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DEPLOYMENT CONCEPTS FOR OVERHEAD HIGH VOLTAGE BROADBAND OVER POWER LINES CONNECTIONS WITH TWO-HOP REPEATER SYSTEM: CAPACITY COUNTERMEASURES AGAINST AGGRAVATED TOPOLOGIES AND HIGH NOISE ENVIRONMENTS

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Abstract—This paper extends the existing transmission and capacity analysis in order to investigate the broadband potential of overhead high-voltage/broadband over power lines (HV/BPL) connections where a single repeater is additively deployed between their existing transmitting and receiving ends (overhead HV/BPL connections with two-hop repeater system). The contribution of this paper is three-fold. First, the broadband performance of various overhead HV/BPL connections with two-hop repeater system has been studied with regard to their cumulative capacity. The analysis and relevant simulations validate the potentially excellent communications medium of overhead HV/BPL channels over a 25 km repeater span well beyond 88 MHz in terms of cumulative capacity. In addition, through the deployment of two-hop repeater systems, apart from the upsurge of cumulative capacity, overhead HV/BPL connections become more adaptive to different capacity requirements. Second, it is found that overhead HV/BPL network capacity performance depends drastically on factors such as the overhead HV grid topology and the noise characteristics. Through the deployment of two-hop repeater systems, capacity losses due to existing aggravated overhead HV/BPL topologies and high noise environments are significantly reduced. Third, the numerical results reveal the importance of considering as suitable mitigation technique the deployment of overhead HV/BPL connections with two-hop repeater system. Except for the low-cost and quick technology upgrade of existing overhead HV/BPL networks, this mitigation

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technique may permit the future broadband exploitation of overhead HV/BPL networks and their interoperability with other broadband technologies.

1. INTRODUCTION

The recent impetus in modernizing the vintage transmission and distribution grids — i.e., high-voltage (HV), medium-voltage (MV), and low-voltage (LV) grids — through developing an advanced IP-based power system equipped with a plethora of potential smart grid (SG) applications and providing broadband last mile access in remote and/or underdeveloped areas may be facilitated via the deployment of broadband over power lines (BPL) networks [1–14]. Recently, significant efforts to exploit BPL potential of HV power transmission grid for BPL transmission have come up [5, 7].

In this paper, an important feature of HV transmission lines is their multiconductor nature. Through the lens of multiconductor transmission line (MTL) theory, specific propagation modes may be supported by each type of cable and MTL configuration. These modes correspond to specific distributions of voltage propagating along the MTL configuration with their own attenuation and phase velocity. The behavior of BPL channels installed on multiconductor overhead HV power lines is studied based on the well established hybrid model that is usually employed to examine the behavior of BPL/MTL structures [1–10, 16–20]. This hybrid model is based on: (i) a bottom-up approach consisting of an appropriate combination of similarity transformations and MTL theory. This approach helps towards the determination of the characteristic impedance and the propagation constant of each mode [3, 9, 10, 15–28]; and (ii) a top-down approach (TM2 method) consisting of the concatenation of multidimensional T-matrices of network modules [1–9, 15, 16, 21, 22]. This approach serves in determining the end-to-end channel attenuation of various HV/BPL connections; En bloc, through this hybrid method, several important transmission and spectral efficient metrics such as end-to-end channel attenuation and capacity are defined [1, 2, 3–6, 29–31].

Observing the numerical capacity results of the aforementioned hybrid model, the potentially excellent communications medium of overhead HV/BPL channels over a 25 km repeater span well beyond 88 MHz is confirmed [5, 7]. However, to use overhead HV/BPL networks as efficient backbone networks that concentrate traffic under specific minimum capacity requirements, overhead HV/BPL networks should adaptively cover long-range transmission areas creating and exploiting ad-hoc less aggravated overhead HV/BPL topologies [32, 33]. Moreover, when high noise environments occur — e.g., transmission near suburban and urban areas, heavy weather conditions, significant narrowband interferences, etc. —, overhead HV/BPL networks should again be ad-hoc transformed into denser overhead HV/BPL topologies so that the capacity threshold is ensured.

Towards that direction, multi-hop communications, which have been widely studied in terrestrial wireless environments [32, 34–36], that increase link reliability and extend communication range are considered for overhead HV/BPL networks. Recently, in the BPL literature, several practical configurations have been proposed in order to explore the benefits of relay-based communications [33, 37–41]. In this paper, the overhead HV/BPL networks that consist of the cascade of overhead HV/BPL connections are modified through the ad-hoc insertion of single repeaters between existing transmitting and receiving ends. These upgraded connections are referred to as overhead HV/BPL connections with two-hop repeater system and exploit the virtues of multi-hop transmission [37–39, 41].

Through the prism of information theory [1, 2], the capacity performance of overhead HV/BPL networks with two-hop repeater system validates the significant mitigation of capacity losses due to aggravated overhead HV/BPL topologies and/or high noise environments. Therefore, exploiting the delivered scalable capacities and depending on purpose, overhead HV/BPL networks with two-hop repeater system may either operate as backbone BPL network concentrating local traffic from other already existing surrounding broadband systems or simply interoperate with other broadband technologies — wired, such as fiber and DSL, and wireless, such as WiFi and WiMax — or intraoperate with other overhead and underground HV/BPL, MV/BPL, and LV/BPL systems in the SG landscape [1, 2, 5–9, 42, 43].

The rest of the paper is organized as follows: In Section 2, the overhead HV MTL configuration and indicative overhead HV/BPL topologies adopted in this paper are demonstrated. Section 3 summarizes the fundamental principles of overhead HV/BPL transmission via the hybrid model: MTL theory, eigenvalue decomposition (EVD) analysis, TM2 method, and the coupling scheme concerning injection of BPL signals into the HV power lines. Section 4 briefly deals with electromagnetic interference (EMI) regulations and their respective power constraints, noise characteristics, and the evaluation of the capacity delivered by overhead HV/BPL networks with two-hop repeater system. In Section 5, numerical results and conclusions are provided, aiming at revealing the significant role of overhead HV/BPL networks with two-hop repeater system towards the capacity alleviation of inherent and imposed drawbacks of the overhead HV grid. Section 6 concludes the paper.

2. OVERHEAD HV TRANSMISSION POWER NETWORKS

2.1. Overhead HV MTL Configuration

Overhead HV power transmission systems are mainly classified in the electrical power industry by: (i) the voltage levels (from 150 kV up to 1000 kV); (ii) the number of MTL circuits per each tower (mainly, either single- or double-circuit). In the case of single-circuit three-phase overhead HV systems, each tower supports three phase conductors whereas in the case of double-circuit three-phase overhead HV systems, each tower supports six phase conductors; and (iii) the number of neutral conductors per each tower [5, 7, 44–47].

Overhead 400 kV double-circuit overhead HV transmission phase lines with radii $r_p^{400\,\mathrm{kV}} = 15.3\,\mathrm{mm}$ hang at typical heights $h_p^{400\,\mathrm{kV}}$ equal to 20 m above ground — conductors 1, 2, 3, 4, 5, and 6 —. These six

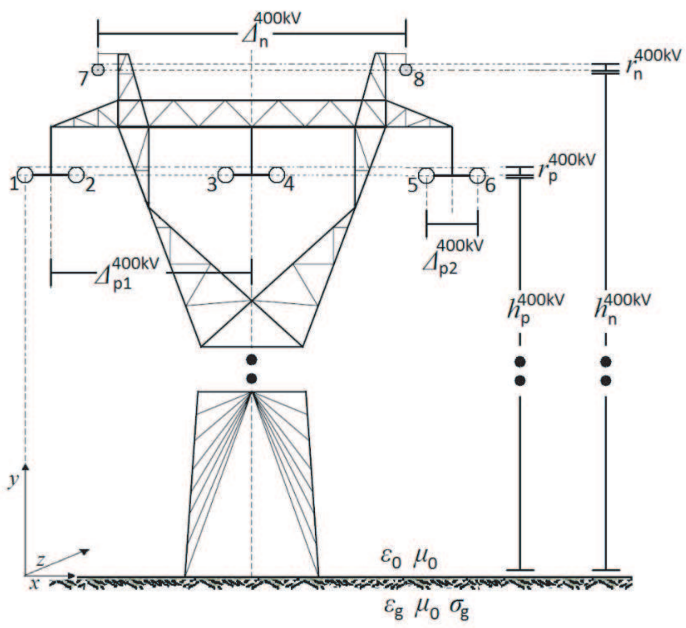

Figure 1. Typical overhead 400 kV double-circuit HV multiconductor structures [48–52].

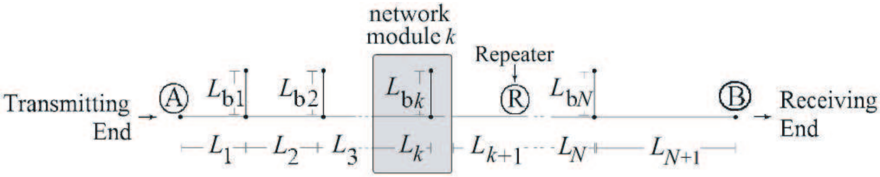

Figure 2. End-to-end HV/BPL connection with N branches [1–3, 5–9, 11, 15].

phase conductors are divided into three bundles; the phase conductors of each bundle are connected by non-conducting spacers and are separated by $\Delta_{p2}^{400\,\mathrm{kV}}$ equal to 400 mm, whereas bundles are spaced by $\Delta_{p1}^{400\,\mathrm{kV}}$ equal to 10 m. Moreover, two parallel neutral conductors with radii $r_n^{400\,\mathrm{kV}} = 9\,\mathrm{mm}$ spaced by $\Delta_n^{400\,\mathrm{kV}}$ equal to 12 m hang at heights $h_n^{400\,\mathrm{kV}}$ equal to 23.7 m — conductors 7 and 8 —. This double-circuit eight-conductor ($n^{400\,\mathrm{kV}} = 8$) overhead HV distribution line configuration is considered in the present work consisting of ACSR conductors — see Fig. 1 — [5, 7, 44–52]. The ground is considered as the reference conductor. The conductivity of the ground is assumed $\sigma_g = 5\,\mathrm{mS/m}$ and its relative permittivity $\varepsilon_g = 13$ which is a realistic scenario [1, 3, 5, 7, 17, 53]. The impact of imperfect ground on signal propagation via overhead power lines was analyzed in [1, 2, 3–8, 17, 53–57] and will not be treated in this study.

2.2. Overhead HV/BPL Topologies

Today, thousands of km of overhead HV lines are installed in above of 120 countries. These lines stretch from approximately 25 km to 190 km from the generation points before reaching any population centers. Shorter branches in the range of 10 km to 50 km are used in order to connect overhead HV transmission lines either between them or with HV/MV substations [7, 10, 12, 48–50, 58–60]. In the following analysis, relatively dense overhead HV/BPL connections of path length up to 25 km are assumed.

The simple overhead HV/BPL connection of Fig. 2, being bounded by transmitting and receiving end and having N branches, has been considered. In order to apply the hybrid model, which is analytically presented in [1–10, 15–20] and briefly outlined in Section 3, an end-to-end overhead HV/BPL connection is separated into segments (network modules), each of them comprising the successive branches encountered.

With reference to Fig. 2, the following four representative overhead HV/BPL topologies are examined:

(1) A typical urban topology (urban case) with $N = 3$ branches ($L_1 = 1.15\,\text{km}$, $L_2 = 12.125\,\text{km}$, $L_3 = 8.425\,\text{km}$, $L_4 = 3.3\,\text{km}$, $L_{b1} = 27.6\,\text{km}$, $L_{b2} = 17.2\,\text{km}$, $L_{b3} = 33.1\,\text{km}$).

(2) A typical suburban topology (suburban case) with $N = 2$ branches ($L_1 = 9.025\,\text{km}$, $L_2 = 12.75\,\text{km}$, $L_3 = 3.225\,\text{km}$, $L_{b1} = 46.8\,\text{km}$, $L_{b2} = 13.4\,\text{km}$).

(3) A typical rural topology (rural case) with only $N = 1$ branch ($L_1 = 3.75\,\text{km}$, $L_2 = 21.25\,\text{km}$, $L_{b1} = 21.1\,\text{km}$).

(4) The "LOS" transmission along the average end-to-end distance $L = L_1 + \ldots + L_{N+1} = 25\,\text{km}$ when no branches are encountered. This topology corresponds to Line-of-Sight transmission in wireless channels.

3. THE BASICS OF OVERHEAD HV/BPL TRANSMISSION ANALYSIS

As it has also been analyzed in other BPL systems [1–9, 15], 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 [1–9, 15, 24, 25]. These eight modes that are supported by the overhead HV MTL case of Fig. 1 and propagate through overhead HV/BPL topologies of Fig. 2 are [1–9, 12, 15–18, 21, 22, 24, 25, 48–50, 53–58, 61–65]: (i) the Common Mode of overhead BPL transmission (CM); and (ii) the seven Differential Modes of overhead BPL transmission (DM_i, $i = 1,\ldots,8$). Their spectral behavior is thoroughly investigated in [5, 7].

As it has already been presented in [1–9, 15], the TM2 method, which is based on the scattering matrix theory [1–9, 15, 16, 18–22, 27, 64, 66, 67] and presented analytically in [9], models the spectral relationship between $V_i^m(z)$, $i = 1,\ldots,8$ and $V_j^m(0)$, $j = 1,\ldots,8$ proposing operators $H_{i,j}^m\{\cdot\}$, $i,j = 1,\ldots,8$ so that

$$\mathbf{V}^m(z) = \mathbf{H}^m\{\mathbf{V}^m(0)\} \tag{1}$$

where $\mathbf{V}^m(z) = [V_1^m(z) \ldots V_8^m(z)]^T$ are the EVD modal voltages, $[\cdot]^T$ denotes the transpose of a matrix, $\mathbf{H}^m\{\cdot\}$ is the 8×8 EVD modal transfer function matrix whose elements $H_{i,j}^m\{\cdot\}$, $i, j = 1, \ldots, 8$ are the EVD modal transfer functions, and $H_{i,j}^m\{\cdot\}$ denotes the element of matrix $\mathbf{H}^m\{\cdot\}$ in row i of column j [1–9, 15].

According to how signals are injected onto overhead HV/BPL transmission lines, two different coupling schemes exist [5, 7]: (i) Wire-to-Wire (WtW) coupling schemes when the signal is injected between two conductors; and (ii) Wire-to-Ground (WtG) coupling schemes when the signal is injected onto one conductor and returns via the ground. As it has already been reported in [5, 7], WtW coupling schemes are primarily affected by the propagation of DMs, whereas WtG coupling schemes are influenced mostly by CM behavior. From [5, 7], since CM demonstrates the best transmission and capacity results among the other supported DMs, WtG coupling schemes attain more favorable results in terms of transmission and capacity metrics in comparison with the WtW ones. However, the significant EMI of WtG coupling schemes to other already licensed wireless communications due to CM is their main drawback [7, 68–70]. As today's EMI regulations provide the required protection of BPL operation against other radioservices regardless of the coupling scheme applied, the main issue of capacity maximization still remains. Anyway, without losing the generality of the analysis, only WtG coupling schemes will be preferred for the rest of the analysis [5, 7].

Assuming WtG coupling scheme between conductor s, $s = 1, \ldots, 8$ and the ground, the coupling WtG transfer function $H^{\mathrm{WtG}^s}\{\cdot\}$ is given from [5, 7].

$$H^{\mathrm{WtG}^s}\{\cdot\} = [\mathbf{C}^{\mathrm{WtG}^s}]^T \cdot \mathbf{T}_V \cdot \mathbf{H}^m\{\cdot\} \cdot \mathbf{T}_V^{-1} \cdot \mathbf{C}^{\mathrm{WtG}^s} \tag{2}$$

where $\mathbf{C}^{\mathrm{WtG}^s}$ is the 8×1 WtG coupling column vector with zero elements except in row s where the value is equal to 1, and $\mathbf{T}_V$ is 8×8 matrix depending on the overhead power grid type, the frequency, the physical properties of the cables, and the geometry of the MTL configuration [3–5, 7, 16, 24, 25, 48–50, 53, 58, 61, 63, 65]. WtG coupling between conductor s and ground will be detoned as WtG^s , hereafter.

4. EMI REGULATIONS, NOISE, AND CAPACITY OF OVERHEAD HV/BPL CONNECTIONS WITH TWO-HOP REPEATER SYSTEM

4.1. EMI Regulations and Power Constraints

Becoming both EMI source and EMI victim, the successful symbiosis of BPL systems with other already existing wireless and telecommunication systems is ensured through proposals given by a significant number of regulatory bodies [1, 2, 68–74]. As it has already presented in [1, 2], a simple regulatory approach is to avoid formal EMI compliance tests by limiting injected power spectral density (IPSD) to a level that, in most circumstances, does not produce EMI that exceeds certain thresholds.

Among the different IPSD limits proposals, the IPSD limits proposed by Ofcom for compliance with FCC Part 15, which are presented in [68–70, 73, 74], are the most cited due to their proneness towards the deployment of high-bitrate BPL technology. More specifically, for overhead HV/BPL networks, according to Ofcom, in the 1.705–30 MHz frequency range maximum levels -60 dBm/Hz constitute appropriate IPSD limits $p(f)$ providing presumption of compliance with the current FCC Part 15 [1, 2, 69, 75, 76]. In the 30–88 MHz frequency range, maximum IPSD limits $p(f)$ equal to -77 dBm/Hz for overhead HV/BPL systems are assumed to provide a presumption of compliance in this frequency range [1, 2, 75, 76].

4.2. Noise Characteristics

According to [1, 2, 17, 53, 77–79], two types of noise are dominant in overhead HV/BPL networks: (i) *Colored background noise* that is the environmental noise which depends on weather conditions, humidity, geographical location, height of cables above the ground, corona discharge, etc. [17, 53, 55, 74, 80, 81]; and (ii) *Narrowband noise* that is the sum of narrowband interference from other wireless services which exhibits local variations and is time-dependent [1, 2, 53, 80, 81].

As it regards the noise properties of overhead HV/BPL networks, to extend this analysis in the 1.705–88 MHz range, uniform additive white Gaussian noise (AWGN) PSD level $N(f)$ will be assumed [1, 2, 17, 53, 75, 76, 82, 83]. In detail, since noise models are based on empirical noise measurements [1, 2, 17, 37, 38, 42, 53, 84], to evaluate the capacity of overhead HV/BPL systems, a uniform AWGN/PSD level is assumed that varies from -95 dBm/Hz (noise type A) to -115 dBm/Hz (noise type B) with average value equal to -105 dBm/Hz. Noise type A and B represent the bad and the good noise scenario, respectively.

4.3. Capacity

According to information theory, capacity is defined as the maximum achievable transmission rate over an overhead HV/BPL channel and depends on the applied MTL configuration of overhead HV/BPL network, the overhead HV topology, the coupling scheme applied, the

EMI limits adopted, and the noise characteristics. With reference to Fig. 2, in the case of overhead HV/BPL connections, the overall capacity C, which is the end-to-end capacity from A to B, is determined from [1, 2].

$$C = C_{A \mapsto B} = f_s \sum_{q=0}^{K-1} \log_2 \left\{ 1 + \left[\frac{\langle p(qf_s) \rangle_L}{\langle N(qf_s) \rangle_L} \cdot |H_{A \mapsto B}(qf_s)|^2 \right] \right\} \quad (3)$$

where $[\cdot]_{A \mapsto B}$ determines the transmitting (A) and receiving (B) end point, $\langle \cdot \rangle_L$ 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 [1, 2, 72].

With reference to Fig. 2, let assume that a two-hop repeater system is installed at the point R of an overhead HV/BPL connection. Hence, overhead HV/BPL connection is divided into two new overhead HV/BPL topologies. Due to the bus-bar connection of these two new topologies, in the light of information theory [33, 37–41], the new overall capacity C' of the overhead HV/BPL connection is determined as the minimum value of the capacities of these two topologies; say $C_{A \mapsto R}$ and $C_{R \mapsto B}$. Based on (3), the new overall capacity is determined from

$$C' = \min \{C_{A \mapsto R}, C_{R \mapsto B}\} \quad (4)$$

where $\min \{x, y\}$ returns the smallest value between either x or y.

Based on (3) and (4), the cumulative capacity is defined as the cumulative upper limit of information which can be reliably transmitted over the end-to-end overhead HV/BPL connection.

5. NUMERICAL RESULTS AND DISCUSSION

The simulation results of various types of overhead HV/BPL connections with two-hop repeater system aim at investigating: (a) their broadband HV/BPL capacity performance; and (b) their counteracting role against capacity losses due to aggravated topologies and high noise environments.

As mentioned in Section 3, 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 [1–9, 15–19, 21, 22, 24–26, 53].

For the numerical computations, the 400 kV double-circuit overhead HV transmission line configuration depicted in Fig. 1 has been considered and the simple overhead topology of Fig. 2, 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, the transmitting and the receiving ends are assumed matched to the characteristic impedance of the modal channels, whereas the branch terminations are assumed open circuit [1, 2, 4, 5, 7, 8, 12, 17, 48–51, 58].

Finally, only one of the WtG coupling schemes — say WtG^1 coupling scheme — will be examined in the rest of this paper without affecting the generality of the analysis, due its favorable capacity performance results [5, 7, 9].

5.1. Influence of Overhead HV Grid Topology on Capacity Performance and the Role of Overhead HV/BPL Networks with Two-Hop Repeater System

The potential capacity performance in terms of cumulative capacity in the 3–88 MHz frequency band is evaluated based on the application of FCC Part 15 (under the assumption of Ofcom/IPSDM limits) when different indicative overhead HV/BPL topologies — presented in Subsection 2.2 — occur. To evaluate the capacity of overhead HV/BPL connections, the average uniform AWGN/PSD level, which is equal to −105 dBm/Hz, is assumed in this subsection.

In Fig. 3(a), the cumulative capacity is plotted versus frequency for the urban, suburban, rural, and "LOS" transmission case when legacy overhead HV/BPL systems are installed. Observing Fig. 3(a) and in accordance with, the simulations of various overhead HV/BPL topologies unveil the potentially excellent communications medium of overhead HV grid when BPL connections deployed even over a 25 km repeater span well beyond 88 MHz. The fact that overhead HV/BPL lines resemble a low-loss flat-fading transmission system with high-capacity characteristics shows as an attractive broadband last mile alternative and SG backbone solution [1, 2, 5, 7, 48, 51].

Despite these favorable high-capacity characteristics, the taxonomy of channel classes of other MV/BPL and LV/BPL channels still occurs in the case of overhead HV/BPL channels [1–9, 15, 29, 85]. According to the picture obtained from their capacity behavior, the overhead HV/BPL topologies may be classified into three major channel classes: *"LOS" class* that corresponds to the best possible overhead HV/BPL capacity conditions; *Good class* that corresponds to the majority of cases near rural and suburban areas and are characterized by their average capacity performance; and *Bad class* that corresponds to the worst possible overhead HV/BPL capacity performance and are

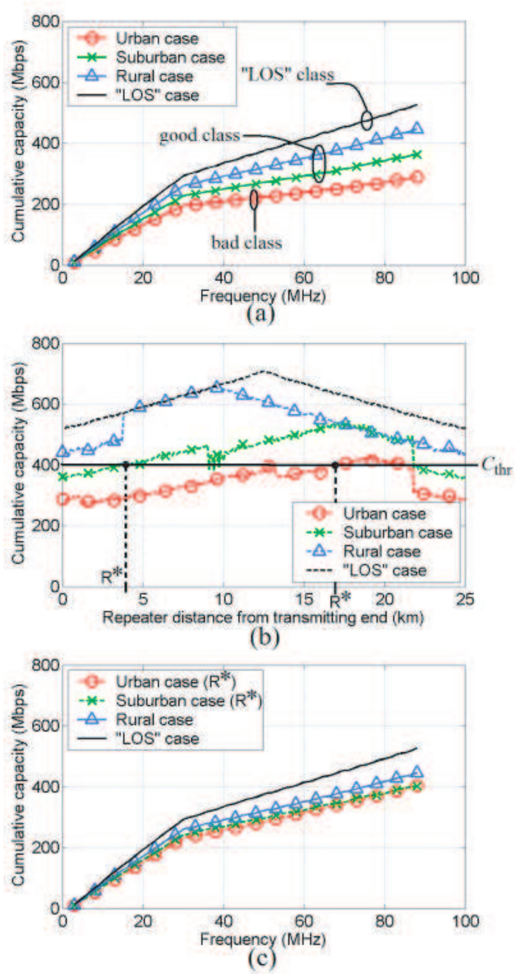

Figure 3. Broadband potential of overhead HV/BPL connections in the 3–88 MHz frequency range. (a) Cumulative capacity versus frequency for urban, suburban, rural, and "LOS" transmission case of legacy overhead HV/BPL connections. (b) Cumulative capacity versus repeater distance from point A — see Fig. 2 — when one repeater is deployed in the above cases of legacy overhead HV/BPL connections. (c) Cumulative capacity versus frequency for urban case and suburban case of overhead HV/BPL connections with two-hop repeater system for given capacity threshold C_{thr} — denoted with (R*) —; and rural case and "LOS" transmission case of legacy overhead HV/BPL connections.

present near aggravated environments such as suburban and urban areas.

Although the cumulative capacities of the indicative overhead HV/BPL topologies are ranging from 289 Mbps to 527 Mbps in the 3–88 MHz frequency range when FCC Part 15 is adopted, which reveal the strong broadband potential of overhead HV/BPL networks, the aforementioned taxonomy of channel classes is reflected on the capacity difference between "LOS" and bad classes; the capacity difference between urban and "LOS" topologies remains asymmetrically high being equal to 238 Mbps. The need of: (i) intraoperability/interoperablity of overhead HV/BPL networks with other broadband technologies under the aegis of a unified SG network [1, 2, 5, 31, 48, 51]; and (ii) overhead HV/BPL networks to operate as backbone network that efficiently concentrates local traffic either from other already existing surrounding telecommunications systems or directly through their wireless interfaces due to special conditions; urges the guarantee of scalable capacities among different topologies defining a more advanced and useful complementary proposal to the existing one of standardized topologies [10, 12, 71, 86, 87].

Taking under consideration the high investment cost of the already installed overhead HV/BPL network infrastructure and the prohibitively high installation cost of a new denser overhead HV/BPL network, with reference to Fig. 2, the appropriate installation position R of a two-hop repeater system across the end-to-end transmission path of the existing overhead HV/BPL topologies define a convenient and quick solution while, at the same time, the demand of scalable capacities may be promoted. In Fig. 3(b), the cumulative capacity of overhead HV/BPL connection with a two-hop repeater system is plotted versus the repeater distance from the transmitting end for the aforementioned overhead HV/BPL topologies.

From Fig. 3(b), it is obvious that the insertion of two-hop repeater system significantly improves the cumulative capacities of overhead HV/BPL connections; in urban, suburban, rural, and "LOS" transmission case, there is a potential cumulative capacity percentage increase up to 48.8%, 48.9%, 48.9%, and 36.6%, respectively. This cumulative capacity increase is significantly crucial for aggravated overhead HV/BPL connections, such as urban and suburban cases, since the design of high-bitrate overhead HV/BPL networks imposes strict requirements concerning overall network capacity.

More specifically, with reference to Fig. 3(b), let's assume that a cumulative capacity threshold C_{thr}, which is equal to 400 Mbps, is imposed across an overhead HV/BPL network in order to deliver emergent high local traffic appeared across the network. Each overhead

HV/BPL network consists of the cascade connection of aforementioned indicative overhead HV/BPL connections. With reference to Fig. 3(a), urban and suburban topologies do not satisfy this cumulative capacity threshold restriction. However, with reference to Fig. 3(b), through the deployment of two-hop repeater systems at appropriate positions across their end-to-end transmission paths, the cumulative capacity threshold restriction can be satisfied for all indicative connections examined.

In Fig. 3(c), the cumulative capacity is plotted versus frequency for: (i) the urban case — denoted as urban case (R*) — and suburban case — denoted as suburban case (R*) — when two-hop repeater system is deployed at repeater distance from the transmitting end R* equal to 17 km and 4 km, respectively; and (ii) the rural case and "LOS" transmission case of the legacy overhead HV/BPL systems. The technique of deploying two-hop repeater system to the existing overhead HV/BPL topologies may drastically improve the cumulative capacity of the connections offering potential cumulative capacity percentage increase ranging from 36.6% to 48.9%. Depending on the capacity requirements and other technoeconomic issues, denser multi-hop repeater systems may be deployed in order either to serve urgent local traffic or to permit the future broadband upgrade of the existing overhead HV/BPL grid.

5.2. Effect of Noise Environment on Capacity Performance and the Role of Overhead HV/BPL Connections with Two-Hop Repeater System

Except for overhead HV/BPL topologies, in order to establish high-bitrate data communications with capacities in the range of hundreds of Mbps or even Gbps in overhead HV/BPL networks, the consideration of the hostile noise environment properties is required. For the design of appropriate modulation and coding schemes, detailed knowledge of the noise properties in the frequency range up to 88 MHz is essential. As it has already been presented in Subsection 4.2, opposite to many other broadband communications systems, the nature of overhead HV/BPL noise is highly variable depending on either inherent environmental factors or imposed narrowband interference conditions [1, 2, 17, 53, 55, 74, 77–81].

The following discussion focuses on the capacity capabilities in terms of cumulative capacity in the 3–88 MHz frequency band through the application of FCC Part 15 (under the assumption of Ofcom/IPSDM limits). Based on the indicative overhead HV/BPL topologies presented in Subsection 2.2, the following analysis investigates: (i) the influence of different noise environments to overall capacity; and (ii) the mitigation of capacity losses due to noise variability through the installation of two-hop repeater systems.

In Figs. 4(a)–(c), the cumulative capacity is plotted versus frequency for the urban, suburban, rural, and "LOS" transmission case of legacy overhead HV/BPL systems in the 3–88 MHz frequency range when noise type A, average noise, and noise type B are considered, respectively.

Figures 4(a)–(c) reveal how significant for BPL transmission is the noise variance [80, 81]. In fact, capacity differences of the order of hundreds of Mbps are observed among the three different noise types considered; say, in "LOS" transmission case, cumulative capacity is equal to 287 Mbps, 527 Mbps, and 803 Mbps for noise type A, average noise, and noise type B, respectively. It should also be noted that if worst noise environments than noise type A occur, BPL performance is seriously restricted even if power injection is constrained by the highest today's EMI limits that are those described in FCC Part 15: in urban case, cumulative capacity is equal to 125 Mbps, 281 Mbps, and 530 Mbps for noise type A, average noise, and noise type B, respectively.

Taking under consideration: (i) the already installed overhead HV/BPL network infrastructure; and (ii) the assumption that, due to long-range transmission across overhead HV/BPL networks, the favorable and aggravated noise environments are sporadically and locally distributed; with reference to Fig. 2, the appropriate installation position R of a two-hop repeater system across the end-to-end transmission path of the existing overhead HV/BPL topologies is preferred against the installation of a new denser overhead HV/BPL network. In Fig. 4(d), the cumulative capacity of overhead HV/BPL connections with a two-hop repeater system is plotted versus the repeater distance from the transmitting end for the aforementioned overhead HV/BPL topologies when noise type A occurs. In Figs. 4(e) and 4(f), similar curves are given in the case of average noise and noise type B, respectively.

Comparing Figs. 4(d)–(f), two-hop repeater systems significantly improve the cumulative capacities of overhead HV/BPL connections, more specifically: (i) for noise type A, in urban, suburban, rural, and "LOS" transmission case, there is a potential percentage increase of cumulative capacity up to 61%, 70.5%, 72.2%, and 49.8%, respectively; (ii) for average noise, the corresponding potential percentage increase has been presented in Subsection 5.1; and (iii) for noise type B, in urban, suburban, rural, and "LOS" transmission case, there is a potential percentage increase of cumulative capacity up to 30.2%, 32.2%, 31.0%, and 23.5%, respectively. The most encouraging outcome

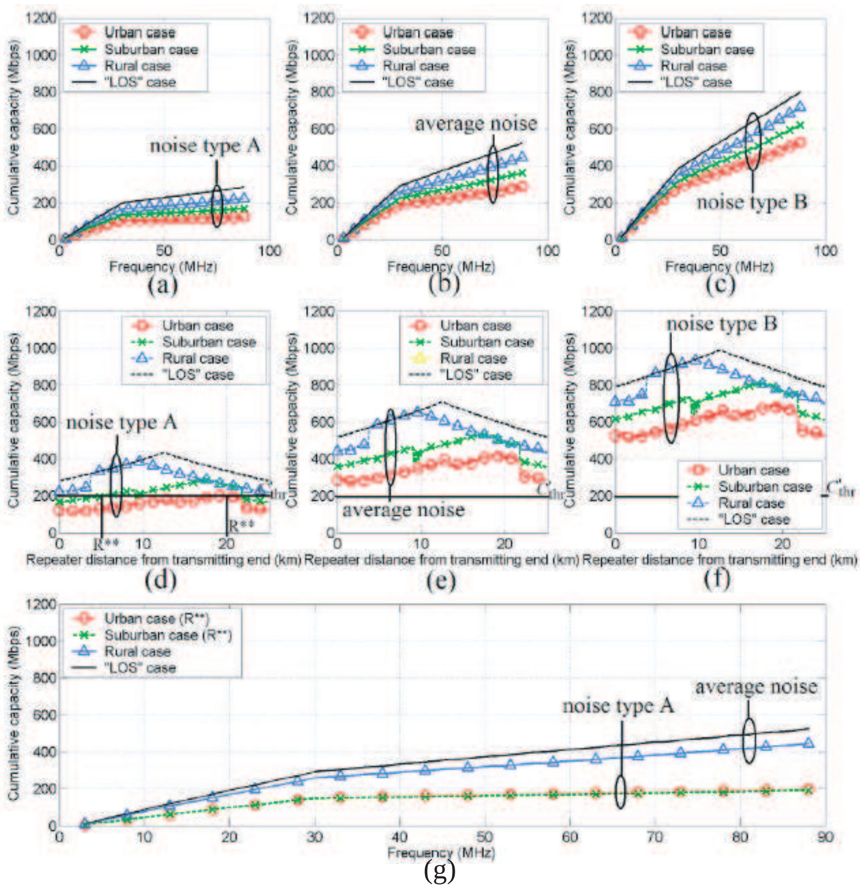

Figure 4. Broadband potential of overhead HV/BPL systems in the 3–88 MHz frequency range. (a), (b), (c) Cumulative capacity versus frequency for urban, suburban, rural, and "LOS" transmission case of legacy overhead HV/BPL systems when noise type A, average noise, and noise type B occur, respectively. (d), (e), (f) Cumulative capacity versus repeater distance from point A — see Fig. 2 — when one repeater is deployed in the above cases of legacy overhead HV/BPL connections for noise type A, average noise, and noise type B, respectively. (g) Cumulative capacity versus frequency for urban case and suburban case of overhead HV/BPL connections with two-hop repeater system for given cumulative capacity threshold C'_{thr} — denoted with (R**) —; and rural case and "LOS" transmission case of legacy overhead HV/BPL connections.

concerning the above results is that the potential increase becomes greater as the noise environments aggravation gets higher. Thus, the use of overhead HV/BPL systems with two-hop repeater systems will be mainly concentrated on suburban and urban centres where either high noise environments or aggravated overhead HV/BPL topologies are present.

With reference to Figs. 4(d)–(f), through the deployment of two-hop repeater systems at appropriate positions across their end-to-end transmission paths, the capacity losses due to noise can be mitigated; let's assume that an overhead HV/BPL network is present in a region with average noise characteristics apart from one indicative overhead HV/BPL topology of its cascaded connections that is affected by severe conditions (noise type A), i.e., either weather or EMI ones. Furthermore, let's assume that a cumulative capacity threshold C'_{thr}, which is equal to 200 Mbps, is imposed across the overhead HV/BPL network.

Similarly to Fig. 3(b), with reference to Fig. 4(d), through the deployment of two-hop repeater systems at appropriate positions across the end-to-end transmission paths, the cumulative capacity threshold restriction can be satisfied. In Fig. 4(g), the cumulative capacity is plotted versus frequency for: (i) the urban case — denoted as urban case (R**) — and suburban case — denoted as suburban case (R**) — when two-hop repeater system is deployed at repeater distance from the transmitting end R** equal to 20 km and 6.2 km, respectively; and (ii) the rural case and "LOS" transmission case of the legacy overhead HV/BPL systems in the 3–88 MHz frequency range. Similar cases may be examined when connections of overhead HV/BPL network are characterized by favorable noise conditions (noise type B) and the remaining connections of overhead HV/BPL network are improved through the installation of two-hop repeater system. Moreover, comparing Figs. 4(d)–(f), regardless of noise type, for given overhead HV/BPL topology, the maxima of overhead HV/BPL connections with two-hop repeater system occur at the same repeater distance from the transmitting end facilitating the integrated design/operation of two-hop repeater system across same overhead HV/BPL connections.

Actually, in cooperation with the deployment of two-hop repeater systems that helps aggravated overhead HV/BPL topologies, depending on the capacity requirements and other technoeconomic issues, a more general multi-hop repeater system framework may be introduced where the deployment of repeaters occurs in order to mitigate capacity losses due to either aggravated topologies or poor noise conditions.

6. CONCLUSIONS

This paper has focused on the broadband potential of overhead HV/BPL connections with two-hop repeater system associated with aggravated overhead HV/BPL topologies and high noise environments.

Based on the results of metrics such as cumulative capacity, major features of overhead HV/BPL connections with two-hop repeater system have been reviewed for use in today's overhead HV/BPL transmission grid. In the light of information theory, the existing capacity performance of all considered overhead HV/BPL topologies can be further exploited if capacity losses due to existing aggravated overhead HV/BPL topologies and high noise environments are significantly reduced through the appropriate insertion of two-hop repeater systems in the existing overhead HV/BPL connections.

The numerical results validate the significant capacity improvement that is achieved through this technique. Overhead HV/BPL connections with two-hop repeater systems provide a low-cost and quick technology upgrade of the already installed overhead HV/BPL systems offering an important step towards the design/operation of faster and more interoperable/intraoperable BPL systems in the oncoming SG network.

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