	[187.47m 812.53m 0m 0m] [171.92m 0m 0m] [812.53m 187.47m 0m 0m] [171.92m 0m 0m]	225.76m 123.48m	
	(10%,45%,45%)	[248.28m 748.62m 0m 0m] [183.84m 0m 0m] [748.62m 248.28m 0m 0m] [183.84m 0m 0m]	192.26m 91.50m	Default Operation Settings B + 2 hidden layers
	(30%,35%,35%)	[297.78m 899.66m 0m 0m] [81.95m 0m 0m] [899.66m 297.78m 0m 0m] [81.95m 0m 0m]	235.60m 145.30m	
	(50%,25%,25%)	[252.84m 665.95m 0m 0m] [180.89m 0m 0m] [665.95m 252.84m 0m 0m] [180.89m 0m 0m]	171.31m 75.77m	
	(70%,15%,15%) Default	[247.53m 772.84m 0m 0m] [215.07m 0m 0m] [772.84m 247.53m 0m 0m] [215.07m 0m 0m]	196.56m 92.84m	
	(80%,10%,10%)	[255.63m 742.63m 0m 0m] [302.62m 0m 0m] [742.63m 255.63m 0m 0m] [302.62m 0m 0m]	183.61m 76.71m	
	(90%,5%,5%)	[215.75m 795.23m 0m 0m] [266.35m 0m 0m] [795.23m 215.75m 0m 0m] [266.35m 0m 0m]	208.73m 102.26m	
	(98%,1%,1%)	[208.65m 791.35m 0m 0m] [279.41m 0m 0m] [791.35m 208.65m 0m 0m] [279.41m 0m 0m]	209.33m 102.58m	
	(10%,45%,45%)	[250.39m 799.33m 0m 0m] [172.89m 0m 0m] [799.33m 250.39m 0m 0m] [172.89m 0m 0m]	206.28m 105.74m	Default Operation Settings B +

	(30%,35%,35%)	[242.37m 714.46m 0m 0m] [183.29m 0m 0m] [714.46m 242.37m 0m 0m] [183.29m 0m 0m]	185.32m 85.83m	3 hidden layers
	(50%,25%,25%)	[99.70m 900.25m 0m 0m] [299.56m 0m 0m] [900.25m 99.70m 0m 0m] [299.56m 0m 0m]	267.41m 160.50m	
	(70%,15%,15%) Default	[216.21m 784.78m 0m 0m] [160.92m 0m 0m] [784.78m 216.21m 0m 0m] [160.92m 0m 0m]	212.03m 111.65m	
	(80%,10%,10%)	[220m 780m 0m 0m] [300m 0m 0m] [780m 220m 0m 0m] [300m 0m 0m]	203.12m 96.21m	
	(90%,5%,5%)	[218.74m 767.11m 0m 0m] [251.74m 0m 0m] [767.11m 218.74m 0m 0m] [251.74m 0m 0m]	200.88m 94.95m	
	(98%,1%,1%)	[220m 780m 0m 0m] [300m 0m 0m] [780m 220m 0m om] [300m 0m 0m]	203.12m 96.21m	
	(10%,45%,45%)	[81.83m 869.35m 0m 0m] [294.75m 0m 0m] [869.35m 81.83m 0m 0m] [294.75m 0m 0m]	264.26m 157.58m	Default Operation Settings B + 4 hidden layers
	(30%,35%,35%)	[336.45m 745.92m 0m 0m] [214.26m 0m 0m] [745.92m 336.45m 0m 0m] [214.26m 0m 0m]	167.53m 68.33m	
	(50%,25%,25%)	[148.85m 912.52m 0m 0m] [36.01m 0m 0m] [912.52m 148.85m 0m 0m] [36.01m 0m 0m]	276.69m 181.44m	
	(70%,15%,15%) Default	[233.58m 728.75m 0m 0m] [274.36m 0m 0m] [728.75m 233.58m 0m 0m] [274.36m 0m 0m]	186.32m 80.11m	
	(80%,10%,10%)	[186.30m 827.32m 0m 0m] [279.94m 0m 0m] [827.32m 186.30m 0m 0m] [279.94m 0m 0m]	224.93m 118.17m	
	(90%,5%,5%)	[220m 780m 0m 0m] [300m 0m 0m]	203.12m	

		[780m 220m 0m 0m] [300m 0m 0m]	96.21m	
	(98%,1%,1%)	[220m 780m 0m 0m] [300m 0m 0m] [780m 220m 0m om] [300m 0m 0m]	203.12m 96.21m	
	(10%,45%,45%)	[180.87m 632.44m 0m 0m] [88.01m 0m 0m] [632.44m 180.87m 0m 0m] [88.01m 0m 0m]	198.08m 115.89m	Default Operation Settings B + 5 hidden layers
	(30%,35%,35%)	[424.35m 860.32m 0m 0m] [268.28m 0m 0m] [860.32m 424.35m 0m 0m] [268.28m 0m 0m]	186.61m 99.55m	
	(50%,25%,25%)	[199.88m 800.01m 0m 0m] [300.00m 0m 0m] [800.01m 199.89m 0m 0m] [300.00m 0m 0m]	213.84m 106.94m	
	(70%,15%,15%) Default	[50m 950m 0m 0m] [300m 0m 0m] [950m 50m 0m 0m] [300m 0m 0m]	293.99m 187.08m	
	(80%,10%,10%)	[259.42m 753.73m 0m 0m] [285.93m 0m 0m] [753.73 259.42m 0m 0m] [285.93m 0m 0m]	185.67m 78.92m	
	(90%,5%,5%)	[229.20m 935.03m 0m 0m] [260.65m 0m 0m] [935.03m 229.20m 0m 0m] [260.65m 0m 0m]	246.49m 142.91m	
	(98%,1%,1%)	[220m 780m 0m 0m] [300m 0m 0m] [780m 220m 0m om] [300m 0m 0m]	203.12m 96.21m	

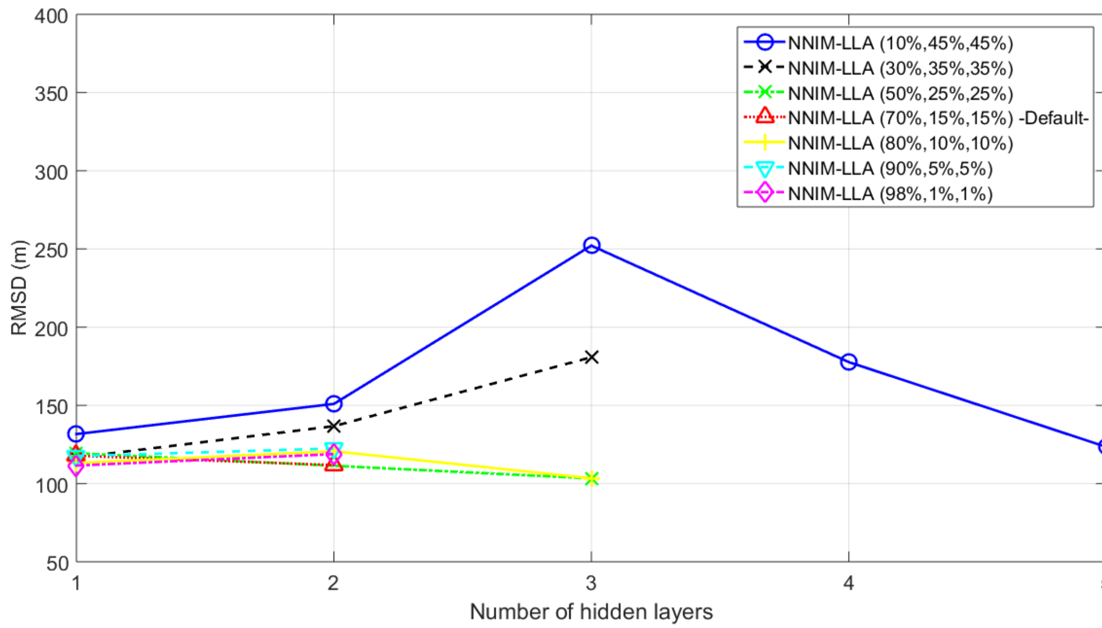

Figure 5. The best approximation RMSDs of NNIM-LLA for the urban case A for different participation percentages of training, validation and testing when the remaining default operation settings B are assumed.

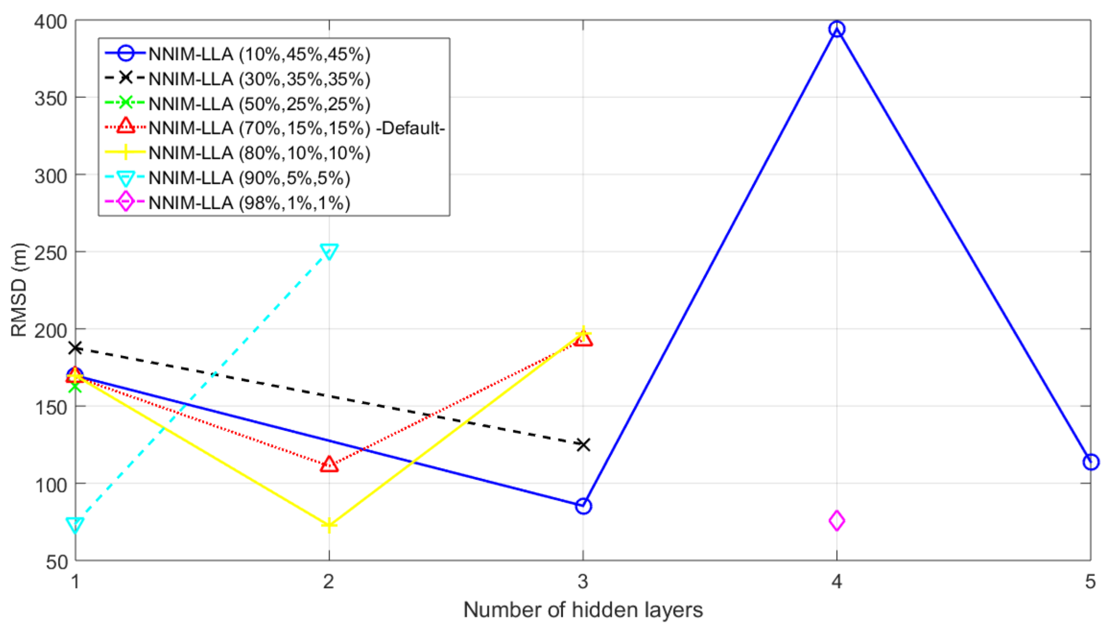

Figure 6. The best approximation RMSDs of NNIM-LLA for the suburban case for different participation percentages for training, validation and testing when the remaining default operation settings B are assumed.

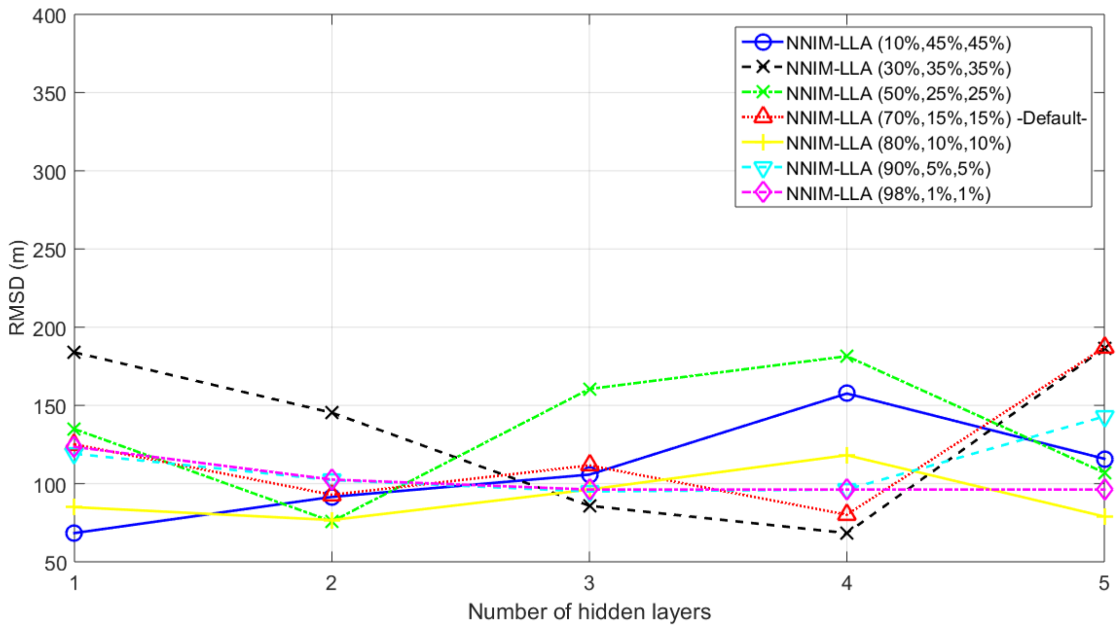

Figure 7. The best approximation RMSDs of NNIM-LLA for the rural case for different participation percentages for training, validation and testing when the remaining default operation settings B are assumed.

For the analysis of the NNIM-LLA approximations when different participation percentages of the three phases are applied, a balanced ratio among the participation percentages is here promoted for achieving lower RMSDs with an emphasis on the training participation percentage. In total, the default set (70%, 15%, 15%) of participation percentages in the operation settings B allows NNIM-LLA to satisfactorily approximate the distribution and branch line lengths of all the indicative OV LV BPL topologies of Table 1. Note that the RMSD of the default set of participation percentages is almost equal to the minimum RMSD in urban case A and rural case whilst the RMSD of the default set of participation percentages remains close to the minimum RMSD in suburban case.

4.4 TIM-LLA and NNIM-LLA Performance during the Default Operation Settings B and Possible Improvements

In this subsection, a briefing of the previous TIM-LLA and NNIM-LLA performance results is attempted so that the overall numerical performance comparison between these two proposed methods may become easy when the default operation settings B are assumed (see Sec. 4.1). In addition, the possible performance improvements, which may occur for the various R values of TIM-LLA presented in Sec. 4.2 and the different participation percentages of the three phases of NNIM-LLA presented in Sec. 4.3, are also presented.

In Table 11, the minimum RMSDs and the corresponding distribution and branch line length approximations of TIM-LLA and NNIM-LLA are reported with reference to Table 2 and Figure 1 for the urban case A when the default operation settings B are assumed. To examine the possible TIM-LLA performance improvement, the minimum RMSD, the difference between the minimum RMSDs of the default operation settings B and of the improvement action, the corresponding distribution and branch line length approximation and the corresponding *R* value of TIM-LLA are also presented in Table 11 with reference to Table 5 and Figure 4 for the various *R* values of TIM-LLA of Sec. 4.2. To examine the possible NNIM-LLA performance improvement, the minimum RMSD, the difference between the minimum RMSDs of the default operation settings B and of the improvement action, the corresponding distribution and branch line length approximation, the corresponding set of participation percentages of the three phases of NNIM-LLA and the corresponding number of hidden layers are also reported in Table 11 with reference to Table 8 and Figure 5 for the various sets of participation percentages and number of hidden layers of NNIM-LLA of Sec. 4.3. Of course, the real distribution and branch line lengths of the urban case A of Table 1 are also provided for comparison reasons. In Tables 12 and 13, same Tables with Table 11 are demonstrated but for the suburban and rural case, respectively.

Some final thoughts and observations can be outlined for the performance of TIM-LLA and NNIM-LLA by observing Tables 11-13:

- The difference values between the minimum RMSDs of the default operation settings B and of the previous improvement actions reveal the nature of TIM-LLA and NNIM-LLA; say:
    - TIM-LLA is a deterministic methodology and for that reason the RMSD differences remain marginal ranging from 0 to -13.12m (or -7.77%). Note that only negative RMSD differences are expected since the TIM OV LV BPL topology database is the operation basis of the deterministic concept of TIM-LLA and only improvement may occur.
    - NNIM-LLA is a stochastic methodology where AI, machine learning and neural networks coexist and for that reason the RMSD differences remain mixed and significant ranging from +15.63m (+17.83%) to -38.56m (-34.69%). Due to the simulation process of NNIM-LLA, positive RMSD differences can be observed and the values of the minimum RMSD depend on the simulation process.

  In general, TIM-LLA is a deterministic methodology with a steady and rather predictable performance behavior whereas NNIM-LLA is a stochastic methodology that may achieve better performances in comparison with the TIM-LLA one but a lot of settings are required to be further investigated prior to the NNIM-LLA operation in each BPL topology (*e.g.*, number of hidden layers, number of executions, participation percentages of its three phases). Similarly to [1], TIM-LLA and NNIM-LLA present advantages and disadvantages concerning their application towards the tomography of the OV LV BPL topologies while their performances can be considered to be comparable.

Table 11
Best Distribution and Branch Line Length Approximations of TIM-LLA and NNIM-LLA for the Urban Case A (Default Operation Settings B and Possible Improvements)

Indicative OV LV BPL Topologies of Table 1	**Urban case A (Typical urban case)**		**RMSD (m) RMSD Difference (m, %)**	**Notes**
Distribution Line Length L =$[L_1 \quad L_2 \quad L_3 \quad L_4]$ **Branch Line Length** $\mathbf{L_b}$ =$[L_{\mathrm{b1}} \quad L_{\mathrm{b2}} \quad L_{\mathrm{b3}}]$	[500m 200m 100m 200m] [8m 13m 10m]		-	-
TIM-LLA (Default) **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{TIM-LLA}}$ = $[L_{1,\mathrm{TIM-LLA}} \quad L_{2,\mathrm{TIM-LLA}} \quad L_{3,\mathrm{TIM-LLA}} \quad L_{4,\mathrm{TIM-LLA}}]$ **(Approximated Branch Line Length)** $\mathbf{L}_{\mathrm{b,TIM-LLA}}$ = $[L_{\mathrm{b1,TIM-LLA}} \quad L_{\mathrm{b2,TIM-LLA}} \quad L_{\mathrm{b3,TIM-LLA}}]$	[640m 80m 80m 200m] [160m 0m 80m]		94.55m	Default Operation Settings B
NNIM-LLA (Default) **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{NNIM-LLA}}$ = $[L_{1,\mathrm{NNIM-LLA}} \quad L_{2,\mathrm{NNIM-LLA}} \quad L_{3,\mathrm{NNIM-LLA}} \quad L_{4,\mathrm{NNIM-LLA}}]$ **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,NNIM-LLA}}$ = $[L_{\mathrm{b1,NNIM-LLA}} \quad L_{\mathrm{b2,NNIM-LLA}} \quad L_{\mathrm{b3,NNIM-LLA}}]$	3 hidden layers	[559.97m 184.02m 29.39m 226.51m] [126.66m 137.30m 131.44m]	87.68m	Default Operation Settings B
TIM-LLA (Improvement Action) **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{TIM-LLA}}$ = $[L_{1,\mathrm{TIM-LLA}} \quad L_{2,\mathrm{TIM-LLA}} \quad L_{3,\mathrm{TIM-LLA}} \quad L_{4,\mathrm{TIM-LLA}}]$ **(Approximated Branch Line Length)** $\mathbf{L}_{\mathrm{b,TIM-LLA}}$ = $[L_{\mathrm{b1,TIM-LLA}} \quad L_{\mathrm{b2,TIM-LLA}} \quad L_{\mathrm{b3,TIM-LLA}}]$	[633.33m 66.67m 66.67m 233.33m] [133.33m 0m 66.67m]		90.13m -4.42m (-4.67%)	R=3 + Default Operation Settings B
NNIM-LLA (Improvement Action) **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{NNIM-LLA}}$ = $[L_{1,\mathrm{NNIM-LLA}} \quad L_{2,\mathrm{NNIM-LLA}} \quad L_{3,\mathrm{NNIM-LLA}} \quad L_{4,\mathrm{NNIM-LLA}}]$ **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,NNIM-LLA}}$ = $[L_{\mathrm{b1,NNIM-LLA}} \quad L_{\mathrm{b2,NNIM-LLA}} \quad L_{\mathrm{b3,NNIM-LLA}}]$	3 hidden layers	[668.38m 85.22m 51.72m 194.67m] [102.01m 121.44m 111.15m]	103.31m +15.63m (+17.83%)	(50%,25%,25%) + Default Operation Settings B

Table 12
Best Distribution and Branch Line Length Approximations of TIM-LLA and NNIM-LLA for the Suburban Case (Default Operation Settings B and Possible Improvements)

Indicative OV LV BPL Topologies of Table 1	**Suburban case**		**RMSD (m) RMSD Difference (m, %)**	**Notes**
Distribution Line Length L =$[L_1 \quad L_2 \quad L_3 \quad 0]$ **Branch Line Length** $\mathbf{L_b}$ =$[L_{\mathrm{b1}} \quad L_{\mathrm{b2}} \quad 0]$	[500m 400m 100m 0m] [50m 10m 0m]		-	-
TIM-LLA (Default) **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{TIM-LLA}}$ = $[L_{1,\mathrm{TIM-LLA}} \quad L_{2,\mathrm{TIM-LLA}} \quad L_{3,\mathrm{TIM-LLA}} \quad 0]$ **(Approximated Branch Line Length)** $\mathbf{L}_{\mathrm{b,TIM-LLA}}$ = $[L_{\mathrm{b1,TIM-LLA}} \quad L_{\mathrm{b2,TIM-LLA}} \quad 0]$	[780m 100m 120m 0m] [140m 160m 0m]		168.78m	Default Operation Settings B
NNIM-LLA (Default) **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{NNIM-LLA}}$ = $[L_{1,\mathrm{NNIM-LLA}} \quad L_{2,\mathrm{NNIM-LLA}} \quad L_{3,\mathrm{NNIM-LLA}} \quad 0]$ **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,NNIM-LLA}}$ =	2 hidden layers	[632.36m 164.18m 203.43m 0m] [68.58m 57.94m 0m]	111.14m	Default Operation Settings B

$[L_{\mathrm{b1,NNIM-LLA}} \quad L_{\mathrm{b2,NNIM-LLA}} \quad 0]$				
TIM-LLA (Improvement Action) **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{TIM-LLA}} =$ $[L_{\mathrm{1,TIM-LLA}} \quad L_{\mathrm{2,TIM-LLA}} \quad L_{\mathrm{3,TIM-LLA}} \quad L_{\mathrm{4,TIM-LLA}}]$ **(Approximated Branch Line Length)** $\mathbf{L}_{\mathrm{b,TIM-LLA}} =$ $[L_{\mathrm{b1,TIM-LLA}} \quad L_{\mathrm{b2,TIM-LLA}} \quad L_{\mathrm{b3,TIM-LLA}}]$	[700m 100m 200m 0m] [150m 150m 0m]		155.66m -13.12m (-7.77%)	R=10 + Default Operation Settings B
NNIM-LLA (Improvement Action) **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{NNIM-LLA}} =$ $[L_{\mathrm{1,NNIM-LLA}} \quad L_{\mathrm{2,NNIM-LLA}} \quad L_{\mathrm{3,NNIM-LLA}} \quad L_{\mathrm{4,NNIM-LLA}}]$ **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,NNIM-LLA}} =$ $[L_{\mathrm{b1,NNIM-LLA}} \quad L_{\mathrm{b2,NNIM-LLA}} \quad L_{\mathrm{b3,NNIM-LLA}}]$	2 hidden layers	[516.86m 341.28m 141.86m 0m] [158.49m 150.07m 0m]	72.58m -38.56m (-34.69%)	(80%,10%,10%) + Default Operation Settings B

Table 13
Best Distribution and Branch Line Length Approximations of TIM-LLA and NNIM-LLA for the Rural Case (Default Operation Settings B and Possible Improvements)

Indicative OV LV BPL Topologies of Table 1	**Rural case**		**RMSD (m)** **RMSD Difference (m, %)**	**Notes**
Distribution Line Length L $=[L_1 \quad L_2 \quad 0 \quad 0]$ **Branch Line Length** $\mathbf{L}_{\mathrm{b}}$ $=[L_{\mathrm{b1}} \quad 0 \quad 0]$	[600m 400m 0m 0m] [300m 0m 0m]		-	-
TIM-LLA (Default) **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{TIM-LLA}} =$ $[L_{\mathrm{1,TIM-LLA}} \quad L_{\mathrm{2,TIM-LLA}} \quad 0 \quad 0]$ **(Approximated Branch Line Length)** $\mathbf{L}_{\mathrm{b,TIM-LLA}} =$ $[L_{\mathrm{b1,TIM-LLA}} \quad 0 \quad 0]$	[780m 220m 0m 0m] [300m 0m 0m]		96.21m	Default Operation Settings B
NNIM-LLA (Default) **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{NNIM-LLA}} =$ $[L_{\mathrm{1,NNIM-LLA}} \quad L_{\mathrm{2,NNIM-LLA}} \quad 0 \quad 0]$ **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,NNIM-LLA}} =$ $[L_{\mathrm{b1,NNIM-LLA}} \quad 0 \quad 0]$	1 hidden layer	[733.33m 266.67m 0m 0m] [233.33m 0m 0m]	75.59m	Default Operation Settings B
TIM-LLA (Improvement Action) **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{TIM-LLA}} =$ $[L_{\mathrm{1,TIM-LLA}} \quad L_{\mathrm{2,TIM-LLA}} \quad L_{\mathrm{3,TIM-LLA}} \quad L_{\mathrm{4,TIM-LLA}}]$ **(Approximated Branch Line Length)** $\mathbf{L}_{\mathrm{b,TIM-LLA}} =$ $[L_{\mathrm{b1,TIM-LLA}} \quad L_{\mathrm{b2,TIM-LLA}} \quad L_{\mathrm{b3,TIM-LLA}}]$	[780m 220m 0m 0m] [300m 0m 0m]		96.21m 0m (0%)	R=5 + Default Operation Settings B
NNIM-LLA (Improvement Action) **Approximated Distribution Line Length** $\mathbf{L}_{\mathrm{NNIM-LLA}} =$ $[L_{\mathrm{1,NNIM-LLA}} \quad L_{\mathrm{2,NNIM-LLA}} \quad L_{\mathrm{3,NNIM-LLA}} \quad L_{\mathrm{4,NNIM-LLA}}]$ **Approximated Branch Line Length** $\mathbf{L}_{\mathrm{b,NNIM-LLA}} =$ $[L_{\mathrm{b1,NNIM-LLA}} \quad L_{\mathrm{b2,NNIM-LLA}} \quad L_{\mathrm{b3,NNIM-LLA}}]$	4 hidden layers	[745.92m 336.45m 0m 0m] [214.26m 0m 0m]	68.33m -7.26m (-9.60%)	(30%,35%,35%) + Default Operation Settings B

- The approximated OV LV BPL topologies by TIM-LLA and NNIM-LLA that have been reported in Tables 11-13 are those between the corresponding original and symmetrical approximated ones that have the best RMSD in each case. In real life, the selection between the original and the symmetrical approximated OV LV BPL topologies by TIM-LLA and NNIM-LLA requires any additional topological pieces of information or empirical observations so that the distinction between these approximated OV LV BPL topologies can be feasible in each case (*e.g.,* any distribution or branch line length information can be useful).
- With reference to [1], the representativeness attribute and the accuracy degree of the TIM OV LV BPL topology database had a significant impact on the performance of TIM-BNI and NNIM-BNI. In this paper, the representative sets of the TIM OV LV BPL topology database have been adopted by default during the preparation of the default operation settings B; say, only the OV LV BPL topologies with the same number of branches with the examined one are considered from the TIM OV LV BPL topology database in each approximation of the TIM-LLA and NNIM-LLA. As the accuracy degree of the TIM OV LV BPL topology database is concerned, the following modifications have been made in default operation settings B in comparison with the default operation settings A, namely:
    - The length spacing for branch distance is equal to 100m and remains the same between the default operation settings A and B. Also, the length between the transmitting and receiving ends of all the OV LV BPL topologies remains the same for the default operation settings A and B and is assumed to be equal to 1000m;
    - To better approximate OV LV BPL topologies of larger branches (*e.g.,* rural case of Table 1), the length spacing for branch length is assumed to be equal to 100m while the branch line length may range from 0m to 300m in default operation settings B. The respective values are equal to 25m and 0m-100m in default operation settings A and B. However, the higher length spacing for branch length has a negative impact on the approximation of the short branches thus creating higher RMSDs.
    - In default operation settings B, the frequency range and the flat-fading subchannel frequency spacing are assumed to be equal to 3-88MHz and 1MHz, respectively. During the preparation of the default operation settings B, more frequencies are used per coupling scheme channel transfer function for the examined OV LV BPL topologies so as to facilitate the operation of TIM-LLA and NNIM-LLA. In fact, the frequency range had been assumed equal to 3-30MHz while the flat-fading subchannel frequency spacing had been equal to 1MHz in operation settings A of [1].

Here, it should be reminded that there is a trade-off relationship between the accuracy degree of the TIM OV LV BPL topology database and the execution time of TIM-LLA and NNIM-LLA. For the previous reason, a compromise between the accuracy and the execution time is made either in this extension paper or in [1] during the preparation of the corresponding default operation settings. In fact, the aforementioned trade-off relationship is stronger in this extension paper since the tomography requirements have been proved to be higher in comparison with the ones during the branch number identification of [1].

Already been mentioned in [1], on the basis of the factors that affect the accuracy degree of the TIM OV LV BPL topology database, the impact of lower values of the length spacing L_s for both branch distance and branch length and of higher values of the maximum branch length $L_{b,max}$ during the preparation of the TIM OV LV BPL topology database on the approximation performance of TIM-LLA and NNIM-LLA is a subject of future research.

5. Conclusions

In this extension paper, the distribution and branch line length approximation methods of TIM-LLA and NNIM-LLA have been proposed as extensions of the respective TIM-BNI and NNIM-BNI of [1] while the factors that affect their approximation performance have been recognized and benchmarked. Learning from the good practices of [1] concerning the factors that affect the preparation of the TIM OV LV BPL topology database, the accuracy degree and the representativeness of the TIM OV LV BPL topology database have been taken into account during the preparation of the default operation settings B of this paper thus having improved RMSD values of the distribution and branch line length approximations of both TIM-LLA and NNIM-LLA by default. As the operation of TIM-LLA is concerned, it has been revealed that TIM-LLA is a deterministic methodology with a steady and rather predictable performance behavior in terms of the appeared RMSD differences. TIM-LLA better approximates the distribution and branch line lengths when the number of branches of the examined OV LV BPL topology remains high (i.e., urban case A). Also, satisfactory TIM-LLA approximations may occur when OV LV BPL topologies of 1 branch are examined (i.e., rural case). Learning from the good practice of [1] concerning the *R* value factor that affects the operation of the TIM OV LV BPL topology database, the assumption of the *R* value that was equal to 5 in the operation settings B has allowed TIM-LLA to decently approximate the distribution and branch line lengths of all the indicative OV LV BPL topologies. As the operation of NNIM-LLA is concerned, it has been revealed that NNIM-LLA is a stochastic methodology that may achieve better performances in comparison with the TIM-LLA one but a lot of settings are required to be investigated prior to the NNIM-LLA operation (i.e., number of hidden layers, number of executions, participation percentages of its three phases). Conversely to [1], a balanced ratio among the NNIM-LLA participation percentages has been highlighted in this extension paper for achieving lower RMSDs with a more emphasis on the training participation percentage. Anyway, mixed RMSD differences of significant range may occur since NNIM-LLA is based on simulations where AI, machine learning and neural networks coexist. Similarly to [1], the accuracy degree of the TIM OV LV BPL topology database again remains critical for the performance of TIM-LLA and NNIM-LLA thus promising significantly lower RMSDs for both approximation methods when higher accuracy degree is going to be adopted in exchange with higher execution times due to the preparation of the TIM OV LV BPL topology database. Especially, the approximation of the branch line length remains a more difficult task and demands significantly higher accuracy degrees in comparison with the approximation of the distribution line lengths and branch number identification. In the future research steps, TIM-LLA and NNIM-LLA are going to be further elaborated, expanded and cooperate in order to cope with the fervent tomography issues of the operation of the smart grid (e.g. fault identification, measurement noise mitigation).

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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