Trends in Renewable Energy
OPEN ACCESS ISSN:2376-2144
Peer-Reviewed Article futureenergysp.com/index.php/tre

Virtual Topologies for Populating Overhead Low-Voltage Broadband over Powerlines Topology Classes by Exploiting Neural Network Topology Generator Methodology (NNTGM) - Part 2: Numerical Results

Athanasios G. Lazaropoulos*

School of Electrical and Computer Engineering / National Technical University of Athens / 9 Iroon Polytechniou Street / Zografou, GR 15780

Received July 23, 2024; Accepted September 1, 2024; Published September 15, 2024

In [1], Neural Network Topology Generator Methodology (NNTGM) has been theoretically proposed, so that its generated overhead low-voltage broadband over power lines topologies (NNTGM OV LV BPL topologies) may populate the existing OV LV BPL topology classes. Apart from the methodology, NNTGM default operation settings and the applied performance metrics, such as the average theoretical channel attenuation (ACA) and the root mean square delay-spread (RMS-DS), have been presented in [1]. In this companion paper, the new OV LV BPL topology class maps, which are defined by the graphical combination of ACA and RMS-DS of the OV LV BPL topologies, are shown. With reference to the graphical combination of ACA and RMS-DS, NNTGM OV LV BPL topology footprints for given indicative OV LV BPL topology are demonstrated on the OV LV BPL topology class maps. The impact on the relative position and the size of the NNTGM OV LV BPL topology footprints is assessed with reference to the following factors that affect the preparation of the Topology Identification Methodology (TIM) OV LV BPL topology database being used during the NNTGM operation, namely: (i) The inclusion or not of the examined indicative OV LV BPL topology; (ii) the length of the distribution / branch line segments; and (iii) the number of the distribution / branch line segments. The performance assessment of NNTGM is supported by suitable Graphical Performance Indicators (GPIs).

Keywords: Smart Grid; Broadband over Power Lines (BPL) networks; Power Line Communications (PLC); Distribution and Transmission Power Grids; Neural Networks; Simulation; Modeling

Introduction

In Broadband over Power Lines (BPL) networks, populating BPL topology classes can become a crucial task for optimizing network performance and reliability. Neural Network Topology Generator Methodology (NNTGM) that has been theoretically proposed in [1] addresses this need by generating overhead low-voltage BPL topologies (NNTGM OV LV BPL topologies) based on the indicative OV LV BPL topologies of the topology classes, thus simulating channel attenuation behavior for NNTGM virtual topologies that maintain the same topological characteristics as the indicative ones.

**Corresponding author:* AGLazaropoulos@gmail.com

Tr Ren Energy, 2024, Vol.10, No.3, 315-334. doi: 10.17737/tre.2024.10.3.00182

Actually, NNTGM, which is the new member of the neural network identification methodology (NNIM) -based family products; say, neural network identification methodology for the branch number identification (NNIM-BNI) [2] and neural network identification methodology for the line length approximation (NNIM-LLA) [3-5], enhances the speed of populating OV LV BPL topology classes, thus facilitating better planning and management of OV LV BPL networks. Exploiting artificial intelligence (AI), machine learning (ML) and neural network (NN) features, the ability of NNTGM to create virtual topologies that imitate the characteristics of real-world topologies may allow communications engineers to predict and mitigate potential issues, leading to more robust and resilient communication systems [6-8]. Therefore, the adoption of NNTGM for populating OV LV BPL topology classes offers a significant advancement in the field of BPL networks, ensuring efficient and reliable network operation.

To examine the statistical and graphical similarity of the NNTGM OV LV BPL topologies with the respective indicative OV LV BPL topologies and to evaluate the procedure of populating of the OV LV BPL topology classes, new class maps have been described in [1] and are going to be implemented in this companion paper. The new class maps exploit the NNTGM performance metrics; say, the average theoretical channel attenuation (ACA) and the root mean square delay-spread (RMS-DS) [9]. With reference to other versions of class maps that have been used in OV LV BPL topologies so far [10]-[13], the OV LV BPL topology class maps, which are based on the graphical ACA / RMS-DS combination, allows the graphical examination of the vicinity of the NNTGM OV LV BPL topologies to their respective indicative OV LV BPL topologies while the group of the NNTGM OV LV BPL topologies defines the NNTGM virtual topology footprint. Then, the impact of the parameters of the NNTGM default operation settings on the relative position and the size of the NNTGM virtual topology footprints are further graphically assessed in this companion paper through the prism of the Graphical Performance Indicators (GPIs); say, the percentage of the NNTGM OV LV BPL topologies that remain inside the OV LV BPL topology class of their respective indicative OV LV BPL topology and the percentage of the NNTGM OV LV BPL topologies that remain inside specific ACA / RMS-DS limits with respect to their indicative OV LV BPL topology. In accordance with [1] and with reference to the class maps and the GPIs, the impact of the following parameters on the NNTGM virtual topology footprints is going to be assessed, namely: (i) The inclusion or not of the examined indicative OV LV BPL topology in the Topology Identification Methodology (TIM) OV LV BPL topology database during the NNTGM operation; (ii) the length of the distribution / branch line segments; and (iii) the number of the distribution / branch line segments.

The rest of this paper is organized as follows: Section 2 presents the new class maps with respect to the indicative OV LV BPL topologies of [1]. Then, the superimposition of NNTGM virtual topology footprints on the class maps and the application of GPIs are analyzed when the NNTGM default operation settings of [1] are adopted. In Section 3, the impact of the aforementioned parameters of the NNTGM default operation settings on the NNTGM virtual topology footprints and GPIs is assessed. Section 4 concludes this paper.

OV LV BPL Topology Class Maps and NNTGM Default Operation Settings

In this Section, the four indicative OV LV BPL topologies that are the representative ones of the four main OV LV BPL topology classes of [1, 10-14] are here adopted. With respect to these OV LV BPL topology classes, the OV LV BPL topology class map, which is based on the graphical ACA / RMS-DS combination, is first presented with reference to the NNTGM default operation settings of [1]. Then, NNTGM virtual OV LV BPL topologies per indicative OV LV BPL topology are graphically grouped into the respective NNTGM virtual topology footprints that are going to be superimposed on the class maps. Finally, GPIs that are going to be applied across the result presentation of this companion paper are reported.

OV LV BPL Topologies and Respective Topology Classes

As already mentioned in [1, 3, 15-19], OV LV BPL networks are divided into cascaded OV LV BPL topologies of typical lengths of 1000 m while a typical OV LV BPL topology is shown in Figure 1 of [1]. In Table 1 of [1], the topological characteristics for the four indicative OV LV BPL topologies of interest –*i.e.*, Line-Of-Sight (LOS) case, rural case, suburban case and urban case A– are reported. The aforementioned four indicative OV LV BPL topologies are the representative ones of the respective OV LV BPL topology classes, which have extensively been used until now [10, 12, 13]. Deterministic Hybrid Model (DHM), which describes the BPL signal propagation and transmission across the OV LV BPL topologies [16, 17, 20-26], is here used for evaluating the theoretical channel attenuation of the four indicative OV LV BPL topologies with reference to the NNTGM default operation settings analyzed in [1]. Then, NNTGM performance metrics of ACA and RMS-DS that are going to be used in class maps are calculated for the four indicative OV LV BPL topologies.

In Figure 1, the OV LV BPL topology class map, which is based on the graphical ACA / RMS-DS combination of the four indicative OV LV BPL topologies, is plotted with reference to ACA and RMS-DS when the NNTGM default operation settings of [1] are applied. From Figure 1, the following observations can be made:

- In accordance with [16, 20, 27, 28], LOS case is characterized by the lowest value of ACA among all the OV LV BPL topologies. Since no spectral notches are observed, low value of RMS-DS is also shown. Anyway, LOS case is a unique OV LV BPL topology and there is no need for supporting an OV LV BPL topology class with NNTGM virtual topologies. In the rest of this companion paper, LOS case is not presented on the class maps and is not populated by NNTGM virtual topologies.
- In accordance with [10, 11, 16, 17, 20], in general terms, as the number of branches of the OV LV BPL topologies increases, their theoretical channel attenuation described by DHM is getting higher thus entailing higher values of ACA. Conversely, as the length of branches of the OV LV BPL topologies decreases, their theoretical channel attenuation described by DHM is getting higher due to the resulting stressed multipath environment thus entailing higher values of RMS-DS. The combination of the aforementioned two general principles of the OV LV BPL topologies explains the ranking and the position of the four indicative OV LV BPL topologies on the class map of Figure 1.

- In order to define the OV LV BPL topology class areas, the class borderlines that spatially demarcate the class areas are roughly derived as the median lines between the neighboring indicative OV LV BPL topologies that anyway define the class areas. Beyond that, around each indicative OV LV BPL topology, the ACA / RMS-DS box of ±10% is here defined and represented with dashed lines around each examined topology in Figure 1, resulting from the variation of ±10% in the values of ACA and RMS-DS of the examined topology.

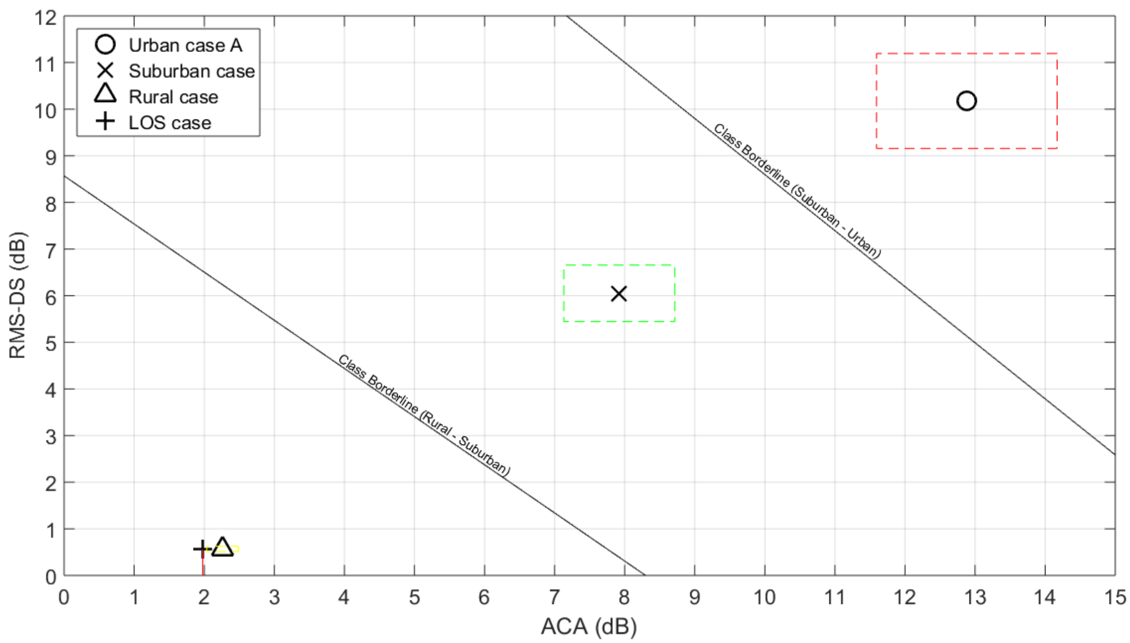

Fig. 1. OV LV BPL topology class map when the NNTGM default operation settings are applied.

OV LV BPL Topology Class Map and NNTGM Virtual Topology Footprints

NNTGM virtual topologies are expected to present similar theoretical channel attenuation behaviors, ACA and RMS-DS with the ones of the respective indicative OV LV BPL topologies but not the same ones. This inherent property of NNTGM virtual topologies securely allows populating of the OV LV BPL topology classes given the indicative OV LV BPL topology in each case. In accordance with the NNTGM default operation settings of [1], 100 NNTGM virtual topologies are assumed to be generated per each indicative OV LV BPL topology thus forming the respective NNTGM virtual topology footprints.

In Figure 2, the OV LV BPL topology class map of Figure 1 enhanced with the NNTGM virtual topology footprints of the rural case, suburban case and urban case A is presented. Observing Figure 2, it is evident that 100 NNTGM virtual topologies are related with each indicative OV LV BPL topology thus defining respective footprints that remain inside the respective class area in all the classes examined. In fact, the majority of the NNTGM virtual topologies remain significantly close to the respective indicative OV LV BPL topologies and inside the ACA / RMS-DS box of ±10% in each case.

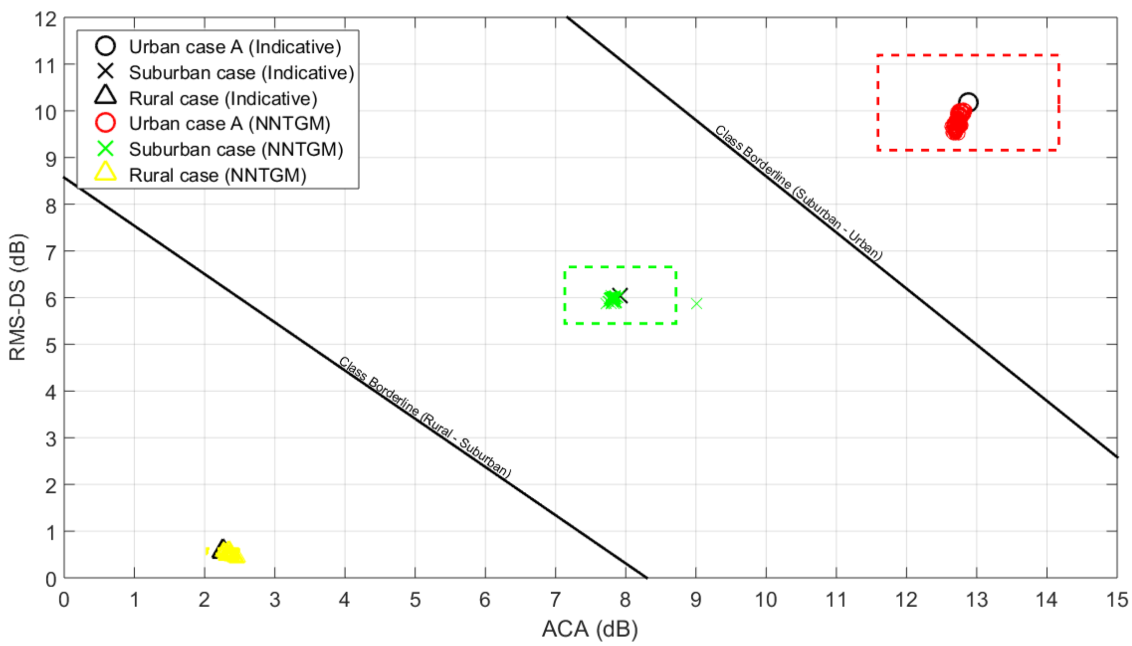

Fig. 2. OV LV BPL topology class map with NNTGM virtual topology footprints of the three indicative OV LV BPL topologies when the NNTGM default operation settings are applied.

On the basis of the aforementioned observations regarding the extent and the relative position of NNTGM virtual topology footprints in Figure 2, two GPIs can be defined in order to evaluate the populating of the OV LV BPL topology classes, namely:

- *Inside the class*: This GPI has to do with the percentage of the NNTGM OV LV BPL topologies that remain inside the OV LV BPL topology class of their respective indicative OV LV BPL topology, and
- *Inside the box*: The percentage of the NNTGM OV LV BPL topologies that remain inside the ACA / RMS-DS box of ±10% with respect to their indicative OV LV BPL topology.

With reference to Figure 2, the aforementioned GPIs are applied to the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes and are reported in Table 1. Indeed, the three NNTGM virtual topology footprints remain tightly near their respective indicative OV LV BPL topologies when the NNTGM default operation settings are assumed. 100% of the NNTGM OV LV BPL topologies remain inside the OV LV BPL topology class regardless of the examined indicative OV LV BPL topologies while the majority of the NNTGM OV LV BPL topologies (*i.e.*, above 84%) remain inside the ACA / RMS-DS box of ±10% of the examined indicative OV LV BPL topologies. From Table 1, it is evident that NNTGM default operation settings may support NNTGM virtual topology footprints of reduced extents with positions that stand close to the indicative OV LV BPL topologies of origin.

The impact of the parameters of the NNTGM default operation settings on the relative position and the size of the NNTGM virtual topology footprints can further be graphically examined and numerically assessed by GPIs so that footprints of custom

Table 1. GPIs of the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes (NNTGM default operation settings are applied)

GPI	OV LV BPL topology class		
	Rural case class	Suburban case class	Urban case A class
Inside the class (%)	100	100	100
Inside the box (%)	84	99	100

relative positions and size can later be produced on demand. In accordance with [1] and with reference to the class maps and the GPIs, the effect of certain parameters of the NNTGM default operation settings of [1] on the NNTGM virtual topology footprints is going to be assessed in the following Section.

The Impact of the Different NNTGM Operation Settings on the NNTGM Virtual Topology Footprints

In this Section, the effect of the following parameters of the NNTGM default operation settings of [1] on the NNTGM virtual topology footprints is going to be investigated, namely: (i) The inclusion or not of the examined indicative OV LV BPL topology in the TIM OV LV BPL topology database during the NNTGM operation; (ii) the length of the distribution / branch line segments; and (iii) the number of the distribution / branch line segments.

Excluding Indicative OV LV BPL Topologies from TIM OV LV BPL Topology Database and Its Impact on NNTGM Virtual Topology Footprints

In accordance with [1], the NNTGM default operation settings assume that the inclusion of the indicative OV LV BPL topology in the TIM OV LV BPL topology database during the operation of NNTGM for given indicative OV LV BPL topology is the default option of the parameter. Indeed, the total number of the OV LV BPL topologies that are added in the TIM OV LV BPL topology database is given in eq. (9) of [1]. The concept for including the indicative OV LV BPL topology in the TIM OV LV BPL topology aims at preserving the representativeness principle of [3] for the TIM OV LV BPL topology database rather than enhancing the richness and the diversity of the applied big data.

In this subsection, the option of excluding the indicative OV LV BPL topology from the TIM OV LV BPL topology database during the operation of NNTGM for given indicative OV LV BPL topology is investigated. Anyway, the theoretical study of the aforementioned exclusion, which is the variant option of the parameter, concerning the total number of the OV LV BPL topologies that are added in the TIM OV LV BPL topology database has been given in eq. (10) of [1]. Here, the preservation of the representativeness of the TIM OV LV BPL topology database is challenged through excluding the indicative OV LV BPL topology from the TIM OV LV BPL topology database while the remaining NNTGM default operation settings of [1], which anyway support NNTGM virtual topology footprints of reduced extents as presented in Section 2.2, remain the same.

In Figure 3, the OV LV BPL topology class map and the NNTGM virtual topology footprints of the rural case, suburban case and urban case A are illustrated when the NNTGM default operation settings are applied but the indicative OV LV BPL topologies are excluded from the TIM OV LV BPL topology database in each examined case. With reference to Figure 3, the GPIs of Section 2.2 are applied to the NNTGM virtual topology footprints of the rural case, suburban case and urban case A and their values are reported in Table 2.

Comparing Figure 3 and Table 2 with Figure 2 and Table 1, respectively, it is evident that the representativeness of the TIM OV LV BPL topology database still occurs even though the indicative OV LV BPL topologies have been excluded from the TIM OV LV BPL topology database. In fact, all the NNTGM virtual topology footprints after the exclusion of the indicative OV LV BPL topologies present almost the same extents, relative positions and GPIs with all the respective NNTGM virtual topology footprints occurring with the inclusion of the indicative OV LV BPL topologies. Anyway, the NNTGM default operation settings allow the TIM OV LV BPL topology database to consist of OV LV BPL topologies presenting similar channel attenuation behavior to the examined indicative OV LV BPL topology in each case. Therefore, the exclusion of the indicative OV LV BPL topology little affects NNTGM virtual topology footprints and corresponding GPIs. Anyway, like the other NNIM-based family products, NNTGM is a stochastic methodology where AI, ML and NN coexist and for that reason small GPI percentage differences are expected even for executions of the same set of NNTGM operation settings. In the following Section, the impacts of the length of the distribution line segments and the number of the distribution line segments on the NNTGM virtual topology footprints are benchmarked.

The Impact of Distribution Line Parameters of the NNTGM Default Operation Settings on NNTGM Virtual Topology Footprints

In accordance with [1], the NNTGM default operation settings assume that the length of the distribution line segments and their number are equal to 1m and 1, respectively. In fact, the length and the number of distribution line segments affect the degree of variation of the amplitude of the coupling scheme channel transfer functions of the OV LV BPL topologies being included in the TIM OV LV BPL topology database that further is going to affect the NNTGM results.

Length of Distribution Line Segments of the NNTGM Default Operation Settings and NNTGM Virtual Topology Footprints

In Figure 4(a), the OV LV BPL topology class map and the NNTGM virtual topology footprints of the rural case, suburban case and urban case A are illustrated when the NNTGM default operation settings are applied but the length of the distribution line segments is equal to 10m. In Figure 4(b), similar plots are given with Figure 4(a) but the length of the distribution line segments is equal to 50m. With reference to Figures 4(a) and 4(b), the GPIs of this companion paper are applied to the NNTGM virtual topology footprints of the rural case, suburban case and urban case A and their values are comparatively reported in Table 3.

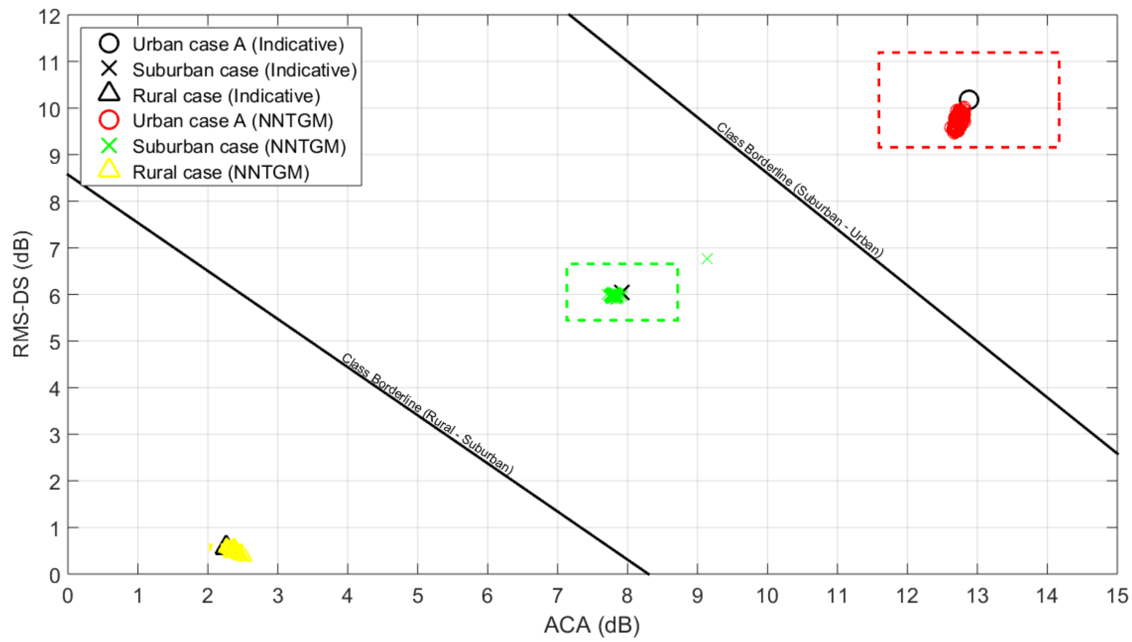

Fig. 3. OV LV BPL topology class map with NNTGM virtual topology footprints of the three indicative OV LV BPL topologies when the NNTGM default operation settings are applied but the indicative OV LV BPL topologies are excluded from the TIM OV LV BPL topology database.

Table 2. GPIs of the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes (NNTGM default operation settings are applied without the indicative OV LV BPL topologies during the preparation of TIM OV LV BPL topology database)

GPI	**OV LV BPL topology class**		
	Rural case class	Suburban case class	Urban case A class
Inside the class (%)	100	100	100
Inside the box (%)	85	99	100

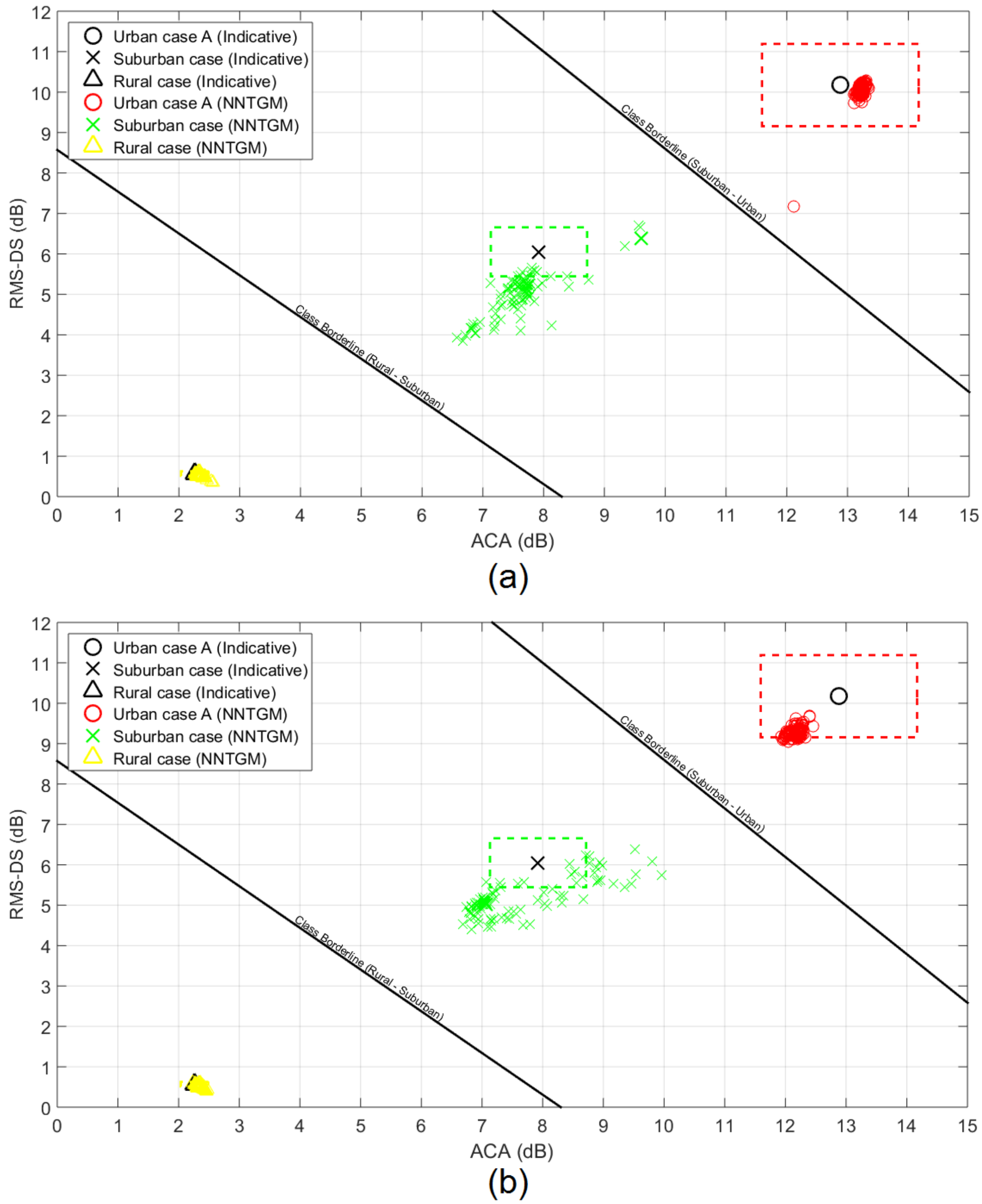

Fig. 4. OV LV BPL topology class map with NNTGM virtual topology footprints of the three indicative OV LV BPL topologies when the NNTGM default operation settings are applied and various lengths of the distribution line segments are considered. (a) 10m, (b) 50m

Table 3. GPIs of the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes (NNTGM default operation settings are applied with various lengths of the distribution line segments)

	OV LV BPL topology class (Distribution line segment length)					
	Rural case class		Suburban case class		Urban case A class	
GPI	(10m)	(50m)	(10m)	(50m)	(10m)	(50m)
Inside the class (%)	100	100	100	100	100	100
Inside the box (%)	75	82	10	9	99	85

Comparing Figures 4(a), 4(b) with Figure 2, it is evident that the change of the distribution line parameter values of the NNTGM default operation settings has a direct impact on the size and the relative position of the NNTGM virtual topology footprints of the examined indicative OV LV BPL topologies. Indeed, as the length of the distribution line segments changes, the NNTGM virtual topology footprints move away from their indicative OV LV BPL topology while their extents get wider thus sparsely populating the respective OV LV BPL topology classes. Although the NNTGM virtual topology footprints cover greater regions of their respective OV LV BPL topology class, they remain strictly within the class boundaries with reference to Table 3.

Comparing "inside the box" GPIs of Tables 3 with the ones of Table 1, it is evident that the length change of the distribution line segments critically affects the position of the NNTGM virtual topology footprints in relation with the ACA / RMS-DS box of ±10% of their respective indicative OV LV BPL topologies. The movement and the wider extents of the NNTGM virtual topology footprints of Figures 4(a) and 4(b) are reflected on lower values of their respective "inside the box" GPIs. More specifically, the "inside the box" GPIs of the NNTGM virtual topology footprints of the suburban case are the most affected ones by the change of the lengths of the distribution line segments since the two branches of the indicative suburban case allow NNTGM to enrich the respective TIM OV LV BPL topology database with OV LV BPL topologies that vary regarding their channel attenuation behavior as well as their multipath environment due to the branch movement. In a similar way, the change of the lengths of the distribution line segments has a less severe effect on the "inside the box" GPIs of the NNTGM virtual topology footprints of the rural case, since the one electrically long branch of the indicative rural case does not allow NNTGM to significantly enhance the diversity of the respective TIM OV LV BPL topology database. In contrast, the different versions of the anyway heavy multipath environment of the indicative urban case A that come from the length increase of the distribution line segments and are included in the TIM OV LV BPL topology database has a small effect on the "inside the box" GPIs of the NNTGM virtual topology footprints of the urban case A.

From the perspective of sparse populating of classes, the increase of the length of the distribution line segments mainly supports sparse NNTGM virtual topology footprints for the suburban class. In the following subsections, apart from the length, the impact of the number of distribution line segments of the NNTGM default operation settings that is expected to focus in a similar way to this subsection on the diversity and the high number of OV LV BPL topologies in the TIM OV LV BPL topology database is investigated.

Number of Distribution Line Segments of the NNTGM Default Operation Settings and NNTGM Virtual Topology Footprints

In Figure 5, the OV LV BPL topology class map and the NNTGM virtual topology footprints of the rural case, suburban case and urban case A are illustrated when the NNTGM default operation settings are applied but the number of the distribution line segments is equal to 2. With reference to Figure 5, the GPIs of this companion paper are applied to the NNTGM virtual topology footprints of the rural case, suburban case and urban case A and their values are reported in Table 4.

Comparing Figure 5 with Figures 4(a) and 4(b), it is evident that the number increase of the distribution line segments of the NNTGM default operation settings presents similar results with the length increase of the distribution line segments on the size and the relative position of the NNTGM virtual topology footprints of the examined indicative OV LV BPL topologies but in a more drastic way for the suburban case. As the position of the NNTGM virtual topology footprints is concerned, even if the default length of the distribution line segments, which is assumed to be equal to 1m, is assumed, the number increase of the distribution line segments achieves to move almost the entire NNTGM virtual topology footprint of the suburban case outside the ACA / RMS-DS box of ±10% of the indicative suburban case. Conversely, the NNTGM virtual topology footprints of the rural case and the urban case A remain inside the ACA / RMS-DS boxes of ±10% of the respective indicative OV LV BPL topologies. Anyway, all the NNTGM virtual topology footprints remain inside the classes of the respective indicative OV LV BPL topologies. In comparison with Figure 2, the NNTGM virtual topology footprints of Figure 5 present comparable relative positions and extents with the ones of Figure 2 except for the NNTGM virtual topology footprint of the suburban case that is significantly dislocated with larger extent due to the fact that OV LV BPL topologies of lengths of distribution line segments that are equal to 2 x 1m = 2m are also included in the TIM OV LV BPL topology database in accordance with eq. (5) of [1]. In comparison with Figures 4(a) and (b), the extent of the NNTGM virtual topology footprints of Figure 5 is significantly reduced than the ones of OV LV BPL topologies with the increased lengths of the distribution line segments of the NNTGM default operation settings.

Synoptically, the impact of the changes of the lengths and the number of distribution line segments of the NNTGM default operation settings on the NNTGM virtual topology footprints of the examined indicative OV LV BPL topologies present similarities concerning their position, their extent and the affected indicative OV LV BPL topologies. In accordance with GPIs, the most affected NNTGM virtual topology footprint from the distribution line segment parameter changes of the NNTGM default operation settings is the one of the suburban case as well as the one of the rural case but in lower intensity. The changes of the distribution line segment parameters of the NNTGM default operation settings little affect the NNTGM virtual topology footprints of the urban case A. In the following subsection, the impacts of the length and the number of the branch line segments on the NNTGM virtual topology footprints are examined.

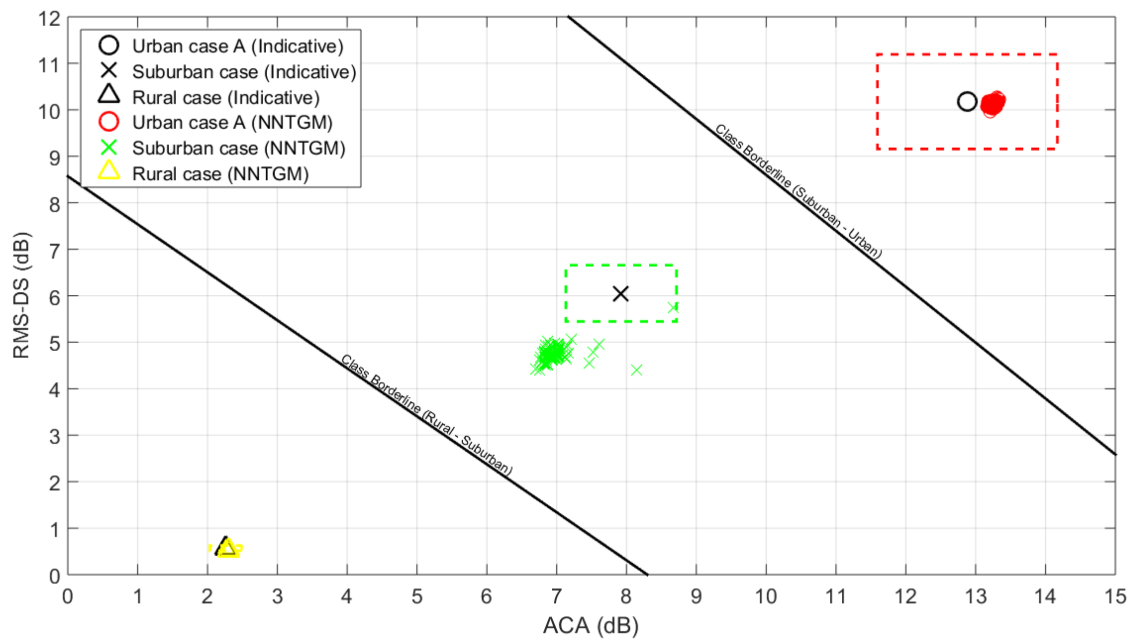

Fig. 5. OV LV BPL topology class map with NNTGM virtual topology footprints of the three indicative OV LV BPL topologies when the NNTGM default operation settings are applied and 2 distribution line segments are considered.

Table 4. GPIs of the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes (NNTGM default operation settings are applied when 2 distribution line segments are assumed)

GPI	OV LV BPL topology class		
	Rural case class	Suburban case class	Urban case A class
Inside the class(%)	100	100	100
Inside the box (%)	100	1	100

The Impact of Branch Line Parameters of the NNTGM Default Operation Settings on NNTGM Virtual Topology Footprints

In accordance with [1], the NNTGM default operation settings assume that the length of the branch line segments and their number are equal to 1m and 1, respectively. In fact, the length and the number of branch line segments affect the number and the depth of the notches of the amplitude of the coupling scheme channel transfer functions of the OV LV BPL topologies being included in the TIM OV LV BPL topology database that further are going to affect the corresponding NNTGM results.

Length of Branch Line Segments of the NNTGM Default Operation Settings and NNTGM Virtual Topology Footprints

In Figure 6(a), the OV LV BPL topology class map and the NNTGM virtual topology footprints of the rural case, suburban case and urban case A are plotted when the NNTGM default operation settings are applied but the length of the branch line segments is equal to 4m. In Figure 6(b), similar plots are given with Figure 6(a) but the length of the branch line segments is equal to 8m. With reference to Figures 6(a) and 6(b), the GPIs of this companion paper are applied to the NNTGM virtual topology footprints of the rural case, suburban case and urban case A and their values are comparatively reported in Table 5.

Comparing Figures 6(a) and 6(b) with Figures 4(a) and 4(b), it is clear that the length change of the branch line segments of the NNTGM default operation settings has an opposite effect on the NNTGM virtual topology footprints of the examined indicative OV LV BPL topologies in relation with the impact of length increase of the distribution line segments. In fact, the length increase of the branch line segments primarily affects the NNTGM virtual topology footprints of the rural case and urban case A. The number and the lengths of the branches determine the number and the depth of the spectral notches across the coupling scheme channel transfer functions of the OV LV BPL topologies being included in the TIM OV LV BPL topology database; say, the intensity of the multipath environment of the OV LV BPL topologies. As the length of the branch line segments changes, the NNTGM virtual topology footprints spread rapidly away from the respective indicative OV LV BPL topologies with wide extents thus sparsely populating the respective OV LV BPL topology classes. In the case of the length increase of the branch line segments of this subsection, the NNTGM virtual topology footprints of rural case and urban case A cover great regions that are beyond their respective OV LV BPL topology class borderlines in many times.

Comparing GPIs of Tables 5 and 3, the opposite effect of the length increase of the branch line segments on the NNTGM virtual topology footprints of the examined indicative OV LV BPL topologies with respect to the length increase of the distribution line segments is quantitatively verified. As the “inside the class” lines of Table 5 are concerned, the “inside the class” GPIs of the NNTGM virtual topology footprints of the rural case are the only affected ones by the change of the length of the branch line segments. As the “inside the box” lines of Table 5 are regarded, the “inside the box” GPIs of the NNTGM virtual topology footprints of primarily the urban case A and of secondarily the rural case are the most affected. In the aforementioned cases, NNTGM enriches the respective TIM OV LV BPL topology database with OV LV BPL topologies that vary regarding their channel attenuation behavior in terms of the number and the depth of notches. In fact, the “inside the box” GPI deterioration for the NNTGM virtual topology footprints of the urban case A is greater when the length of the branch line segments is equal to 4m rather than 8m.

From the perspective of sparsely populating the OV LV BPL topology classes, the increase of the length of the branch line segments mainly supports sparse NNTGM virtual topology footprints for the rural and urban classes. Here, it should be highlighted the complementary NNTGM operation of the change of the length of the branch line segments of this subsection to the one of the change of the length of the distribution line segments, which has been presented in Section 3.2.1. Except for the increase of the length of the branch line segments, the impact of the number of branch line segments of the NNTGM default operation settings on the NNTGM virtual topology footprints is investigated in the following subsection.

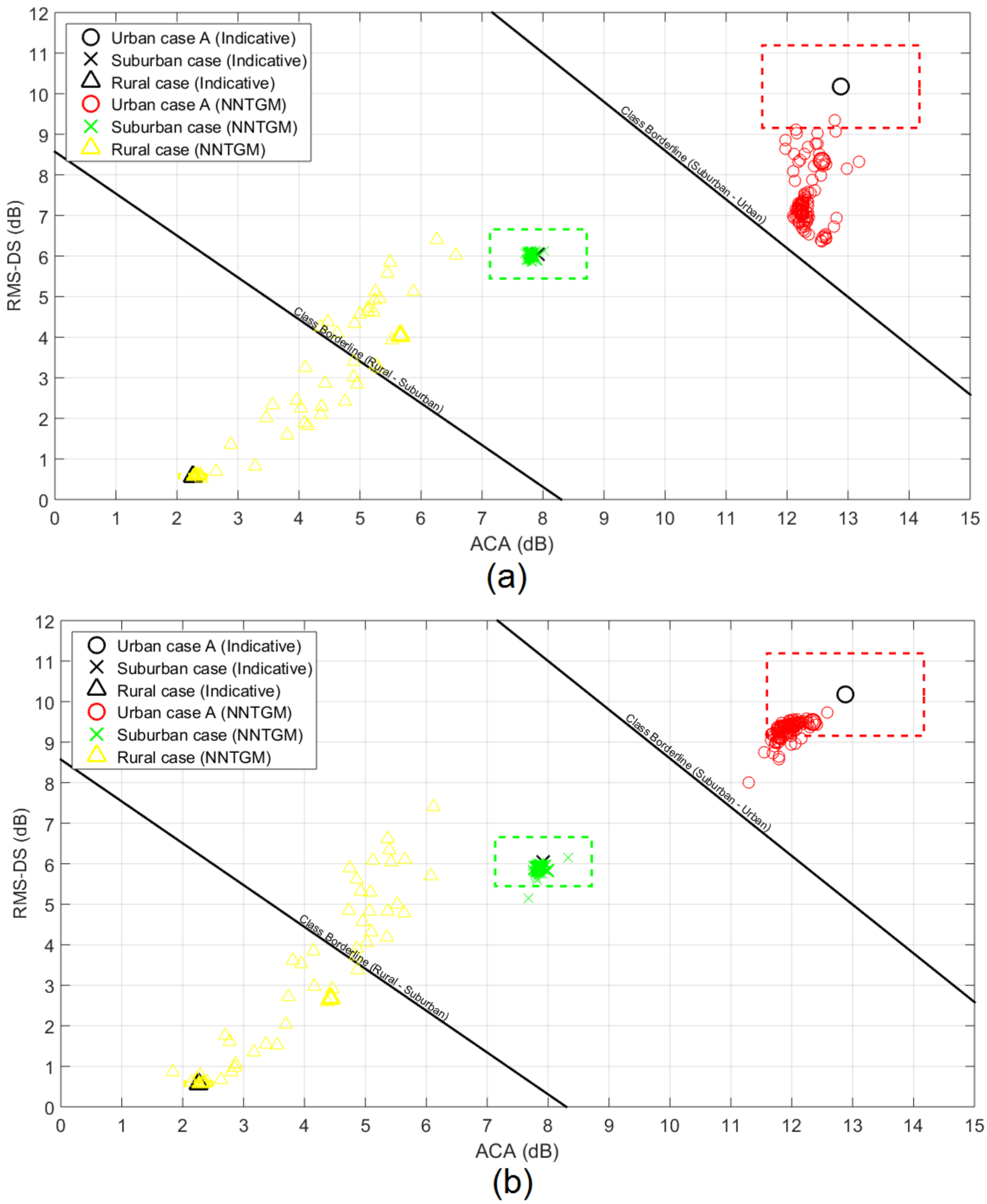

Fig. 6. OV LV BPL topology class map with NNTGM virtual topology footprints of the three indicative OV LV BPL topologies when the NNTGM default operation settings are applied and various lengths of the branch line segments are considered. (a) 4m. (b) 8m.

Table 5. GPIs of the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes (NNTGM default operation settings are applied with various lengths of the branch line segments)

GPI	**OV LV BPL topology class (Branch line segment length)**					
	Rural case class		Suburban case class		Urban case A class	
	(4m)	(8m)	(4m)	(8m)	(4m)	(8m)
Inside the class (%)	80	78	100	100	100	100
Inside the box (%)	61	56	100	99	1	78

Number of Branch Line Segments of the NNTGM Default Operation Settings and NNTGM Virtual Topology Footprints

In Figure 7, the OV LV BPL topology class map and the NNTGM virtual topology footprints of the rural case, suburban case and urban case A are drawn when the NNTGM default operation settings are applied but the number of the branch line segments is equal to 2. With reference to Figure 7, the GPIs of this companion paper are applied to the NNTGM virtual topology footprints of the rural case, suburban case and urban case A and their values are reported in Table 6.

Comparing Figure 7 with Figures 6(a) and 6(b), it is obvious that the number increase of the branch line segments of the NNTGM default operation settings intensifies the NNTGM virtual topology footprint behavior that has been analyzed in the previous subsection where the length increase of the branch line segments has been studied. Indeed, the NNTGM virtual topology footprints of rural case and urban case A still spread away from the respective indicative OV LV BPL topologies demonstrating wide extents. GPIs of Table 6 indicate that the NNTGM virtual topology footprints of rural case and urban case A sparsely populate the respective OV LV BPL topology classes with “inside the class” GPIs that are equal to 93% and 29%, respectively, when the respective “inside the class” GPIs of Table 5 for the scenario of the length increase of the branch line segments were 78%-80% and 100%. But the real critical effect of the number increase of the branch line segments occurs when the “inside the box” GPIs of Table 6 are discussed. The vast majority of the NNTGM OV LV BPL topologies of the NNTGM virtual topology footprints of rural case and urban case A lie outside the ACA / RMS-DS boxes of ±10% of the respective indicative OV LV BPL topologies while the NNTGM virtual topology footprint of suburban case starts to go away from the ACA / RMS-DS boxes of ±10% of the indicative suburban case not being observed so far in the scenarios of the length increase of the branch line segments of Figures 6(a) and 6(b). In contrast with the impact of the distribution line parameters on NNTGM virtual topology footprints of Section 3.2, the extent of the NNTGM virtual topology footprints is significantly increased when higher numbers of branch line segments are assumed than the ones of OV LV BPL topologies with increased lengths of the branch line segments. In total, the impact of the changes of the lengths and of the number of branch line segments of the NNTGM default operation

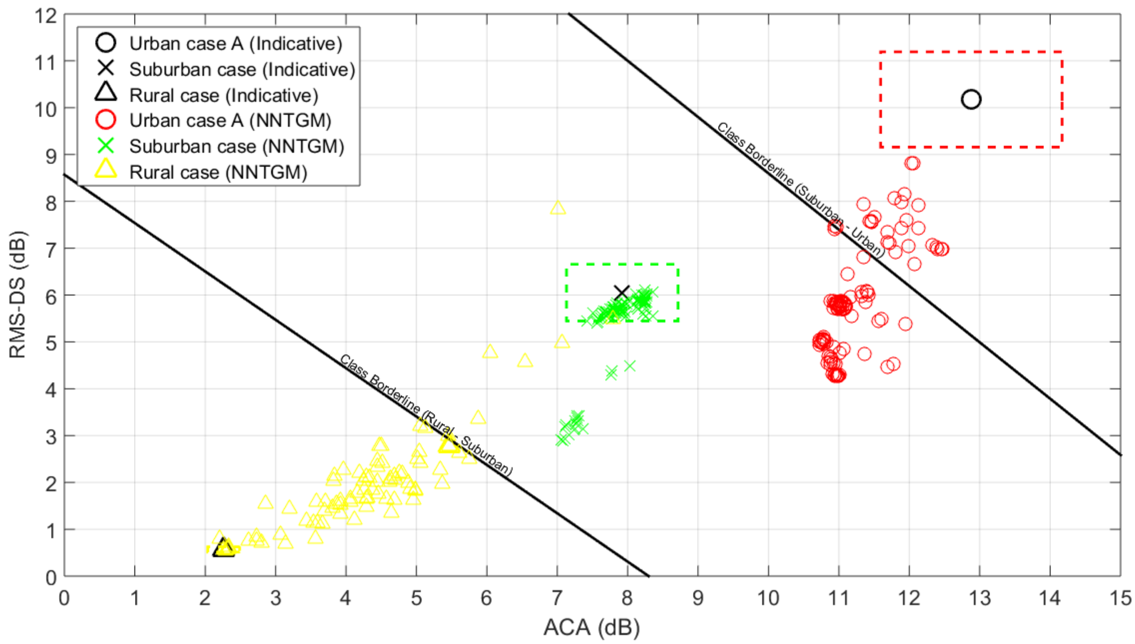

Fig. 7. OV LV BPL topology class map with NNTGM virtual topology footprints of the three indicative OV LV BPL topologies when the NNTGM default operation settings are applied and 2 branch line segments are considered.

Table 6. GPIs of the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes (NNTGM default operation settings are applied when 2 branch line segments are assumed)

GPI	OV LV BPL topology class		
	Rural case class	Suburban case class	Urban case A class
Inside the class (%)	93	100	29
Inside the box (%)	23	79	0

settings on the NNTGM virtual topology footprints of the examined indicative OV LV BPL topologies present similarities concerning their position, their extent and the affected indicative OV LV BPL topologies but differences with the impact of the changes of the lengths and the number of distribution line segments of the NNTGM default operation settings. In accordance with GPIs, the most affected NNTGM virtual topology footprints from the branch line segment parameter changes of the NNTGM default operation settings are the ones of the urban case A and the rural case but also the NNTGM virtual topology footprint of the suburban case may be affected when the number of branch line segment gets increased.

In conclusion, from the perspective of generating virtual topologies for populating OV LV BPL topology classes, the previous findings concerning the impacts of distribution and branch line parameter changes of the NNTGM default operation settings on NNTGM virtual topology footprints may offer a plethora of populating scenarios. Depending on the distribution and branch line parameter of the NNTGM default operation settings, various shapes of NNTGM virtual topology footprints may be generated in terms of their position and extent with respect to their indicative OV LV BPL topologies. Therefore, OV LV BPL topology classes can be populated by NNTGM virtual topologies of different characteristics that may be defined by the user taking into account his simulation scenario requirements.

Conclusions

In this companion paper, the numerical results for populating OV LV BPL topology classes by applying NNTGM are demonstrated and analyzed. In [1], the theory for populating OV LV BPL topology classes by applying NNTGM has been given. With reference to the class maps and the GPIs, the impact of the following NNTGM parameters on the NNTGM virtual topology footprints, whose significance has already been identified in [1], has been assessed, namely: (i) The inclusion or not of the examined indicative OV LV BPL topology in the TIM OV LV BPL topology database during the NNTGM operation; (ii) the length of the distribution / branch line segments; and (iii) the number of the distribution / branch line segments. First, as the inclusion of the examined indicative OV LV BPL topology in the TIM OV LV BPL topology database is concerned, NNTGM virtual topology footprints and GPIs of the indicative OV LV BPL topologies have shown that the TIM OV LV BPL topology database remains robust after the exclusion of the examined indicative OV LV BPL topology thus having small effect on the NNTGM class maps and footprints. Second, the length increases of the distribution and branch line segments of NNTGM default operation settings have complementary impacts on the NNTGM virtual topology footprints of the indicative OV LV BPL topologies. In fact, the length increase of the distribution line segments mainly moves and extends the NNTGM virtual topology footprints of the suburban case while the increase of the branch line segments mainly affects the position and extent of the NNTGM virtual topology footprints of the urban case A and the rural case. The aforementioned complementary behaviors offer an important tool for NNTGM in order to efficiently populate various OV LV BPL topology classes in various patterns. Third, the number increases of the distribution and branch line segments of NNTGM default operation settings present similar impacts on the NNTGM virtual topology footprints of the indicative OV LV BPL topologies of this pair of paper with the ones of the length increases of the distribution and branch line segments, respectively, but in a more drastic way with reference to GPIs of this paper. Concluding this pair of papers, NNTGM can generate theoretical channel attenuation behaviors given the topological characteristics of an indicative OV LV BPL topology, when appropriate NNTGM default operation settings are assumed, while the tuning of NNTGM operation settings may offer a plethora of populating scenarios for OV LV BPL topology classes that may be defined by the user taking into account his simulation scenario requirements.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this paper.

References

[1] Lazaropoulos, A. (2024). Virtual Topologies for Populating Overhead Low-Voltage Broadband over Powerlines Topology Classes by Exploiting Neural Network Topology Generator Methodology (NNTGM) - Part 1: Theory. *Trends in Renewable Energy, 10*(3), 301-314. doi:http://dx.doi.org/10.17737/tre.2024.10.3.00181

[2] Lazaropoulos, A. G. (2021). Information Technology, Artificial Intelligence and Machine Learning in Smart Grid – Performance Comparison between Topology Identification Methodology and Neural Network Identification Methodology for the Branch Number Approximation of Overhead Low-Voltage Broadband over Power Lines Network Topologies. *Trends in Renewable Energy, 7*, 87-113. doi:http://dx.doi.org/10.17737/tre.2021.7.1.00133

[3] Lazaropoulos, A. G., & Leligou, H. C. (2023). 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. *Trends in Renewable Energy, 9*(1), 34-77. doi:http://dx.doi.org/10.17737/tre.2023.9.1.00149

[4] Lazaropoulos, A. G., & Leligou, H. C. (2024). Big Data and Neural Networks in Smart Grid - Part 1: The Impact of Piecewise Monotonic Data Approximation Methods on the Performance of Neural Network Identification Methodology for the Distribution Line and Branch Line Length Approximation of Overhead Low-Voltage Broadband over Powerlines Networks. *Trends in Renewable Energy, 10*, 30-66. doi:https://doi.org/10.17737/tre.2024.10.1.00164

[5] Lazaropoulos, A. G., & Leligou, H. C. (2024). Big Data and Neural Networks in Smart Grid - Part 2: The Impact of Piecewise Monotonic Data Approximation Methods on the Performance of Neural Network Identification Methodology for the Distribution Line and Branch Line Length Approximation of Overhead Low-Voltage Broadband over Powerlines Networks. *Trends in Renewable Energy, 10*, 67-97. doi:https://doi.org/10.17737/tre.2024.10.1.00165

[6] Patel, D. K., Phukan, H., Mansani, S., Singh, J., Sreejith, S., Goswami, A. K., & Patel, R. (2022). Smart Grid Communication and Information Technologies: A Review. In: Dash, R.N., Rathore, A.K., Khadkikar, V., Patel, R., Debnath, M. (eds) *Smart Technologies for Power and Green Energy. Lecture Notes in Networks and Systems, vol 443*. Springer, Singapore. doi:https://doi.org/10.1007/978-981-19-2764-5_5

[7] Marcuzzi, F., & Tonello, A. M. (2023). Topology-based machine learning: Predicting power line communication quality in smart grids. *IEEE Access*, *11*, 24851-24862. doi:https://doi.org/10.1109/ACCESS.2023.3245361

[8] Ustun Ercan, S. (2024). Power line Communication: Revolutionizing data transfer over electrical distribution networks. *Engineering Science and Technology, an International Journal, 52*, 101680. doi:https://doi.org/10.1016/j.jestch.2024.101680

[9] Lazaropoulos, A. G. (2012). Broadband Transmission and Statistical Performance Properties of Overhead High-Voltage Transmission Networks. *Journal of*

Computer Networks and Communications, 2012(1), 875632. doi:https://doi.org/10.1155/2012/875632

[10] Lazaropoulos, A. G. (2020). Business Analytics and IT in Smart Grid - Part 1: The Impact of Measurement Differences on the iSHM Class Map Footprints of Overhead Low-Voltage Broadband over Power Lines Topologies. *Trends in Renewable Energy, 6*(2), 156-186. doi:http://dx.doi.org/10.17737/tre.2020.6.2.00117

[11] Lazaropoulos, A. G. (2020). Statistical Channel Modeling of Overhead Low Voltage Broadband over Power Lines (OV LV BPL) Networks - Part 1: The Theory of Class Map Footprints of Real OV LV BPL Topologies, Branch Line Faults and Hook-Style Energy Thefts. *Trends in Renewable Energy, 6*(1), 61-87. doi:http://dx.doi.org/10.17737/tre.2020.6.1.00112

[12] Lazaropoulos, A. G. (2020). Business Analytics and IT in Smart Grid - Part 2: The Qualitative Mitigation Impact of Piecewise Monotonic Data Approximations on the iSHM Class Map Footprints of Overhead Low-Voltage Broadband over Power Lines Topologies Contaminated by Measurement Differences. *Trends in Renewable Energy, 6*(2), 187-213. doi:http://dx.doi.org/10.17737/tre.2020.6.2.00118

[13] Lazaropoulos, A. G. (2020). Business Analytics and IT in Smart Grid - Part 3: New Application Aspect and the Quantitative Mitigation Analysis of Piecewise Monotonic Data Approximations on the iSHM Class Map Footprints of Overhead Low-Voltage Broadband over Power Lines Topologies Contaminated by Measurement Differences. *Trends in Renewable Energy, 6*(2), 214-233. doi:http://dx.doi.org/10.17737/tre.2020.6.2.00119

[14] Lazaropoulos, A. (2020). Statistical Channel Modeling of Overhead Low Voltage Broadband over Power Lines (OV LV BPL) Networks - Part 2: The Numerical Results of Class Map Footprints of Real OV LV BPL Topologies, Branch Line Faults and Hook Style Energy Thefts. *Trends in Renewable Energy, 6*(1), 88-109. doi:http://dx.doi.org/10.17737/tre.2020.6.1.00113

[15] Lazaropoulos, A. G. (2013). Review and Progress towards the Capacity Boost of Overhead and Underground Medium-Voltage and Low-Voltage Broadband over Power Lines Networks: Cooperative Communications through Two- and Three-Hop Repeater Systems. *International Scholarly Research Notices, 2013*(1), 472190. doi:https://doi.org/10.1155/2013/472190

[16] Lazaropoulos, A. G., & Cottis, P. G. (2009). Transmission characteristics of overhead medium voltage power line communication channels. *IEEE Transactions on Power Delivery*, *24*(3), 1164-1173. doi:https://doi.org/10.1109/TPWRD.2008.2008467

[17] Lazaropoulos, A. G. (2012). Towards Modal Integration of Overhead and Underground Low-Voltage and Medium-Voltage Power Line Communication Channels in the Smart Grid Landscape: Model Expansion, Broadband Signal Transmission Characteristics, and Statistical Performance Metrics (Invited Paper). *International Scholarly Research Notices, 2012*(1), 121628. doi:https://doi.org/10.5402/2012/121628

[18] Meng, H., Chen, S., Guan, Y. L., Law, C. L., So, P. L., Gunawan, E., & Lie, T. T. (2004). Modeling of transfer characteristics for the broadband power line communication channel. *IEEE Transactions on Power delivery*, *19*(3), 1057-1064. doi:https://doi.org/10.1109/TPWRD.2004.824430

[19] Lazaropoulos, A. G., & Leligou, H. C. (2022). Fiber optics and broadband over power lines in smart grid: a communications system architecture for overhead high-voltage, medium-voltage and low-voltage power grids. *Progress in Electromagnetics Research B*, *95*, 185-205. doi:http://dx.doi.org/10.2528/PIERB22062502

[20] Lazaropoulos, A. G., & Cottis, P. G. (2010). Capacity of overhead medium voltage power line communication channels. *IEEE Transactions on Power Delivery*, *25*(2), 723-733. doi:https://doi.org/10.1109/TPWRD.2009.2034907

[21] Lazaropoulos, A. G. (2016). New coupling schemes for distribution broadband over power lines (BPL) networks. *Progress in Electromagnetics Research B*, *71*, 39-54. doi:http://dx.doi.org/10.2528/PIERB16081503

[22] Amirshahi, P., & Kavehrad, M. (2006). High-frequency characteristics of overhead multiconductor power lines for broadband communications. *IEEE Journal on Selected Areas in Communications*, *24*(7), 1292-1303. doi:https://doi.org/10.1109/JSAC.2006.874399

[23] Amirshahi-Shirazi, P. (2006). *Broadband access and home networking through powerline networks*. The Pennsylvania State University. Ph.D. dissertation.

[24] Sartenaer, T. (2004). *Multiuser communications over frequency selective wired channels and applications to the powerline access network* (Ph.D. dissertation). Univ. Catholique Louvain, Louvain-la-Neuve, Belgium.

[25] Sartenaer, T., & Delogne, P. (2006). Deterministic modeling of the (shielded) outdoor power line channel based on the multiconductor transmission line equations. *IEEE Journal on Selected areas in Communications*, *24*(7), 1277-1291. doi:https://doi.org/10.1109/JSAC.2006.874423

[26] Sartenaer, T., & Delogne, P. (2001). Powerline cables modelling for broadband communications. In *Proceedings of the IEEE International Conference on Power Line Communications and Its Applications*, Malmö, Sweden, pp. 331-337.

[27] Lazaropoulos, A. G., & Cottis, P. G. (2010). Broadband transmission via underground medium-voltage power lines-Part I: transmission characteristics. *IEEE Transactions on Power Delivery*, *25*(4), 2414-2424. doi:https://doi.org/10.1109/TPWRD.2010.2048929

[28] Lazaropoulos, A. G., & Cottis, P. G. (2010). Broadband transmission via underground medium-voltage power lines-Part II: capacity. *IEEE Transactions on Power Delivery*, 25(4), 2425-2434. doi:https://doi.org/10.1109/TPWRD.2010.2052113