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Policies for Carbon Energy Footprint Reduction of Overhead Multiple-Input Multiple-Output High Voltage Broadband over Power Lines Networks

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The impact of different environmental policies on the broadband performance of overhead multiple-input multiple-output high-voltage/broadband over power lines (MIMO/HV/BPL) networks is investigated in this paper. The examined environmental policies focus on the carbon energy footprint reduction of overhead MIMO/HV/BPL networks while respecting their broadband character.

The contribution of this paper is three-fold. First, the spectral and environmental performance of various configurations and topologies of overhead MIMO/HV/BPL networks is assessed with regard to respective spectral efficient (SE) and newly presented environmental efficient (EE) metrics. Second, further insights regarding the performance of overhead MIMO/HV/BPL networks highlight the better spectral and environmental performance of these networks against other today's overhead HV/BPL networks, such as single-input single-output (SISO), single-input multiple-output (SIMO), or multiple-input single-output (MISO) ones. Third, the definition of appropriate environmental policies that optimize the coexistence of the three main sectors of concern, which are the Quality of Service (QoS) requirements, protection of existing radioservices and promotion of environmentally aware limits, is promoted. Towards that direction, the proposed SE/EE trade-off relation of this paper is expected to prove an extremely helpful SE/EE optimization technique.

Keywords: Broadband over Power Lines (BPL) modeling; modal analysis; Power Line Communications (PLC); overhead High-Voltage (HV) power lines; capacity; green technology

I. Introduction

The deployment of broadband over power lines (BPL) networks across the entire transmission and distribution grid –i.e., high-voltage (HV), medium-voltage (MV) and low-voltage (LV) grids– may critically facilitate the role of sensing, communications and control across the existing power grid [1]-[4]. On the basis of the modernization of today's power grid towards a smart power network with state-of-the-art communications capabilities, a plethora of potential smart grid (SG) applications, such as grid monitoring, protection and automatic optimization of operations related to network interconnected elements, can be available [5]-[11].

Until now, significant efforts have been made to exploit the broadband potential of HV/BPL, MV/BPL and LV/BPL networks [12]-[30]. Apart from the fervent interest towards the adoption of BPL technology in future's SG installations, new interest arises due to the recent developments regarding multiple-input multiple-output (MIMO)

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transmission technology for BPL networks and the interoperability of the BPL technology with other already established broadband technologies intended to be installed in upcoming SG installations [31]-[33]. Since today's single-input single-output (SISO) HV/BPL systems lack of providing adequate transmission rates so as to cover future SG application requirements in a trustworthy way, the deployment of MIMO configuration schemes in overhead HV/BPL networks, which is firstly presented in [14], [32], [34]-[41], is imminent. Nevertheless, a major disadvantage of overhead HV/BPL systems –either SISO or single-input multiple-output (SIMO) or multiple-input single-output (MISO) or MIMO scheme configurations– is their high energy consumption with regards to their spectral performance.

At the same time, carbon energy footprint reduction in information and communications technology (ICT) becomes a growing concern for providers in order not only to reduce their environmental effect [42] but also to enhance their profitability [7], [43], [44]. Actually, the strong interest of telecom and energy regulatory authorities towards the reduction of ICT carbon energy footprint –including carbon and energy use embodied in the ICT infrastructure– encourages technological innovations so that environmental efficient (EE) improvements can be achieved without significantly affecting the quality of service (QoS) [7], [45]-[52]. In fact, a possible reduction of energy consumption through appropriate techniques may also entail the carbon energy footprint reduction. To define an environmental high-bitrate MIMO/HV/BPL network design, the coexistence of injected power spectral density mask (IPSDM) limits, which assure electromagnetic interference (EMI) protection to primary wireless services that operate at the same frequency bands with BPL systems [17], [19], with environmental policies, which regulate carbon energy footprint and the energy consumption of MIMO/HV/BPL systems, needs to be examined in this paper. On the basis of [7], a modification to the fixed IPSDM limits through the insertion of an appropriate “green factor” is proposed so that the three main sectors of concern, which are the Quality of Service (QoS) requirements, protection of the existing radioservices and promotion of environmentally aware limits, can be compromised.

To assess the spectral and environmental performance of overhead HV/BPL networks, the well-established hybrid method that is usually employed to examine the behavior of BPL transmission channels installed on HV multiconductor transmission line (MTL) structures is also used in this paper. The hybrid method is based on: (i) a bottom-up approach consisting of an appropriate combination of the similarity transformation and MTL theory [12], [16], [21]-[23], [31], [53]-[63]; and (ii) a top-down approach consisting of the exact version of multidimensional chain scattering matrix method [5]-[7], [16]-[23], [53], [58], [59]. Through the bottom-up approach, the modes that may be supported by an overhead HV/BPL configuration are determined concerning their propagation constants and their characteristic impedances whereas, through the top-down approach, the end-to-end attenuation of overhead HV/BPL channels is defined.

With reference to the numerical results of the aforementioned hybrid method, the performance of overhead MIMO/HV/BPL networks is assessed using appropriate transmission, spectral efficient (SE) and EE metrics [5], [16]-[20], [41], [52], [64]-[68]. Extending the energy efficient metrics of [7] to the EE metrics of this paper, the proposed trade-offs between spectral and environmental performance highlight a novel wiser compromise among throughput performance, EMI regulations and environmental awareness. Further insights, such as how to improve the occurred trade-off curves through proper environmental policies and how to tune the operation points of overhead MIMO/HV/BPL networks at the trade-off curves to balance the aforementioned compromise, are expected to influence the practical system design of future's overhead MIMO/HV/BPL networks [42], [45], [66]. Moreover, the strategic turn of countries towards cleaner energy sources is studied through the lens of the proposed trade-off curves. Consequently, this paper introduces a multidisciplinary approach towards a greener sustainable development of overhead MIMO/HV/BPL networks by appropriately combining a wide range of research areas, such as communications and electrical engineering, economic management and environmental planning.

The rest of the paper is organized as follows: In Section II, the overhead HV configuration adopted in this paper is demonstrated. Section III highlights the main features of MIMO/HV/BPL transmission that are MTL theory, eigenvalue decomposition (EVD), singular value decomposition (SVD) modal analyses and hybrid method. Section IV emphasizes to the electromagnetic compatibility (EMC) of overhead HV/BPL systems with other already licensed radioservices, the proposed green modification of existing IPSDM limits, the HV/BPL system power consumption and carbon energy footprint. Section V provides a description of the transmission, SE and EE metrics applied in this paper for the MIMO/HV/BPL network analysis. In Section VI, numerical results and conclusions are presented, aiming at marking out how the various EMI regulations, EE policies and MIMO scheme configurations influence overhead MIMO/HV/BPL transmission, SE and EE metrics. On the basis of the proposed SE/EE trade-off curves, appropriate EE high-bitrate policies are proposed. Section VII concludes the paper.

II. Overhead HV Transmission Power Networks

The overhead HV power grid differs considerably from transmission via twisted-pair, coaxial, or fiber-optic cables due to the significant differences of the network structure and the physical properties of the power transmission cables used [5], [6], [16], [18], [22], [23], [25], [54], [69]-[75].

Overhead 400kV double-circuit overhead HV transmission phase lines with radii r_p^{400kV} =15.3mm hang at typical heights h_p^{400kV} equal to 20m above ground –i.e., conductors 1, 2, 3, 4, 5, and 6–. These six phase conductors are divided into three bundles; the phase conductors of each bundle are connected by non-conducting spacers and are separated by Δ_{p1}^{400kV} equal to 400mm, whereas bundles are spaced by Δ_{p2}^{400kV} equal to 10m. Moreover, two parallel neutral conductors with radii r_n^{400kV} =9mm spaced by Δ_n^{400kV} equal to 12m hang at heights h_n^{400kV} equal to 23.7m –i.e., conductors 7 and 8–. This double-circuit eight-conductor ($n^{400kV} = 8$) overhead HV distribution line configuration is considered in the present work consisting of ACSR conductors –see Fig. 1– [5], [6], [23], [73]-[80].

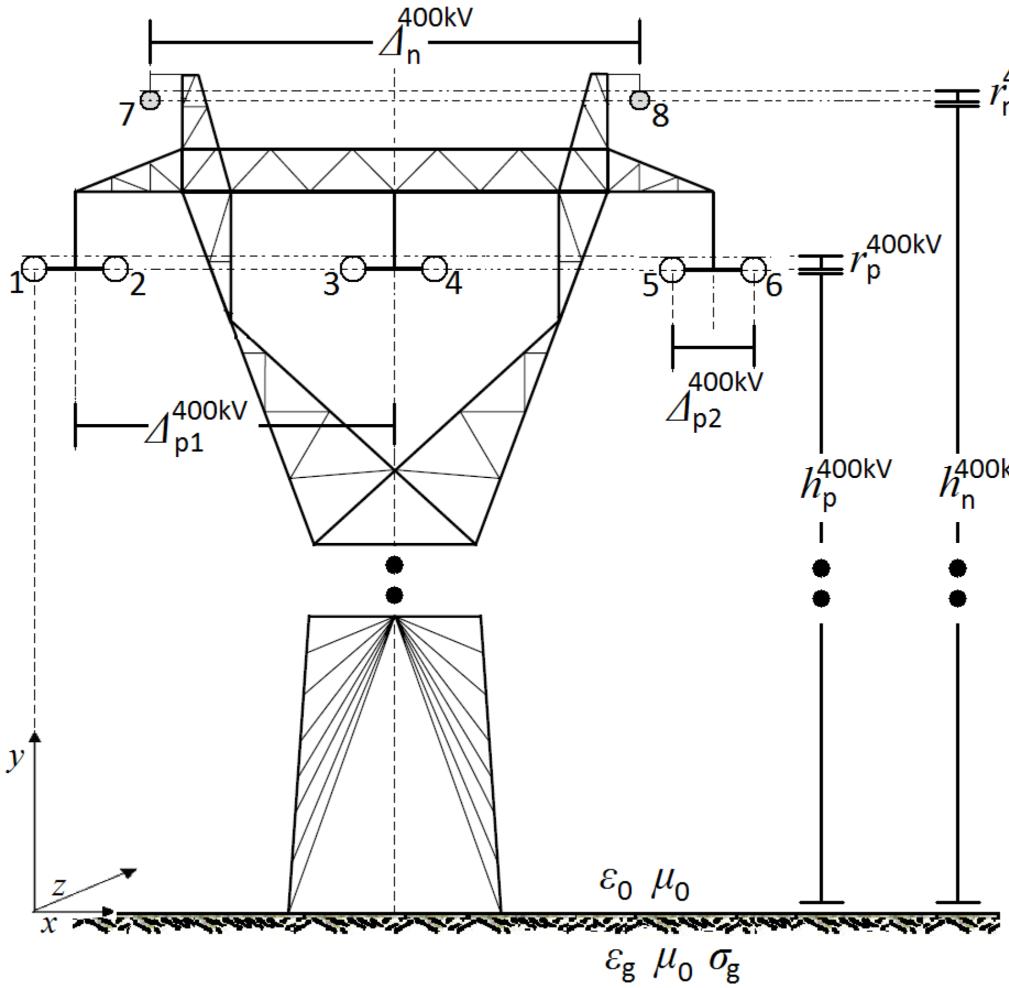

Figure 1. Typical overhead 400kV double-circuit HV multiconductor structures [1], [76]-[80].

The ground is considered as the reference conductor. The conductivity of the ground is assumed σ_g =5mS/m and its relative permittivity ε_{rg}=13, which is a realistic scenario [5], [6], [16], [17], [23], [54], [72]. The impact of imperfect ground on signal propagation via overhead power lines was analyzed in [16], [17], [54], [72], [81]-[84]. Contrary to other available models for overhead power lines [85]-[88], this formulation is suitable for transmission at high frequencies [5], [6], [7], [16]-[20], [23].

III. An Overview of the Modal Analysis of Overhead MIMO/HV/BPL Systems

Through a matrix approach, the standard TL analysis can be extended to the MTL case which involves more than two conductors. Compared to a two-conductor line supporting one forward- and one backward-traveling wave, an MTL structure with eight plus one conductors parallel to the *z* axis as depicted in Fig. 1 may support eight pairs of forward- and backward-traveling waves with corresponding propagation constants. These waves may be described by a coupled set of sixteen first-order partial differential equations relating the line voltages $V_i(z,t)$, $i=1,\ldots,8$ to the line currents

$I_i(z,t),\ i=1,\ldots,8$. Each pair of forward- and backward-traveling waves is referred to as a mode [5]-[7], [16]-[23], [60], [61]. Consequently, in the case of overhead HV transmission lines involving eight conductors over lossy plane ground, eight modes may be supported, namely:

- Common mode of overhead BPL transmission (CM) with propagation constant $\gamma_{\mathrm{CM}} \equiv \gamma_1$. Its spectral behavior is thoroughly investigated in [1], [5], [6].
- Differential modes of overhead BPL transmission (DM_i , $i=1,\ldots,7$) with corresponding propagation constants $\gamma_{\mathrm{DM}i} \equiv \gamma_{\mathrm{i+1}}$, $i=1,\ldots,7$. Their spectral behavior is thoroughly investigated in [1], [5], [6].

The EVD modal voltages $\mathbf{V}^{\mathrm{m}}(z)=\left[V_1^{\mathrm{m}}(z)\ \cdots\ V_8^{\mathrm{m}}(z)\right]^{\mathrm{T}}$ and the EVD modal currents $\mathbf{I}^{\mathrm{m}}(z)=\left[I_1^{\mathrm{m}}(z)\ \cdots\ I_8^{\mathrm{m}}(z)\right]^{\mathrm{T}}$ may be related to the respective line quantities $\mathbf{V}\ (z)=\left[V_1\ (z)\ \cdots\ V_8\ (z)\right]^{\mathrm{T}}$ and $\mathbf{I}\ (z)=\left[I_1\ (z)\ \cdots\ I_8\ (z)\right]^{\mathrm{T}}$ via the similarity transformations

$$\mathbf{V}(z)=\mathbf{T}_{\mathrm{V}}\cdot\mathbf{V}^{\mathrm{m}}(z) \tag{1}$$

$$\mathbf{I}(z)=\mathbf{T}_{\mathrm{I}}\cdot\mathbf{I}^{\mathrm{m}}(z) \tag{2}$$

where $[\cdot]^{\mathrm{T}}$ denotes the transpose of a matrix, $\mathbf{T}_{\mathrm{V}}$ and $\mathbf{T}_{\mathrm{I}}$ are 8×8 matrices depending on the overhead power grid type, the frequency, the physical properties of the cables and the geometry of the MTL configuration [1], [5], [6], [16], [18], [23], [53], [60], [61], [76]-[95].

On the basis of eqs (1) and (2), the line voltages and currents are expressed as appropriate superpositions of the respective EVD modal quantities, namely:

$$\mathbf{V}^{\mathrm{m}}(0)=\left[\mathbf{T}_{\mathrm{V}}\right]^{-1}\cdot\mathbf{V}(0) \tag{3}$$

The TM2 method, which is module of the top-down approach of the hybrid method, is based on the scattering matrix theory and is presented analytically in [7], models the spectral relationship between $V_i^{\mathrm{m}}(z),\ i=1,\ldots,8$ and $V_j^{\mathrm{m}}(0),\ j=1,\ldots,8$ proposing operators $H_{i,j}^{\mathrm{m}}\{\cdot\},\ i,j=1,\ldots,8$ so that

$$\mathbf{V}^{\mathrm{m}}(z)=\mathbf{H}^{\mathrm{m}}\left\{\mathbf{V}^{\mathrm{m}}(0)\right\} \tag{4}$$

where $\mathbf{H}^{\mathrm{m}}\{\cdot\}$ is the 8×8 EVD modal transfer function matrix whose elements $H_{i,j}^{\mathrm{m}}\{\cdot\},\ i,j=1,\ldots,8$ with $i=j$ are the EVD modal co-channel (CC) transfer functions, while those $H_{i,j}^{\mathrm{m}}\{\cdot\}$, $i,j=1,\ldots,8$ with $i\neq j$ are the EVD modal cross-channel (XC) transfer functions and $H_{i,j}^{\mathrm{m}}$ denotes the element of matrix $\mathbf{H}^{\mathrm{m}}\{\cdot\}$ in row i of column j [5]-[7], [16]-[23], [55], [91]. Combining eqs. (1) and (4), the 8×8 transfer function matrix $\mathbf{H}\{\cdot\}$ of overhead HV/BPL transmission network relating $\mathbf{V}(z)$ with $\mathbf{V}(0)$ through

$$\mathbf{V}(z)=\mathbf{H}\{\mathbf{V}(0)\} \tag{5}$$

is determined from

$$\mathbf{H}\{\cdot\}=\mathbf{T}_{\mathrm{V}}\cdot\mathbf{H}^{\mathrm{m}}\{\cdot\}\cdot\left[\mathbf{T}_{\mathrm{V}}\right]^{-1} \tag{6}$$

Since in overhead MIMO/HV/BPL networks, the number of active transmit ports n_T and receive ports n_R may vary from one to eight, through a similar matrix expression to eq. (6), $\min\{n_T, n_R\}$ parallel and independent SISO/HV/BPL channels may occur, appropriately decomposing channel transfer function matrix $\mathbf{H}\{\cdot\}$ using the SVD transformation [32], [35]-[37], [39], [96], [97]:

$$\widetilde{\mathbf{H}}^m\{\cdot\} = \widetilde{\mathbf{T}}_V^H \cdot \mathbf{H}^+\{\cdot\} \cdot \widetilde{\mathbf{T}}_I \tag{7}$$

where

$$H_{ij}^+\{\cdot\} = \left\{ \begin{matrix} H_{ij}\{\cdot\} & ,\text{if } \left(i \in \mathbf{n}_T \text{ and } j \in \mathbf{n}_R\right) \\ 0 & ,\text{otherwise} \end{matrix} \right\} \quad i, j = 1, \ldots, 8 \tag{8}$$

denotes the element of matrix $\mathbf{H}^+\{\cdot\}$ in row i of column j. From eqs. (7) and (8), $\mathbf{H}^+\{\cdot\}$ is the 8×8 extended channel transfer function matrix whose elements $H_{ij}^+\{\cdot\}$, $i, j = 1, \ldots, 8$ are the extended channel transfer functions, $\widetilde{\mathbf{H}}^m\{\cdot\}$ is a diagonal matrix operator whose elements $\widetilde{H}_i^m\{\cdot\}$, $i = 1, \ldots, \min\{n_T, n_R\}$ are the singular values of $\mathbf{H}^+\{\cdot\}$ and, at the same time, the SVD modal transfer functions, $\min\{x, y\}$ returns the smallest value between x and y, $\mathbf{n}_T$ and $\mathbf{n}_R$ are the active transmit port and the active receive port sets, respectively, $[\cdot]^H$ denotes the Hermitian conjugate of a matrix, and $\widetilde{\mathbf{T}}_V$ and $\widetilde{\mathbf{T}}_I$ are 8×8 unitary matrices [36], [39], [98]. Combining eqs. (6)-(8), SVD modal transfer function matrix $\widetilde{\mathbf{H}}^m\{\cdot\}$ may be determined given EVD modal transfer function matrix $\mathbf{H}^m\{\cdot\}$.

IV. Brief Description of Overhead MIMO/HV/BPL Channels

A. Power Constraints due to EMI and Environmental Constraints

A critical issue related to the operation of overhead MIMO/HV/BPL networks has to do with the power constraints (i.e., IPSDM limits) that should be imposed in order to ensure their successful coexistence with other already existing wireless and telecommunication services at the same frequency band of operation [17], [19], [26], [99]. Among regulatory bodies that have established proposals concerning the safe EMI BPL operation, the most important are those of FCC Part 15, German Reg TP NB30, the Norwegian Proposal and the BBC/NATO Proposal [71], [100]-[102].

Especially, the IPSDM limits proposed by Ofcom for compliance with FCC Part 15 that are presented in [71], [100]-[102] are the most cited due to their proneness towards the deployment of high-bitrate BPL networks. More specifically, for overhead HV/BPL networks, according to Ofcom, in the 1.705-30MHz frequency range, maximum levels -60 dBm/Hz constitute appropriate IPSDM limits $p(f)$ providing presumption of compliance with the current FCC Part 15 limits [17], [19], [103], [104]. To extend the capacity analysis in the 30-88MHz range, maximum IPSDM limits $p(f)$ that are equal to -77 dBm/Hz for overhead HV/BPL networks are assumed to provide a presumption of compliance in this frequency range [17], [19], [103], [104]. Note that as it regards the above power constraints of overhead MIMO/HV/BPL scheme configurations, to extend the analysis in the 1.705-88MHz range, common IPSDM limits $p(f)$ between HV/BPL and MV/BPL systems have been assumed exploiting the significant similarities regarding overhead HV/BPL and MV/BPL transmission without harming the generality of the following MIMO analysis [17], [19], [54], [72], [103]-[105].

Different IPSDM limits may provide to the authorities the necessary alternative options in protecting services and, at the same time, permitting energy efficient high-bitrate MIMO/HV/BPL system operation. In accordance with [7], power spectral regulation through the insertion of a suitable green multiplicative factor $[1+\Phi(f)]$ to the existing IPSDM limits (in dBm/Hz) may offer significant flexibility options; since existing IPSDM limits receive negative values, new IPSDM limits $p^{*}(f)=p(f)\cdot[1+\Phi(f)]$ can assure both BPL compatibility with other wireless services and the required energy efficiency. Note that the green factor $\Phi(f)$ that may be defined by both regulatory bodies and network operators can take only positive values in order to maintain the necessary EMC of overhead HV/BPL networks. The factors that determine the imposed green factor depend on the required degree of energy consumption (carbon energy footprint saving), the local traffic, the type of services delivered and QoS threshold criterion imposed. Since lower energy consumption implies higher carbon energy footprint savings, the higher the value of the green factor $\Phi(f)$, the higher the influence of EE policies is. In contrast, when the green factor is equal to 0, no concern for EE policies is taken.

Without affecting the generality of the following analysis, only the class of continuous EE policies will be taken into consideration; this class contains all the EE policies where a constant value of green factor $\Phi \equiv \Phi(f)$ across the entire 1.705-88MHz frequency range is assumed [7].

B. Noise Characteristics

According to [17], [19], [25], [54], [72], [106], [107], two types of noise are dominant in overhead HV/BPL channels:

- *Colored background noise*: This type of noise is dominant in BPL channels. It is the environmental noise that depends on weather conditions, humidity, geographical location, height of cables above the ground, etc. Corona discharge is a major source of colored background noise, especially under humid and severe weather conditions [54], [72], [82], [101], [108], [109].
- *Narrowband noise*: This type of noise is the result of the narrowband interferences from other wireless services operating at the same frequency bands with overhead HV/BPL networks. This kind of noise exhibits local variations and is time-dependent [17], [19], [72], [108], [109].

As it regards the noise properties of overhead MIMO/HV/BPL scheme configurations, to extend this analysis in the 1.705-88MHz range, uniform additive white Gaussian noise (AWGN) PSD level $N(f)$ will be assumed [17], [19], [54], [72], [103]-[105], [110]. In detail, to evaluate the capacity of overhead MIMO/HV/BPL systems, a uniform AWGN/PSD level is assumed equal to -105dBm/Hz [17], [19], [54], [72]. The noise AWGN/PSD of each power grid type is assumed common to all MIMO channels of the MTL configuration. Note that as it regards the above noise features of overhead MIMO/HV/BPL scheme configurations, to extend the analysis in the 1.705-88MHz frequency range, common AWGN PSD level $N(f)$ between HV/BPL and MV/BPL systems has been assumed exploiting the significant similarities regarding overhead HV/BPL and MV/BPL transmission without harming the generality of MIMO analysis.

C. Power Consumption

According to [66], [111]-[114], two types of power consumption occur in overhead MIMO/HV/BPL systems, namely:

- *Power Consumption due to Power Amplifiers.* Power amplifiers are the main power consumption blocks in any advanced communication system due to their needed high RF power amplifier efficiency. This class of power consumption depends mainly on the imposed EE policy [66], [112].
- *Power Consumption due to all other Circuit Blocks.* Apart from power amplifiers, overhead MIMO/HV/BPL systems consist of the Digital-to-Analog Converter (DAC), the mixer, the active filters at the transmitting end, the frequency synthesizer, the low-noise amplifier (LNA), the intermediate frequency amplifier (IFA), the active filters at the receiver side and the Analog-to-Digital Converter (ADC). This type of power consumption is related to all these circuit blocks and depends on the number of active transmit and receive ports of MIMO/HV/BPL systems [66], [112].

The total average power consumption P_{tot} of overhead MIMO/HV/BPL systems is given by the sum of the aforementioned two types of power consumption. Based on the related circuit and system parameters, which are detailed in [66], [111]-[114], an approximation of the actual MIMO/HV/BPL system power consumption is computed.

D. Carbon Emissions

The carbon energy footprint of an overhead MIMO/HV/BPL network depends on its power consumption and on the origin of the electricity production [115]. A metric of carbon energy footprint, which is subject to each country's energy sources, is given by converting power consumption into *gr* of CO_2 per each *kWh* of energy consumption. For anthracite electricity production and gas electricity production of this paper, the carbon energy footprint of an overhead MIMO/HV/BPL system is computed according to

$$K^{CO_2} = 8.64 \cdot 10^{-6} \cdot P_{tot} \cdot X \tag{9}$$

where K^{CO_2} is expressed in *tons* of CO_2 per *year* and X is the conversion metric that is equal to 870$grCO_2/kWh$ and 360$grCO_2/kWh$ for anthracite electricity production and gas electricity production, respectively [115], [116].

V. SE and EE Metrics of Overhead MIMO/HV/BPL Networks

To assess the spectral and environmental performance of overhead MIMO/HV/BPL networks, respective SE and EE metrics are used. SE metrics describe how efficiently BPL networks exploit their allocated frequency band whereas EE metrics correspond each bit per second (bps) to a carbon energy footprint. In this Section, several useful SE and EE metrics are introduced in order to examine the properties of the overhead MIMO/HV/BPL networks, namely:

a. *Capacity.* Capacity is the maximum achievable transmission rate in bps over a BPL channel and depends on the applied configuration of MIMO/HV/BPL network, the system features, the imposed EE policy and the noise characteristics. In this paper, capacity is the considered QoS criterion.

More specifically, the capacity of the SISO/HV/BPL system from transmit port *j* to receive port *i* is given by [7], [17], [19]

$$C_{ij}^{SISO} = f_s \sum_{q=0}^{K-1} \log_2 \left\{ 1 + \left[SNR(qf_s) \cdot \left| H_{ij,q}^{+} \right|^2 \right] \right\}, i, j = 1, \ldots, 8 \tag{10}$$

where

$$SNR(f) = \left\langle [1 + \Phi(f)] p^{*}(f) \right\rangle_L / \left\langle N(f) \right\rangle_L \tag{11}$$

is the BPL signal-to-noise ratio (SNR), $\langle \cdot \rangle_L$ is an operator that converts dBm/Hz into a linear power ratio (W/Hz), K is the number of subchannels in the BPL signal frequency range of interest and f_s is the flat-fading subchannel frequency spacing [17], [19], [99]. As it concerns the characterization of overhead SISO/HV/BPL systems, the elements C_{ij}^{SISO} , $i, j = 1, \ldots, 8$ with $i = j$ and $i \neq j$ characterize SISO/CC HV/BPL and SISO/XC HV/BPL system capacities, respectively.

Similarly, the capacity of the $1 \times n_R$ SIMO HV/BPL systems from the transmit port *j* with n_R receive ports –ranging from two to eight– is given by

$$C_{j}^{SIMO} = f_s \sum_{q=0}^{K-1} \log_2 \left\{ 1 + SNR(qf_s) \cdot \sum_{i \in \mathbf{n}_R} \left| H_{ij}^{+}(qf_s) \right|^2 \right\} \tag{12}$$

In the case of $n_T \times 1$ MISO HV/BPL system, the capacity to the receiving port *i* with n_T transmit ports –ranging from two to eight– is given by [7], [64], [117]

$$C_{i}^{MISO} = f_s \sum_{q=0}^{K-1} \log_2 \left\{ 1 + \frac{SNR(qf_s)}{n_T} \cdot \sum_{j \in \mathbf{n}_T} \left| H_{ij}^{+}(qf_s) \right|^2 \right\} \tag{13}$$

Finally, in the general case of $n_T \times n_R$ MIMO/HV/BPL systems with n_T and n_R ranging both from two to eight, the capacity is determined by [7], [32], [36], [37], [39], [40], [64], [117]

$$C^{MIMO} = f_s \sum_{q=0}^{K-1} \sum_{i=1}^{\min\{n_R, n_T\}} \log_2 \left\{ 1 + \frac{SNR(qf_s)}{n_T} \cdot \left| \widetilde{H}_{i}^{m}(qf_s) \right|^2 \right\} \tag{14}$$

Note that both eqs. (13) and (14) are based on equal power uncorrelated sources as the common case is adopted where the transmitting end does not have channel state information (CSI).

According to the different SISO, SIMO, MISO and MIMO scheme configurations, the resulting single- and multi-port diversities may be classified into two major classes:

- *Pure Scheme Configuration Class*. This class contains the elementary single- and multi-port implementations, namely: 8×8 MIMO, 1×8 SIMO, 8×1 MISO, and all SISO systems –either SISO/CCs or SISO/XCs–.
- *Mixed Scheme Configuration Class*. This class contains all the other multi-port implementations that may be deployed, namely: $n_T \times n_R$ MIMO systems with $1 < n_T, n_R < 8$.

b. *The EE capacity*. It denotes the maximum achievable transmission rate of Mbps that the system can deliver per ugr of CO_2 emitted from it. This EE capacity metric is obtained as the ratio of the capacity to the carbon energy footprint for given EE policy, circuit/system parameters and country's energy sources for electricity production. This EE capacity metric provides a macroscopic qualitative estimate of the role of EE policies and system power consumption during BPL system operation.

VI. Numerical Results and Discussion

The simulation results of various configurations of overhead MIMO/HV/BPL networks aim at investigating: (a) their broadband performance; (b) how the applied SE and EE capacity metrics are influenced by the implementation of various MIMO/HV/BPL scheme configurations; and (c) the occurred SE/EE dynamic equilibria due to the different EE policies.

As mentioned in Section III, since the modes supported by the overhead HV/BPL configurations may be examined separately, it is assumed for simplicity that the BPL signal is injected directly into the EVD modes [5]-[7], [16]-[23], [53]-[56], [58]-[62], [72], [117].

For the numerical computations, the 400kV double-circuit overhead HV transmission line configuration, depicted in Fig. 1, has been considered. The simple overhead topology of Fig. 2(a), having N branches, has been assumed. In order to simplify the following analysis without affecting its generality, the branching cables are assumed identical to the transmission cables and the interconnections between the transmission and branch conductors are fully activated. With reference to Fig. 2(b), the transmitting and the receiving ends are assumed matched to the characteristic impedance of the modal channels supported, whereas the branch terminations $\mathbf{Z}_{bk}$, $k=1,2,\ldots,N$ are assumed open circuit [5]-[8], [16]-[19], [54], [76]-[79], [92].

With reference to Fig. 2(b), four indicative overhead HV topologies concerning end-to-end connections of average lengths equal to 25km are examined. These topologies are [5]-[8], [22]-[24], [69], [73], [74], [76]-[79], [92], [118]-[120]:

(1) A typical urban topology (urban case) with N=3 branches (L_1=1.15km, L_2=12.125km, L_3=8.425km, L_4=3.3km, L_{b1}=27.6km, L_{b2}=17.2km, L_{b3}=33.1km).
(2) A typical suburban topology (suburban case) with N=2 branches (L_1=9.025km, L_2=12.75km, L_3=3.225km, L_{b1}=46.8km, L_{b2}=13.4 km).
(3) A typical rural topology (rural case) with only N=1 branch (L_1=3.75km, L_2=21.25km, L_{b1}=21.1km).
(4) The "LOS" transmission along the average end-to-end distance $L=L_1+\ldots+L_{N+1}$=25km when no branches are encountered. This topology corresponds to Line-of-Sight transmission in wireless channels.

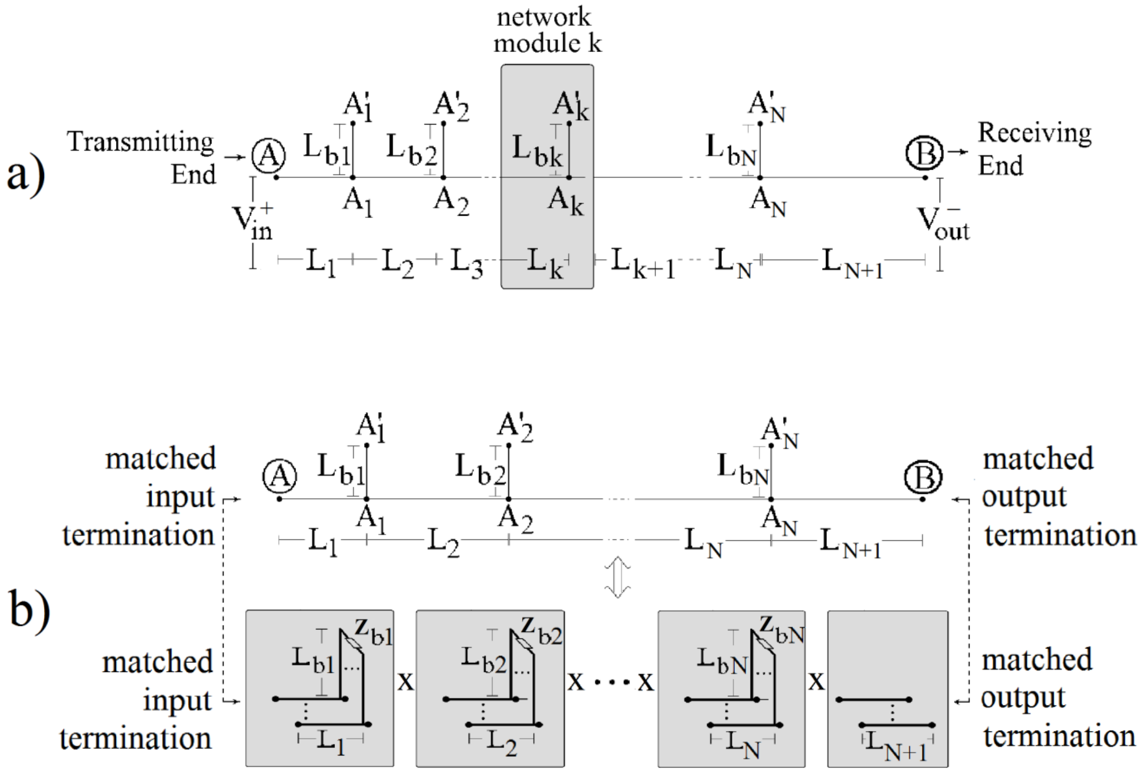

Figure 2. (a) End-to-end overhead HV/BPL connection with *N* branches. (b) An indicative HV/BPL topology considered as a cascade of *N*+1 modules corresponding to *N* branches [5]-[7], [16], [17], [19]-[23].

As it concerns the MIMO transmission scheme assumptions, in the common case, the transmitter does not have CSI –as it has already mentioned– whereas the channel is perfectly known to the receiver (i.e., channel knowledge at the receiver can be maintained via training and tracking). The flat-fading subchannel frequency spacing is assumed equal to $f_s = 10\,\text{kHz}$. The proposed MIMO/HV/BPL system analysis, which is outlined in Section III, is used in the rest of this paper.

As it has already been mentioned in Section IV, to evaluate the capacity of overhead MIMO/HV/BPL networks, a uniform AWGN PSD level is assumed equal to -105dBm/Hz [17], [19], [54], [72]. As it concerns the power consumption of overhead MIMO/HV/BPL systems, the related circuit and system parameters are detailed in [66], [111]-[114] providing a satisfactory approximation towards the actual HV/BPL system power consumption.

A. Effect of HV Grid Topology and MIMO Scheme Configuration on Overhead MIMO/HV/BPL Capacity Performance

The spectral performance in terms of capacity in the 3-88MHz frequency band is evaluated based on the application of FCC Part 15 under the assumption of Ofcom/IPSDM limits when different overhead HV/BPL network configurations occur. In this subsection, it is assumed that only the highest values (upper bound) of capacity of each MIMO/HV/BPL configuration of the same class for each of the aforementioned indicative overhead HV/BPL topologies are going to be presented.

In Figs. 3(a)-(d), the capacity of the overhead MIMO networks for the aforementioned indicative overhead topologies is plotted with respect to the active transmit and receive ports of different MIMO scheme configurations. Moreover, the relative capacity gain concerning each MIMO scheme configuration in relation with the corresponding SISO one for the aforementioned indicative overhead topologies is also demonstrated.

From Figs. 3(a)-(d), it is observed that:

- The high IPSDM limits of FCC Part 15, combined with the relatively low end-to-end channel attenuation and the low noise characteristics of overhead MIMO/HV/BPL networks, reveal their significant broadband potential. Regardless of the high average end-to-end transmission distances occurred in overhead HV grids, capacity and relative capacity gain maintain sufficient high values for all the future's SG applications.
- Observing capacity and relative capacity gain results, SIMO/HV/BPL networks present better results than the corresponding ones of MISO/HV/BPL networks regardless of the topology and the MIMO configuration scheme. This is due to the fact that, in the SIMO cases, all the transmitted power is concentrated at one transmit port and collected from multiple receive ports whereas, in the MISO cases without CSI, the transmitted power is equally allocated among the available transmit ports and collected from one receive port [121].
- Due to the common bus-bar system topology [7], [40], [122], in overhead BPL networks, end-to-end channel attenuation curves between CCs and XCs present similarities indicating the strong coupling among the individual MIMO channels. However, the XC channels present significantly higher end-to-end channel attenuation than CC ones regardless of the network topology [35], [37], [50].
- The increase of the available transmit ports in MISO systems entails higher influence of XC channels in the occurred capacity results and, consequently, lower capacity results in comparison with the upper bound of SISO systems.
- When the number of transmit n_T and receive n_R ports increases, the capacity differences among $n_T \times n_R$ and $n_R \times n_T$ MIMO networks tend to be mitigated.
- MIMO configuration schemes provide dramatic improvement in the capacity results rendering their installation preferable in comparison with the other available SISO, SIMO and MISO alternatives.

Due to their similar capacity behavior, only one overhead HV topology, say "LOS" case, will be examined hereafter.

B. Impact of EE Policies on SE and EE Metrics

Until now, MIMO/BPL research has mainly focused on determining the optimum number of transmit and receive ports, which succeeds the best compromise among system complexity, capacity and system availability [35], [123]-[125]. However, the recent growing communications concern is not only to maximize the spectral efficiency

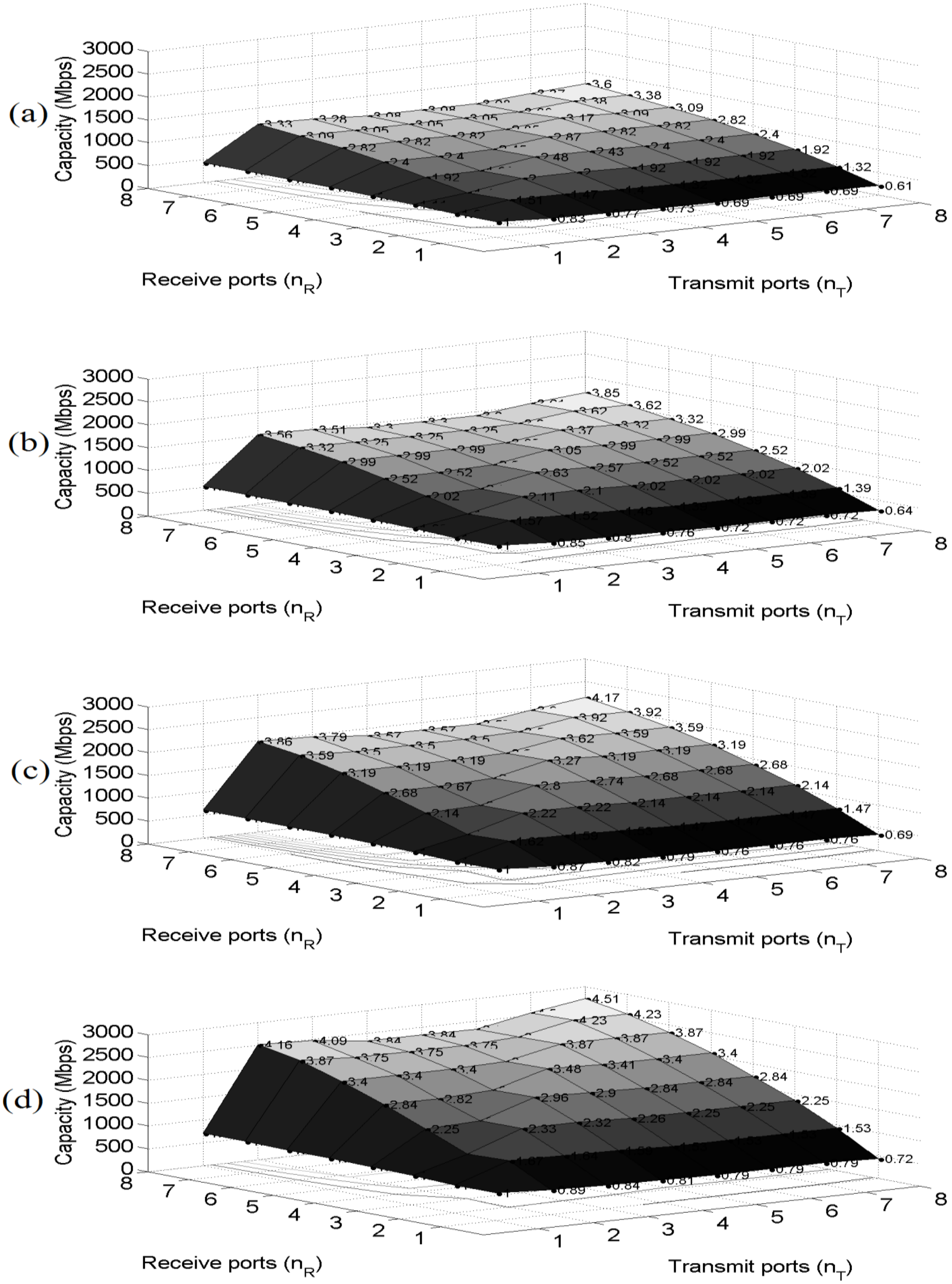

Figure 3. Capacity and relative capacity gain of overhead MIMO/HV/BPL networks for the four indicative topologies (IPSDM limits of the FCC Part 15 limits are applied and the subchannel frequency spacing is equal to 10kHz). (a) Urban case. (b) Suburban case. (c) Rural case. (d) “LOS” case.

of networks and systems but also to increase profitability through energy consumption savings while protecting the environment [42]. Towards that direction, different MIMO/HV/BPL networks arrangements are investigated in this paper when different EE policies are adopted. In the rest of this paper, it is assumed that only the maximum values of all possible SIMO, MISO and MIMO system capacities will be studied in the 3-88MHz frequency band.

As it has already been analyzed in Fig. 3(d), the capacity and relative capacity gain of overhead MIMO/HV/BPL "LOS" case have been plotted for various MIMO scheme configurations when FCC Part 15 is applied. These results define the optimum capacity case when no environmental concern is taken into account (EE1 policy).

Apart from EE1 policy, other five indicative EE policies given in Table 1 have been applied in order to examine how their application affect the SE and EE metrics of this paper (i.e., capacity, carbon energy footprint and EE capacity). Note that as the number x of EEx policy increases so does the environmental awareness. In Table 1, green factor Φ of each EE policy is also reported.

To examine the impact of EE policies on spectral performance of overhead MIMO/HV/BPL networks, in Figs. 4(a)-(g), the capacity and the relative capacity gain of overhead MIMO/HV/BPL networks for the "LOS" case are plotted with respect to the active transmit and receive ports of different MIMO scheme configurations when the six indicative EE policies of Table 1 are applied, respectively. The influence of EE policies on the EE performance of overhead MIMO/HV/BPL networks is examined in Figs. 5(a)-(g) where the corresponding carbon energy footprint is plotted for the above six indicative EE policies, respectively.

The interaction between SE and EE metrics can be examined through the use of suitable combined SE/EE metrics such as EE capacity. In Figs. 6(a)-(g), the corresponding EE capacity and relative EE capacity gain are given for the above six indicative EE policies, respectively. Note that as it regards the carbon emissions of overhead MIMO/HV/BPL scheme configurations, in Figs. 5(a)-(f) and 6(a)-(f), only anthracite electricity production is assumed.

From Figs. 4(a)-(f), 5(a)-(f) and 6(a)-(f), several interesting conclusions may be drawn as follows.

- Capacity and carbon energy footprint of overhead MIMO/HV/BPL networks are very sensitive to IPSDM limit changes as these are imposed by the applied EE policy [17], [19]. However, the strategic choice of the countries to achieve significant carbon emission reductions pushes towards the adoption of EE policies that can diminish the broadband perspectives of overhead MIMO/HV/BPL networks. On the other hand, EE policies that are not environmentally oriented lead to waste of energy since the capacity improvement becomes marginal above a capacity threshold. Therefore, ecologically aware EE policies should be promoted that can lead to energy savings and reduction of carbon emissions while their corresponding capacity results may be carefully adjusted so as to satisfy certain capacity requirements. In fact, it can be seen that by reducing the IPSDM limits by 5% –see EE2 in Table 1 and in Figs. 4(a) and 4(b)–, the capacity reduction of overhead MIMO/HV/BPL networks

Table 1. EE Policies Used

EE Policy (type)	EE1	EE2	EE3	EE4	EE5	EE6
Green factor Φ	0	0.05	0.10	0.20	0.50	1

is ranging from 14.05% to 21.45% while carbon emissions decrease and EE capacity increase are ranging from 44.85%-48.99% and 42.44%-64.59%, respectively. Similar results for the other EE policies reveal the importance of the selection of proper IPSDM limits, capacity threshold and carbon emissions reduction goal.

- Carbon emissions depend drastically on the IPSDM limits that are imposed by the applied EE policy as well as the applied MIMO configuration scheme.
- The traditional belief that MIMO networks are always more energy-efficient and, subsequently, more environmentally friendly in comparison with SISO, MISO and SIMO ones may be misleading when the carbon emissions of overhead MIMO/HV/BPL networks are considered [64], [66], [111], [112]. More specifically, depending on the MIMO configuration scheme, applied EE policy, and SE and EE thresholds imposed, various trade-offs among SE and EE metrics may occur, namely: (i) in approximately 85% of the cases examined, given the number of transmit n_T and receive n_R ports, overhead $n_T \times n_R$ MIMO/HV/BPL networks with $n_T = n_R$ present better EE capacity values in comparison with other equivalent pure and mixed configurations, i.e. $i \times j$ MIMO networks with $1 \le i \le n_T$, $1 \le j \le n_R$; and (ii) Similarly to capacity results, in all the cases examined, overhead $1 \times n_R$ SIMO/HV/BPL networks demonstrate a more environmentally friendly behavior rather than equivalent $n_R \times 1$ MISO/HV/BPL networks. However, in general, by adopting suitable EE policies, the superiority of MIMO systems in terms of EE metrics may be further enhanced [64], [66], [111], [112].
- On the basis of capacity and EE capacity, the exact knowledge of the trade-off relation among IPSDM limits, EE policies and MIMO scheme configurations is essential for the overhead MIMO/HV/BPL network design.

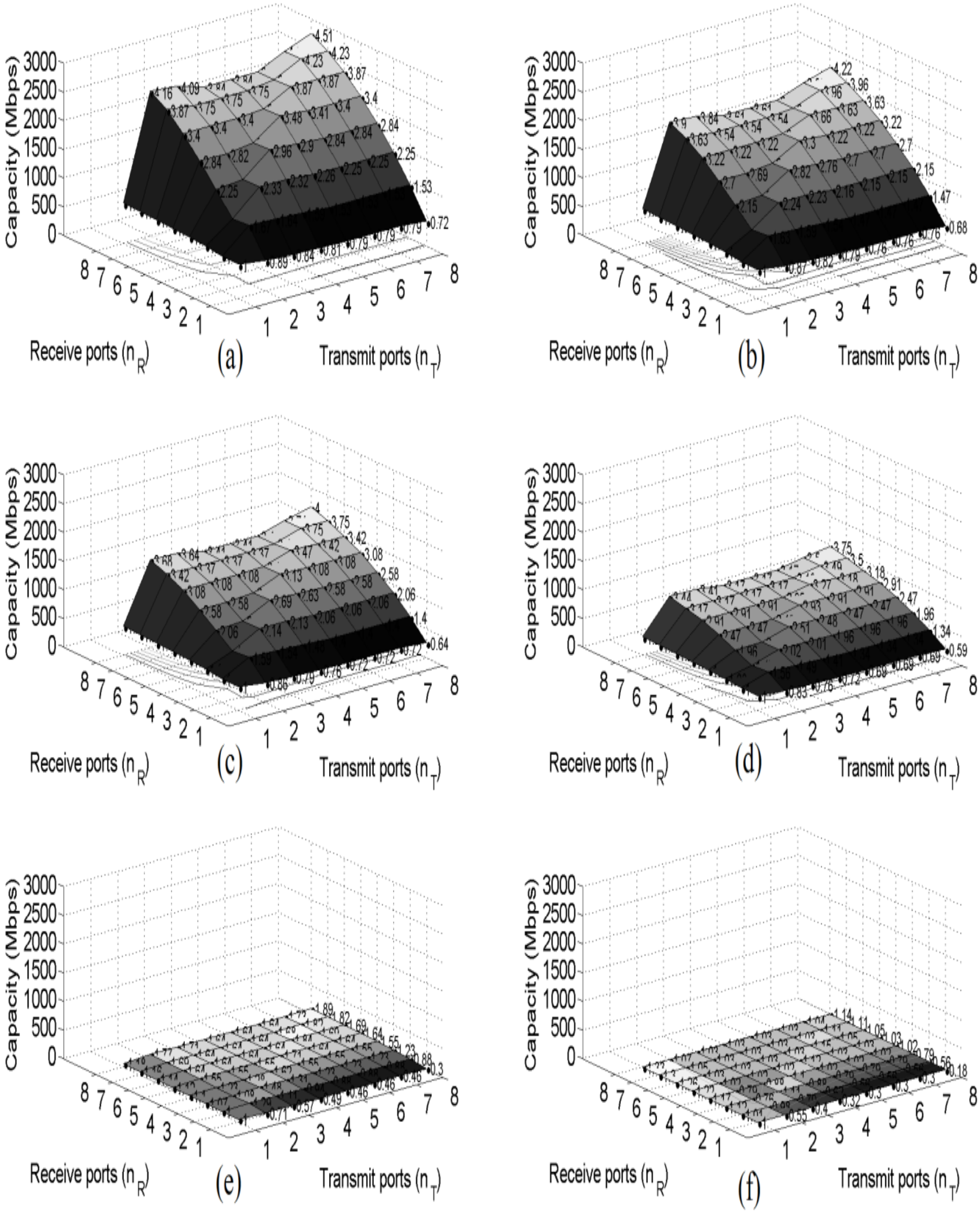

Figure 4. Capacity and relative capacity gain of overhead MIMO/HV/BPL "LOS" case networks for the EE policies of Table 1 (the subchannel frequency spacing is equal to 10kHz). (a) EE1. (b) EE2. (c) EE3. (d) EE4. (e) EE5. (f) EE6.

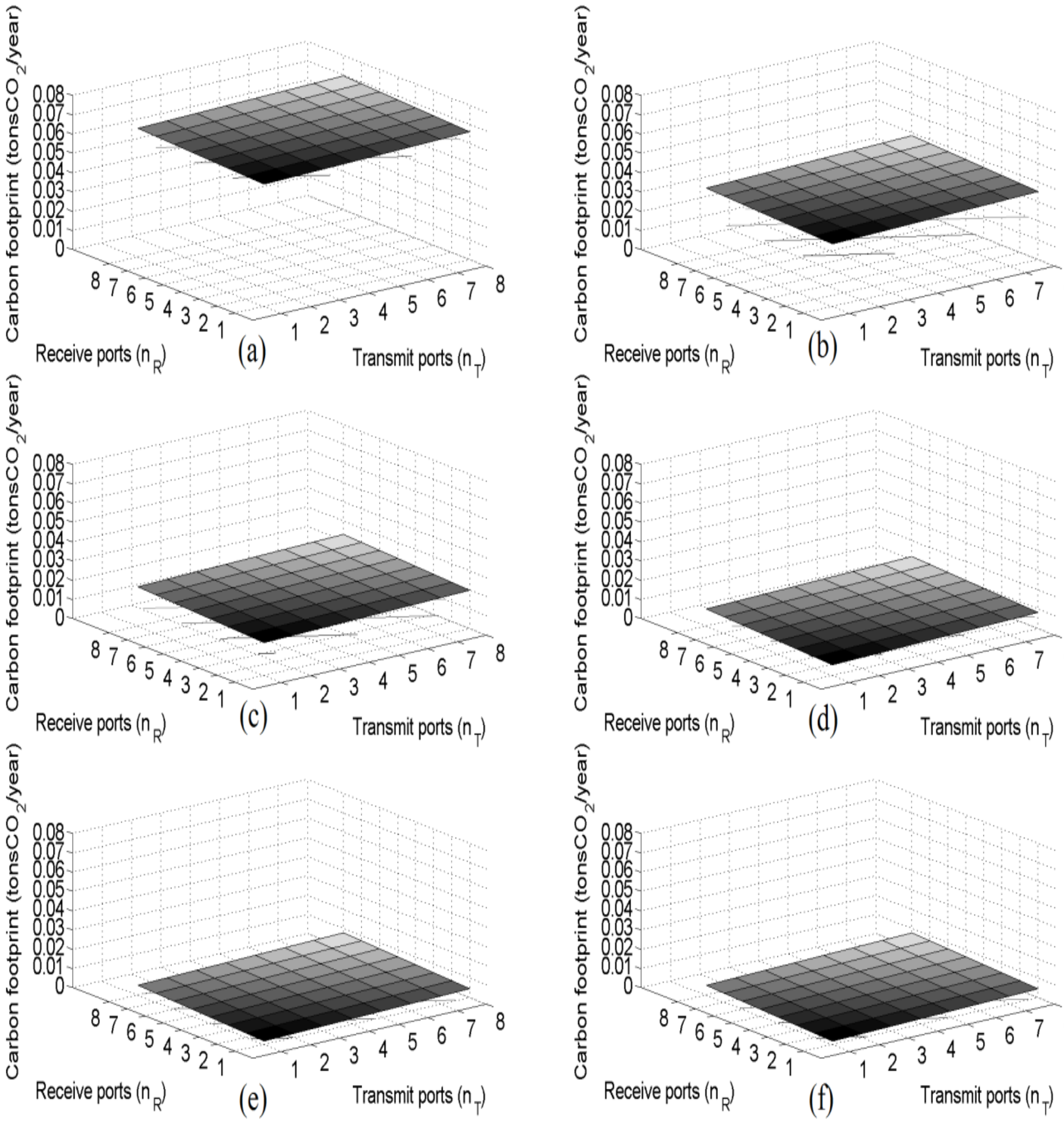

Figure 5. Carbon emissions of overhead MIMO/HV/BPL "LOS" case networks for the EE policies of Table 1 (the subchannel frequency spacing is equal to 10kHz). (a) EE1. (b) EE2. (c) EE3. (d) EE4. (e) EE5. (f) EE6.

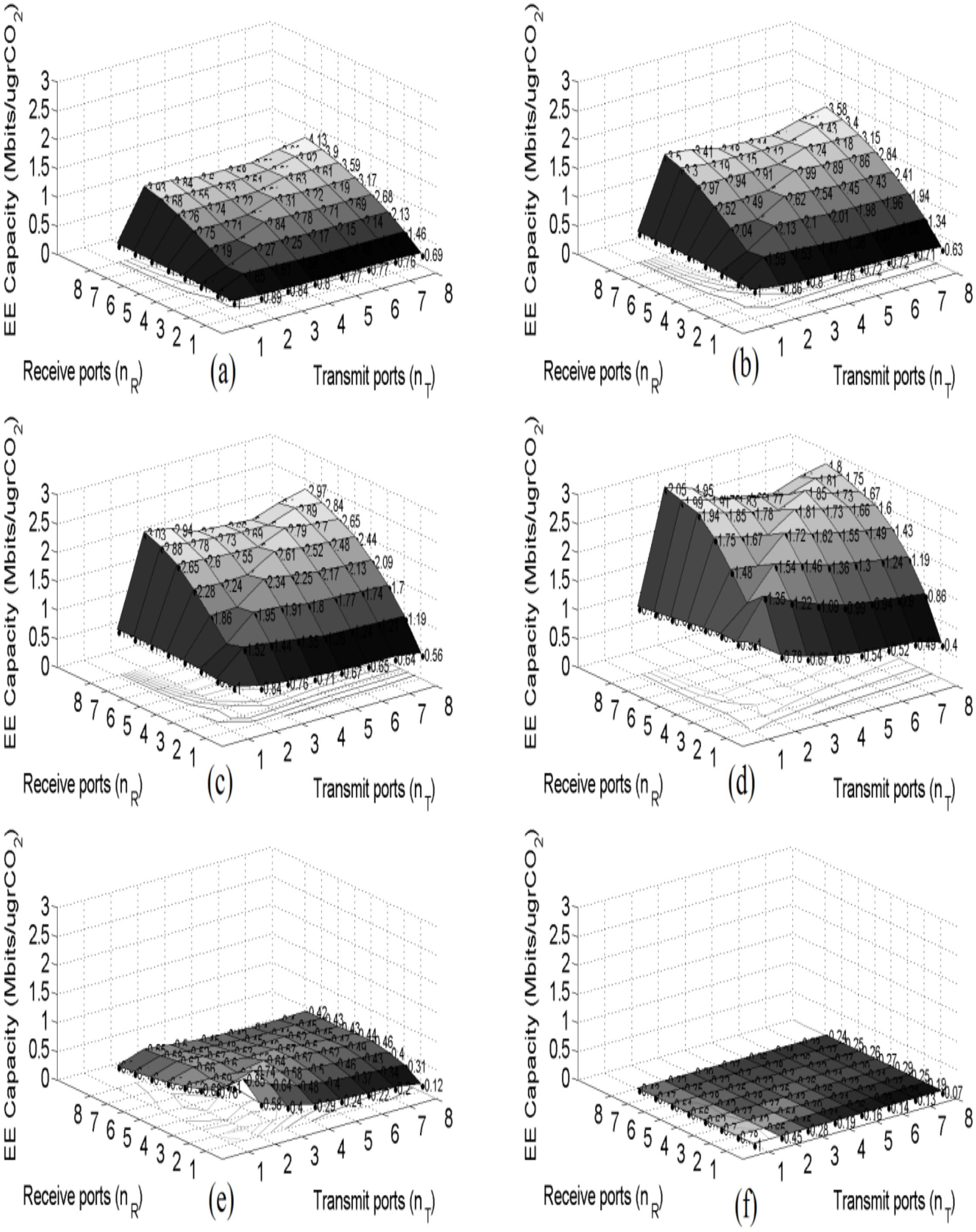

Figure 6. EE capacity and relative EE capacity gain of overhead MIMO/HV/BPL "LOS" case networks for the EE policies of Table 1 (the subchannel frequency spacing is equal to 10kHz). (a) EE1. (b) EE2. (c) EE3. (d) EE4. (e) EE5. (f) EE6.

- Carbon emissions savings in overhead MHMO/HV/BPL networks can be adjusted by appropriately regulating the capacity threshold requirements. Carbon emissions savings decrease as the capacity threshold increases. Therefore, at lower capacity thresholds, MIMO configuration schemes of lower cardinality can be used. As the capacity threshold increases, MIMO configuration schemes of higher cardinality are encouraged to be deployed [67].

C. Capacity and EE Capacity Trade-Off Curves

The aforementioned analysis has focused on the behavior of SE and EE metrics as well as their interaction through the lens of the carbon energy footprint. In fact, the relation between capacity and EE capacity in overhead MIMO/HV/BPL networks has been investigated for different MIMO configuration schemes and EE policies. Their interaction is important for designing greener overhead MIMO/HV/BPL networks since a better balance between spectral performance and environmental awareness can be achieved. In the rest of this paper, it is assumed that only the maximum values of pure scheme configurations (8×8 MIMO, 1×8 SIMO, 8×1 MISO, and SISO systems –either SISO/CCs or SISO/XCs–) of overhead MIMO/HV/BPL "LOS" case networks are going to be studied in the 3-88MHz frequency band.

Until now, the proposal of suitable IPSDM limits has derived from the compromise between BPL technology promotion and the protection of existing radioservices. Hence, during the proposal of today's IPSDM limits, environmental issues have not seriously been addressed. Nowadays, since the adoption of environmental initiatives becomes urgent, the proposed green factor $\Phi(f)$ aids towards that direction during the proposal of future's IPSDM limits in overhead MIMO/HV/BPL networks. Actually, EE1 –see Figs. 4(a) and 6(a)– and EE6 –see Figs. 4(f) and 6(f)– policies define two extreme state conditions of an interesting SE/EE trade-off.

To highlight this interesting SE/EE trade-off, in Fig. 7(a), the EE capacity of pure scheme configurations of the overhead MIMO/HV/BPL "LOS" case network is plotted versus the corresponding capacity for all continuous EE policies when anthracite electricity production is used. The SE/EE trade-off behavior of the above EE policies is compared against respective results of EE policies whose IPSDM limits range from -100 dBm/Hz to 0 dBm/Hz with step 0.1dBm/Hz (denoted as SISO/CC, SISO/XC, 1×8 SIMO, 8×1 MISO, and 8×8 MIMO curves). Similarly to Fig. 7(a), in Fig. 7(b), curves are drawn in the case of gas electricity production.

Combining Figs. 7(a) and 7(b) with the previous figures, several interesting conclusions may be given:

- The type of the electricity production, say either anthracite or gas electricity production of this paper, has strong effect on the carbon energy footprint.
- Similarly to the vintage trade-off between energy-efficient and SE metrics presented in the literature [7], [68], [126], the trade-off between EE capacity/capacity is also expected to be a quasiconcave function determining a dynamic equilibrium that depends on the EE policy, MIMO configuration scheme and the type of electricity production.

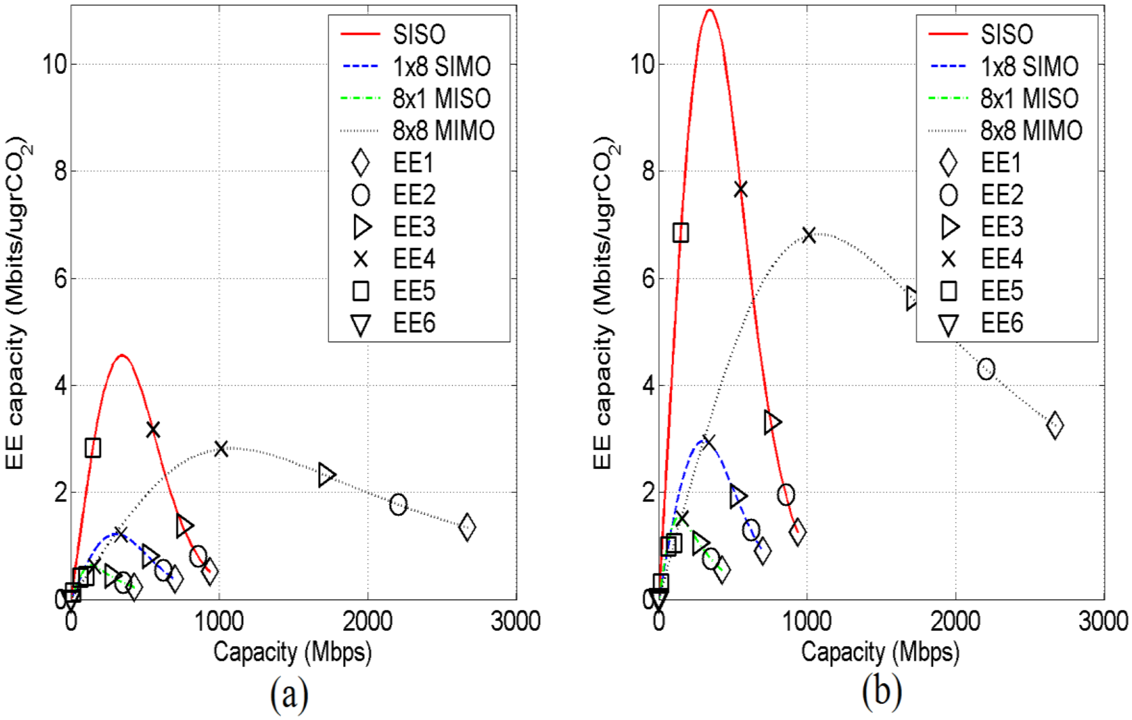

Figure 7. EE capacity and capacity trade-off curves of various single- and multi-port system implementations for the overhead HV/BPL "LOS" case when different EE policies are applied. (a) SISO, 1×8 SIMO, 8×1 MISO, and 8×8 MIMO trade-off curves when anthracite electricity production occurs. (b) SISO/CC, SISO/XC, 1×8 SIMO, 8×1 MISO and 8×8 MIMO trade-off curves when gas electricity production occurs.

- To achieve the best compromise among the different interests of SE- and EE-oriented lobbies, the best proposal is the operation of overhead MIMO/HV/BPL systems near the absolute maxima of trade-off curves presented in Figs. 7(a) and 7(b). Since operation points of today's overhead MIMO/HV/BPL systems are far from the best compromise –see EE1 points of Figs. 7(a) and 7(d)–, imminent IPSDM limits corrections through the proposed greener EE policies are required. In contrast, although very strict IPSDM limits –see EE5 and EE6 points of Figs. 7(a) and 7(d)– facilitate the EMC of BPL networks, the corresponding IPSDM limits push overhead MIMO/HV/BPL networks to operate with poor SE and EE performances. Therefore, observing all the cases examined, regardless of the MIMO configuration scheme and the electricity generation type, EE4 policy offers the best compromise results since its operation points are located at absolute maxima of trade-off curves.
- The countries' strategic frameworks towards cleaner energy sources further improve the SE/EE trade-off curves of overhead MIMO/HV/BPL networks. By interchanging from anthracite electricity production to gas one, EE capacity values get improved by a factor of 2.5 for given EE policy. Moreover, the choice of providers towards distributed energy sources, smart grid solutions and renewable sources tailored to the needs of their countries may, at the same time, skyrocket the EE performance of overhead MIMO/HV/BPL networks.

- The application of well-tuned EE policies combined with the use of adaptive green factor to regulate BPL operation in certain frequency segments according to carbon emission and capacity requirements may provide flexibility in authorities and providers so that the power consumption of overhead MIMO/HV/BPL networks gets reduced with slight deterioration of their capacity. The spectral selectivity is the main advantage of adaptive EE policies against continuous ones.
- Before overhead MIMO/HV/BPL systems interoperate with other broadband technologies –wired, such as fiber and DSL, and wireless, such as WiFi and WiMax–, the overhead HV/BPL systems need to intraoperate with other overhead and underground MV/BPL and LV/BPL that already are installed [5]-[7], [17], [19], [20], [22], [23]. Apart from compatible frequencies, equipment and signaling, BPL standardization and adequate IPSDM limits [26], scalable capacity must be assured taking into account the specific features of MIMO technology, overhead and underground HV/BPL, MV/BPL and LV/BPL transmission and EE issues. Emerging green technology considerations aid towards this direction by introducing suitable EE policies that both respect capacity requirements and ecological awareness.
- Sustainable development and growth is an important issue for countries that historically have been dependent on the exploitation of their natural resources (i.e., forestry, agriculture, mining and fishing) as their economic base [127]. Nowadays, through the prism of the green economy, countries can still commercialize their natural resources in order to financially stimulate their economies [128]. This modern resource harvest can be achieved through microgrids that are owned by the local communities. Microgrids include energy storage systems, distributed generation sources, like microturbines and fuel cell units, renewable energy sources, such as wind turbines and photovoltaic systems and controllable loads [9], [10]. Except for their environmental effect, the operation of microgrids can also significantly improve the SE/EE trade-off curves of overhead MIMO/HV/BPL networks at a local basis. Hence, the future research is going to focus on: (i) the development of new ad-hoc SE/EE trade-off curves of overhead MIMO/HV/BPL networks at a local and daily basis that can combine electricity supply/demand models with the energy source mix of the power grid and the microgrids [129], [130], [131]; and (ii) the stabilization of SE/EE trade-off curves when fluctuations of the energy production in the energy source mix occurs either in the power grid or in microgrids [11], [132]-[134].

VII. Conclusions

This paper has focused on the assessment of the broadband performance of overhead MIMO/HV/BPL networks when environmental policies are adopted. Using suitable SE and EE metrics, major features of today’s BPL networks have been reviewed for use in future’s greener overhead MIMO/HV/BPL networks. In the light of the information theory, the capacity values of all the considered overhead MIMO/HV/BPL networks revealed that these networks can operate both as a robust broadband platform for SG applications across the transmission power grid and as a green communications solution. In the meanwhile, exploiting the proposed SE/EE trade-offs that determine dynamic equilibrium between capacity and EE capacity of the different overhead MIMO/HV/BPL configurations, a wiser compromise among transmission rates, EMI regulations and ecology awareness may occur; an important step towards the design and operation of faster, more electromagnetic compatible and greener overhead MIMO/HV/BPL networks in the oncoming SG network.

Conflicts of Interest

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

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