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# Article Broadband Power Line Communication in Railway Traction Lines: A Survey

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Abstract: Power line communication (PLC) is a technology that exploits existing electrical transmis-1 sion and distribution networks as guiding structures for electromagnetic signal propagation. This 2 facilitates low-rate data transmission for signaling and control operations. As the demand in terms 3 of data rate has greatly increased in the last years, the attention has stepped to broadband PLC (BPLC), capable of supporting data-intensive applications. This concept also extended to railways as 5 broadband traction power line communication (BTPLC), aiming to offer railway operators an alternative data network in areas where other technologies are lacking. However, BTPLC implementation faces challenges due to varying operating scenarios like urban, rural, and galleries. Hence, ensuring 8 coverage and service continuity demands suitable characterization of the communication channel. In 9 this regard, the scientific literature, which is an indicator of the body of knowledge related to BTPLC 10 systems, is definitely poor if compared to that addressed to BPLC systems installed on the electrical 11 transmission and distribution network. The relative papers dealing with BTPLC systems and focus-12 ing on the characterization of the communication channel, show some theoretical approaches and, 13 rarely, measurements guidelines and experimental results. In addition, to the best of the author's knowledge, there are no surveys that comprehensively address these aspects. Aiming at contributing 15 to compensate for this lack of information, a survey of the state of the art concerning BTPLC systems 16 and the measurement methods that assist their installation, assessment, and maintenance is presented. 17 The primary goal is to provide the interested readers with a thorough understanding of the matter 18 and identify the current research gaps, in order to drive future research towards the most significant 19 issues. 20

Keywords:railway systems; broadband powerline communication; channel modeling; channel21characterization; metrological characterization; noise characterization22

# 1. Introduction

The fourth industrial revolution has brought forth a plethora of technological ad-24 vancements that are enabling and/or improving new paradigms, which seem deemed 25 to transform the lives of individuals [1]. Among these, Internet of Things (IoT) [2], ar-26 tificial intelligence (AI) [3], machine and deep learning (ML/DL) [4], cloud computing 27 [5], additive manufacturing [6], augmented and virtual reality (AR/VR) [7], are the most 28 popular. These paradigms rely on several data communication solutions, which are selected 29 according to their specific advantages to face costs, installation, and time-to-market issues. 30 Unexpectedly, even some unusual proposals have been revitalized, such as the power line 31 communication (PLC) technology [8]. 32

PLC harnesses the inherent potential of the electrical distribution network to facilitate data transmission capabilities. By exploiting the existing infrastructure of the power grid, PLC enables the communication of data signals through the electrical power lines [9], allowing the simultaneous transfer of electrical power and data for signaling and remote control [10,11].

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Similarly to the transmission and distribution network, other infrastructures can be exploited as guiding structures to propagate electromagnetic signals. A relevant example is the electrical railway system, where the catenary and the railway tracks can transmit both the power needed to the traction operations as well as the data.

Actually, the growing focus on safety and maintenance of the railway network, and the 42 increase in services offered on board, raise a demand for robust communication technolo-43 gies. These should grant high data rates, low latency, coverage and service continuity, to 44 enable high-speed internet connection for service management and entertainment [12,13]. 45 Railway operators are paying attention indeed to broadband power line communication 46 (BPLC) technologies. These exploit the high frequency range, namely the HF band of the 47 electromagnetic spectrum, and employ suitable solutions to transmit a relevant amount 48 of data in a reduced time interval [14]. More specifically, railway operators have fostered 49 the concept of broadband traction power line communication (BTPLC), where the electric 50 traction line is exploited as a channel for broadband communications rather than for simple 51 signaling and control operations [15]. 52

A BTPLC system is designed with the aim to establish a communication link between on-board and wayside devices, as illustrated in Fig. 1. The link has to cope with the requirements of advanced security systems, predictive maintenance, and other 4.0-driven applications [16].



Figure 1. BTPLC system for data communication between on-board and wayside devices.

BTPLC technology should support the transmission of train-related data and other sensor-derived information. These include position, velocity, and vibration parameters, as well as environmental data in terms of weather conditions, and network-specific data, such as the number of interconnected trains. The subsequent data analysis enables the implementation of useful policies to reduce maintenance costs and operations, improve maintenance scheduling, and ensure the proper operation of the network safely [17–19].

It is expected that BTPLC solutions will play a critical role in predictive maintenance, where are artificial intelligence based approaches are becoming widespread. These approaches necessitate of a substantial volume of data concerning the condition of the railway network, the train, and its components, and hence of effective solutions for transmission and storing operations [20].

The adoption of BPLC technology in railways is further motivated by the increasing focus on sustainable policies. Rail transport is acknowledged as a better alternative to road transport, and a key element in atmospheric emission reduction strategies [21]. Environmental policies, in fact, are driving the transition of the land transportation system from a vehicle-centered model to a rail-centered one [22]. This shift towards the railway system is projected to yield a significant reduction in energy consumption, as appealing as the substitution of the fuel engines with the electric ones in automotive [23].

Taking all these factors into account, it becomes evident that BPLC technology is 75 intriguing to railway operators that have to fulfill more and more advanced service deliv-76 ery. But, utilizing the pre-existing network, originally designed for electrical distribution 77 purposes, poses various technical challenges, that need to be addressed when employ-78 ing it for high-frequency data transmission [24]. Unlike several networks used for low and medium-voltage power distribution, those employed in the railway sector present 80 additional challenges. The main ones are related to the existence of different network 81 topologies, which are difficult to characterize, to the time-varying nature of the system, 82 which impacts the communication channel behavior, and to the numerous sources of noise 83

and interference [25]. Recently, researchers have pointed out the need for effective methodologies to address 85 the design, implementation, and evaluation of broadband communication channels exploit-86 ing electric traction lines for signal propagation. In this regard, several contributions have 87 put forth intriguing methodologies. However, to the best of the author's knowledge, a comprehensive overview encompassing both theoretical notes and experimental protocols, 89 to be considered at design, installation, assessment, and maintenance stages, is still absent. In an effort to address this dearth of information, the authors have produced a survey that 91 delineates the current state of BTPLC systems, where a special attention is paid to the test and measurement activities needed at installation, evaluation, and maintenance. More 93 specifically, the survey presents the performance metrics and measurement apparatuses 94 adopted to characterize the electric traction lines in the light of installing solutions for 95 broadband power line communications. Its goal is to systematically analyze and evaluate the existing literature in order to provide a comprehensive understanding of the topic and 97 guide future research efforts. 08

The survey has considered the papers published from 2006, which are closely related 99 to the deployment of BPLC technologies in the railway domain. A search on the Scopus 100 Database using the keywords PLC, broadband, and railway yielded a total of 54 papers 101 as of July 2023. From this set, nine papers were carefully selected for a comprehensive 102 and detailed comparison. The selection criteria for these papers primarily emphasized 103 articles published in scientific journals that clearly outlined the operation of the BTPLC 104 system. In particular, each of the chosen papers presented an improved model or methods 105 for characterizing the BTPLC channel. 106

The survey starts with an overview of the PLC fundamentals with an emphasis on the taxonomy of the technology in Section 2. Subsequently, Section 3 reviews the literature highlighting the typical architectures adopted in BTPLC systems and the features and parameters of interest related to the communication channel. Then, Section 4 explores the key findings extracted from the literature analysis, distinguishing between top-down and bottom-up approaches, and comments on them. Finally, conclusions are drawn.

# 2. Background on PLC technology

PLC is a concept born at the beginning of the 20-th century, developed for signaling 114 and control operations [26]. As mentioned in Section 1, it refers to the technology that 115 allows for data communication over existing electrical power lines, providing for the simultaneous transfer of electrical power and data. PLC technologies effectively utilize 117 the existing infrastructure, enabling a cost-efficient and streamlined deployment approach. 118 They represent an appealing alternative to those solutions that necessitate the installation of 119 new networks for several reasons. First of all, the use of an already installed cable network 120 allows cost and installation time reductions in the deployment of the communication system 121 [27]. PLC solutions are not affected by the typical problems of systems that exploit the free 122 propagation of the electromagnetic signal, which candidates them to better performance in 123 those scenarios of rural area or where obstacles limit wireless communications [28]. In fact, 124 wireless setups are generally more delicate and vulnerable compared to power lines [29]. It 125 is worth highlighting that the aforementioned issues have already paved the way to the 126 implementation of communication channels that are integrated into the existing electrical 127

transmission and distribution network. These communication channels have shown to be a viable solution for the service providers to afford important managing tasks and meet the stringent service delivery demands. In a believable way, for a wide range of application scenarios, including railways, the PLC technology has still a role to play.

### 2.1. Taxonomy

PLC technologies can be classified based on the characteristics of the underlying electrical system and/or specific features as described in the following.

*Current regime*: It is a distinction based on the utilization of the direct current (DC) or alternating current (AC) regime. The first is often preferred due to its simpler structure, as the AC regime requires phase and reactive power control; for PLC applications the installation seems facilitated upon lines operated in DC regime [30].

Nominal voltage: It is a distinction based on the operating voltage value of the powergrid on which the PLC is installed. According to the European Norm EN 50160 [31], powergrids can be classified as low voltage (LV) if the nominal voltage is less than 1 kV, mediumvoltage (MV) if it is within the range (1-35) kV, and high voltage (HV) if it is above 35 kV.LV and MV power grids are generally used for electricity supply in urban and suburbanareas, while HV grids are used for long-distance power transmission.

*Frequency range*: PLC technologies can be categorized according to the range of operating frequency values of transmitted signals [32].

This feature is indicative of data transmission speed and distance. According to the literature, the frequency range in which PLC systems can operate covers frequencies from 125 Hz to 100 MHz [33–35]. PLC systems are usually referred to as shown in Table 1: 149

	Identified by the operating frequency range (125-3000) Hz. Ultra-narrowband PLC (UN-
Ultra-	PLC) technology typically guarantees transmission over long distances, although the data
	rate is typically in the order of kbps [28]. Example of UN-PLC are the home automation
INUTTOWDUNU	system by Pico Electronics X10 deployed since 1975 [34], and the two-way automatic
	communication system (TWACS) by Aclara [28].
	Identified by the operating frequency range (3-500) kHz. Narrowband PLC (NPLC)
	technologies are characterized by variable data rates from 1 kbps up to 1 Mbps, and
Narrowband	are capable of guaranteeing medium/long transmission distances [28]. In Europe, they
	are distinguished into four frequency bands, standardized by the European Committee
	for Electrotechnical Standardization (CENELEC) in 1992 [28]: CENELEC-A (3-95 kHz),
	CENELEC-B (95-125 kHz), CENELEC-C (125-140 kHz) and CENELEC-D (140.0-148.5 kHz).
	According to the data transmission rate, NPLC systems are also referred to as low data rate
	(LDR) and high data rate (HDR). LDR systems adopt single-carrier modulations whereas
	HDR exploit multi-carrier modulations to achieve data rates up to 1 Mbps [28].
Broadband	Characterized by a data rate above 200 Mbps and shorter transmission distance than
	NB-PLC [14]. The operating frequency range is not uniformly established: according to
	the Institute of Electrical and Electronic Engineers (IEEE) [35] it ranges from 1.8 MHz up to
	100.0 MHz; the International Telecommunication Union (ITU) specifies instead a frequency
	range up to 300 MHz [36]; the standards developed by the HomePlug Powerline Alliance,
	use the frequency ranges (1.8-30.0) MHz and (1.8-86.0) MHz [36].

**Table 1.** PLC systems according to the frequency range.

*Transmission distance*: The distinction is made between short-range PLC systems, with transmission distances of up to 80 km, medium-range systems, spanning between 80 km and 250 km, and long-range systems, designed for transmission distances exceeding 250 km [36].

*Indoor/outdoor environment*: Indoor PLC refers to the use of power line communication technology within indoor environments such as homes, offices, or industrial buildings. 155 It typically operates within a confined space and utilizes the existing electrical wiring 156 infrastructure to transmit data signals [37]. Outdoor PLC involves the deployment of 157 power line communication technology in outdoor settings, such as urban lighting or 158 surveillance systems, or smart grid applications. Much more than indoor systems, outdoor 159 PLC systems are designed to withstand harsh environmental conditions. These can be due 160 to large temperature variations, moisture, dust, and potential electrical interference caused 161 by nearby power lines or other outdoor equipment [38]. 162

For clarity, Fig. 2 illustrates a schematic representation of the categorization of PLC systems, highlighting the relevant categories in which BTPLC technology falls, as indicated in bold.



**Figure 2.** Details of the PLC categorizations: The categories in which BTPLC technology falls are indicated in bold.

# 2.2. Further remarks

PLC technology, initially utilized for indoor applications, is experiencing a significant expansion into outdoor settings, particularly in the areas of Smart Grid applications and Railway Traction Lines.

This expansion is evident in the increasing utilization of PLC-based applications for 170 Grid Monitoring and IoT services. PLC technology has garnered substantial interest and 171 conquered the attention of railway system operators as they offer enhanced capabilities 172 and growth opportunities. Traditionally, railway systems were designed as closed systems 173 with limited interaction and data exchange with other systems to minimize the risk of 174 malfunctions in railway infrastructures. However, PLC technology is serving as the en-175 abling technology for railways to integrate them into the smart city ecosystem [39]. With 176 the growing interest in applications like advanced metering and home automation, the 177 global PLC technology market surpassed \$ 8 billion in 2021 and is projected to reach \$ 178 35 billion by 2030 [40]. This increased investment in PLC technology is also linked to 179 the railway industry, which has experienced a 2.6 % increase in passenger traffic in rail 180 transport between 2015 and 2019 [41]. 181

#### 3. Body of knowlegde regarding BTPLC systems

This section aims to survey the body of knowledge that can be extracted by the scientific literature about BTPLC systems.

## 3.1. BTPLC architectures

BTPLC systems are typically composed of six major blocks, as shown in Fig. 3.

The first block comprises the *Power Distribution System*, which encompasses the traction power substations (TPSS). TPSS nodes form the foundation of the *Medium Voltage* (*MV*) substations, connected to the high-voltage grid. They receive high-voltage electricity from the grid, which is then converted into a suitable form for supplying power to train engines. In direct current (DC) traction systems, power substations consist of transformers and rectifiers, the latter responsible for converting alternating current (AC) into direct current (DC) [42].

The second block is constituted by the *Power line*, which encompasses the catenary to convey the electric power along the line, facilitating the *Power supply distribution*. In detail, power is transmitted through the catenary to the train by means of one or a couple of pantographs. In the context of Power Line Communication (PLC), the catenary also serves as the *Medium* through which data transmission occurs.

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**Figure 3.** Main blocks of a BTPLC architecture: the solid line represents the power transfer between the blocks, the dashed line indicates both power and data transfer, and the dotted line uniquely stands for data transfer between blocks.

In Europe, the components found in the first and second blocks are common across 199 various railway infrastructures, despite the presence of different electrification systems. 200 It is crucial to differentiate between rail network categories, as they give rise to notable 201 disparities in the selection of the devices and techniques employed at the implementation 202 stage. As early as 1933, Garczynski [43] observed that the United States and Europe adopted 203 different methods of line coupling owing to differences in power line voltages and network 204 topologies. In relation to railway lines, they are often classified into four main categories: 205 regional, urban, inter-city, and high-speed. Table 2 presents the main differences among 206 these categories, taking into account the Italian framework as an example. The allocation 207 of a limited number of services for the higher classes, or a single unitary service in the case 208 of urban routes, reflects the current state of affairs. However, with the implementation of 209 BPLC technology, an increase in rail services is likely even for the urban category. 210

Table 2. Rail networks categories in Italy [12].

Features	Regional	Urban	Inter-City	High-speed
Maximum speed (km/h)	70	70-160	160-250	>250
Line length (km)	<20	20-100	100-250	>250
Number of provided services	Single	Low	In the middle	Large

The third and fifth blocks pertain to the Coupler units employed for on-board and 211 wayside BTPLC devices, respectively. In both cases, the coupler serves as a crucial device 212 situated between the modems and the power line [44]. Its functions include both the protec-213 tion against potential damage, and the transmission and reception of the communication signal via transmission line. Note that the transmitted signals must be superimposed to 215 the waveform of the power supply, whereas the received signals must be separated from 216 the waveform of the power supply. Coupler devices are adopted to this end. They can 217 be classified upon the voltage level, the DC or AC regime, the frequency band, the physi-218 cal connection type (capacitive, inductive, resistive), the mode of propagation (common 219 or differential), and the number of connections (single-input-single-output, single-input-220 multi-output, or multi-input-multi-output) [45]. To ensure electrical isolation between the 221 power distribution line and the data line, couplers are typically equipped with an isolation 222 transformer [46]. The transformer also provides impedance matching between the two 223 lines [47]. Impedance mismatch, resulting from the time-frequency varying behavior of the 224 line impedance [48], can in fact significantly degrade transmission power [49]. Coupling 225 devices, acting as high-pass filters, should exhibit a fine frequency response within the PLC 226 transmission band to reject the supply voltage [50]. Capacitive couplers are commonly 227 employed for power line communications [51]. Additional protection circuits may be 228 employed to safeguard the PLC modem against overvoltages. However, attention must be 220 given to their impedance to prevent the creation of low-impedance paths. 230

The fourth block encompasses BTPLC devices (i.e., modems), which are installed 231 on-board the train or tram. These devices are typically equipped with features like smart 232 sensors and cameras, serving various purposes such as onboard security. On the other 233 hand, the sixth block comprises BTPLC devices placed on the ground or along the power line, which operate as repeaters or control devices. These ground-based devices establish 235 communication with the onboard devices, facilitating ground-vehicle communication. The on-board BTPLC devices need to be installed on every vehicle within the operational fleet. 237 They are responsible for enabling communication within each individual vehicle. In contrast, the wayside BTPLC devices consist of multiple devices that facilitate communication 239 between the ground-based and the on-board devices. This allows for communication between the vehicles and the ground infrastructure. Both the on-board and ground-based 241 devices must support an ethernet interface to access IP-based networks. The onboard devices are integrated into the onboard local area network (LAN), while the ground-based 243 devices are integrated into the ground or distribution networks. 244

To simplify the description of the architecture, the remote control equipment, including alarm control and management stations for managing network switches, has been excluded from the representation. Also, the bidirectionality shared by all the blocks (except the first), has not been explicitly depicted. It is important to note that in a two-way communication setup, the onboard devices receive data transmitted by other onboard BTPLC devices on different vehicles within the fleet, as well as by wayside BTPLC devices. 240

In BTPLC systems one can distinguish between (i) train-to-infrastructure, (ii) train-251 to-train, and (iii) infrastructure-to-infrastructure communication links. For all the three 252 links the communication can be bidirectional, but the performance requirements can vary 253 depending on the type of communication and the specific application [12]. Furthermore, 254 the choice of the most suitable BPLC apparatuses for specific applications depends on the transmission channel of the network where the BPLC technology is deployed. Charac-256 terizing the channel is therefore essential in order to design the PLC system, facilitate its 257 deployment, and ensure optimal performance [52]. According to the existing literature, the 258 characterization of the communication channel is typically conducted by focusing on the 259 major aspects indicated in Fig. 4, which are described in detail in the following subsections. 260



Figure 4. Major aspects regarding the characterization of BPLC transmission channels.

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3.2. BTPLC features

The typical BTPLC features, regarding grid topology, noise and emissions, and frequency selectivity, are listed as follows. 263

# 3.2.1. Grid Topology

The first feature of interest is the power grid topology, which refers to the arrangement 265 and configuration of the electrical power distribution network. It plays a crucial role in determining how PLC operates and performs in a given area. The grid structure differs 267 from country to country and even within countries, making standardization of the PLC 268 transmission channel complex. Additionally, the multipath nature of the grid is another 269 crucial aspect, as the signal can be split between useful and parasitic paths, and can 270 undergo abrupt power reductions. [53]. Moreover, short-time changes in the grid structure 271 encompass alterations in the properties of the propagating medium, resulting from load 272 insertion and detachment. This phenomenon is caused by reflections of the transmitted 273 signal along the transmission line. This phenomenon is contingent upon the interplay 274 between the wavelengths of the data signal and the physical length of the line, as well as 275 the impedance mismatch between the line and the connected devices. 276

Since BTPLC systems fall under the outdoor PLC category, the transmission channel is also subject to phenomena that complicate its characterization compared to indoor channels [54]. Among them, there are the state of the train, taking into account factors such as its speed and acceleration, and the impact of weather conditions on the traction line. 270 271 272 273 274 276 276 278 279

The lack of changes in grid topology, a condition deemed realistic for short durations and controlled circumstances, does not ensure the time-invariance of the transmission channel. This is because the characteristics of the devices connected to the grid are contingent upon the instantaneous amplitude of the supply voltage, which can fluctuate due to periodic variations in the load impedance. Then the time-varying channel can be considered cyclostationary, subject to short-term cyclic variations [55].

At the state of the art, there have been few measurement campaigns conducted 287 to represent time-varying effects accurately. The scarcity of information regarding the 288 characterization of the transmission channel for outdoor grids is primarily attributed to the 289 costs associated with conducting experimental activities for BPLC systems of this nature. 290 These costs stem from the requirement for a specialized electrical team and its mobilization, 291 the need for a variety of instruments, and auxiliary devices to grant the safety of operation. 292 Nonetheless, a measurement campaign requires the complete control of the railway path 203 and rolling stocks, that during the most of the experimental activities are set temporarily 294 unavailable to the public [56]. 295

# 3.2.2. Noise and emissions

Noise and emissions can be considered challenges of BTPLC, as they have a significant 297 impact on the performance and regulatory compliance of PLC systems. BPLC systems 298 are subject to regulations that prescribe permissible limits for electromagnetic radiation 299 [57], in order to address the adverse impacts they have on PLC communication. Noise 300 and non-intentional emissions (NIE) in BPLC systems [58,59], are primarily attributed to the utilization of the power-line communication (PLC) grid as a high-frequency data 302 transmission channel [60]. In the far field, the emissions undergo mutual cancellation owing 303 to the inherent symmetry present in the system [61]; this symmetry generally stands because 304 of the power balance maintained across each phase of the transmission power system (TPS). 305 But, this balance can occasionally be disrupted for uneven power consumption among 306 locomotives connected to each catenary [62,63], or unpredictable meteorological events. 307 This is an issue for the railway system as well that is contrasted by means of rail power 308 conditioners (RPCs) [64] or power electronics converter [65], that help in restoring the 309 equilibrium and mitigating any associated problems. 310 Table 3. Contributions to NIEs.

Background noise	Known as continuous time-invariant noise, it is a noise with a mean square value of constant amplitude in time windows of fixed duration. In the context of an AC power grid, these time windows extend beyond the duration of the voltage cycle. It primarily manifests in the high-frequency range (beyond 10 <i>MHz</i> ) [66], with a greater power concentration at lower frequencies, below 1 MHz [24,66].	
Continuous time- varying noise	It is a noise with synchronous variations with respect to the mains supply voltage, with a period that corresponds to half the period of the voltage in the case of an AC supply network.	
Impulsive noise	It is characterized by high amplitude and short time duration, typically on the order of $\mu$ s - ms. It is the predominant nature of the noise in a BTPLC channel operating under a DC current regime [67]. Impulsive noise was classified into synchronous periodic, asynchronous periodic and isolated, with primary causes respectively attributed to rectifiers, switched-mode power supplies, and insertion and disconnection of devices from the power distribution network.	
Narrowband noise	It originates from wireless communication systems [68] with components in the fre- quency interval (1-88) MHz.	
Crosstalk	This noise is generated in a transmission cable as a result of conductive, capacitive, or inductive coupling effects, caused by the proximity of a signal-carrying cable [69].	

The levels of noise and NIEs are known for the frequency interval (2-150) kHz, while they, as well as the disturbance they may cause in communication systems, are not known for operating frequencies above 1 MHz. Also, for conductive and radiated emissions, there is a lack of standards in outdoor applications [70,71].

To enhance the robustness of communication and mitigate the detrimental effects of 318 NIEs and noise on data transmission quality, coding and modulation techniques are com-319 monly employed. Among these techniques, orthogonal frequency division multiplexing 320 (OFDM) is widely recognized and extensively studied in the literature. It is a modulation 321 scheme that partitions the transmitted data into blocks and transfers them simultaneously 322 over parallel independent sub-carriers [72]. Since OFDM simultaneously transmits symbols 323 on each sub-carrier, the effects of impulsive noise are spread out over multiple symbols 324 [72], so that the overall data are not affected by the noise [73]. 325

# 3.2.3. Frequency selectivity

The channel frequency selectivity plays a critical role in determining both the amplitude distortion and delay. The frequency response of the PLC channel, typically expressed in the frequency domain by H(f), can show notable variations in channel characteristics. In recent years, the frequency response has also been suggested as a means to estimate the impedance [74]. In the context of linear time-invariant systems, the frequency response H(f) is defined as the ratio of the output voltage to the input voltage of the channel.

# 3.3. BTPLC parameters

The typical BTPLC parameters, regarding signal attenuation, line impedance, and frequency response, are listed as follows. 334

# 3.3.1. Signal attenuation

One of the primary challenges for PLC systems is facing signal attenuation along the channel. Signal attenuation refers to the decrease in power level between the signal generated by the transmitting device and the signal received by the receiving device. This attenuation is primarily caused by energy absorption in the transmitting medium, signal reflections resulting from impedance mismatches, dispersion along the line into other devices, and branching of the guiding structure into different paths [75]. The loss in transmission, denoted as  $L_t$ , can be expressed in dB as shown in Equation (1), where  $P_0$ 

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represents the signal power received at the receiving device, and  $P_i$  represents the signal power transmitted by the transmitting device. 345

$$L_t = 10 \log_{10}(\frac{P_0}{P_i}) \tag{1}$$

Several factors contribute to the attenuation of the signal in addition to the topology. 346 These factors include: type of cables, ancillary devices acting as loads, including couplers, 347 frequency range chosen for the modulated data, line length in different sections, and 348 overall line length [76]. As expected, signal attenuation is directly proportional to both 349 distance and frequency [77]. Tonello et al. [78] demonstrated that attenuation significantly 350 increases with higher frequencies, reaching values exceeding 50 dB/km for frequencies 351 greater than 1 MHz. These substantial power losses cannot be compensated by increasing 352 the transmitted signal power. In fact, electromagnetic compatibility issues put restrictions 353 on the transmitted signal power; nonetheless there are physical limitations of the devices in 354 the network that put an inherent limit to the output power. The skin effect, as described by 355 [79], also results in signal attenuation along the PLC line, which increases upon the square 356 root of the frequency. The outdoor PLC environment exhibits higher attenuation and less 357 variation compared to the indoor environment. Moreover, Kiedrowski et al. [80] found that 358 the primary contributor to attenuation is the mismatch between the modem and the line, 350 rather than the cable length. This mismatch is due to the difference between the values of 360 the impedance of the modem and input impedance  $Z_i(f)$ , i.e. the impedance seen by the 361 transmitter. It is related to the line impedance value  $Z_0$ , which is defined as the load seen by the transmitter. Since it is related to the amount of reflected power, its value directly 363 impacts the design of the analog front-end component of the PLC modem.

### 3.3.2. Input impedance

The input impedance can be obtained as [81]:

$$Z_i(f) = Z_0 \frac{1 + s_{11}(f)}{1 - s_{11}(f)}$$
<sup>(2)</sup>

where  $Z_0$  is the line impedance, and  $s_{11}$  the reflection coefficient of the input port. The 367 coefficient  $s_{11}$  is one of the 4 scattering parameters  $s_{ij}$  (*i*, *j* = 1, 2), generally used to describe 368 the behavior of a system or device or verify the impedance matching quality. These 369 parameters are arranged into a scattering matrix, which describes the correlation between 370 the incident and reflected power at the input and output ports. Apart from the reflection 371 coefficient of the input port  $s_{11}$ , the other parameters are the reflection coefficient of the 372 output port  $s_{22}$ , the forward gain  $s_{21}$ , and the reverse gain  $s_{12}$ . In general, the line impedance 373 is characterized by both time and frequency variations [82]. In addition, due to resonant 374 effects, impedance values can greatly vary even within a narrow frequency range [83]. 375 These effects are responsible for impedance mismatches. Due to this, real-time impedance estimation can be used to improve the impedance matching with the line. Despite this 377 variation over time and frequency, with lower values for low frequencies and higher values for higher frequencies, it is assumed that the frequency-dependent variation is smaller in 379 broadband systems [84]. This simplifies the choice of impedance matching techniques for 380 BTPLC technologies, which are made necessary to avoid reflection phenomena. 381

#### 3.3.3. Frequency response

Further metrics of interest, derived from the frequency response, are explained in 383 [85–91] and briefly summarized in Table 4. 384

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Impulse response duration	It refers to the time duration that encompasses a specified percentage of the total energy contained in the impulse response [42].
Average channel gain	It denotes the channel gain averaged over the band of interest. It is expressed as $G_c = 10 \log_{10} (\frac{1}{N} \sum_{i=0}^{N-1}  H_i ^2)$ , where $H_i$ denotes the i-th sample of the channel frequency response [85], typically measured on a discrete grid of uniformly spaced points. A related metric is the average channel attenuation $A_c = -G_c$ [86].
Average de- lay	It is a measure of the mean delay of signals, and it is represented by the first-order moment of the delay power spectrum. Its typical value is in the range (160 ns-4.2 µs) [87]
Root Mean Square De- lay Spread (RMS-DS)	It is defined as the square root of the second-order central moment of the power delay profile, and represents the distribution of transmitted power in the time domain over the different paths in the PLC network [88]. The RMS-DS can be considered as a measure of the time dispersion, due to the reflections at the joint of different branches with impedance mismatch [89]. Denoting with $T_s = 1/f_s$ the sampling period, the RMS-DS metric is expressed by $\sigma_{\tau} = \sqrt{\mu'_0 - \mu_0^2} = T_s \sigma_0$ , where $\sigma_0$ is the RMS-DS normalized for unit sampling time, $\mu_0$ the average delay normalized for the unit sampling time, $\mu'_0$ is its second-order central moment. Its typical value is less than 0.5 $\mu$ s [87].
Channel ca- pacity	It represents the maximum amount of information in bytes that can be reliably transmitted along the channel in a given period of time, expressed in seconds, and in a given frequency interval $(f_1, f_2)$ . It is denoted in bps, namely $C = \max_{P_t(f)} \int_{f_1}^{f_2} \log_2 \left(1 + \frac{ H(f) ^2 P_t(f)}{P_n(f)}\right) df$ , where $P_t(f)$ and $P_n(f)$ are the power spectral density (PSD) of the transmitted signal and of the noise, respectively [90]; in the given scenario, the noise is assumed to be background Gaussian noise.
Coherence bandwidth	By considering the bandwidths of the transmitted signal, this metric provides crucial insights into the necessity of employing channel protection techniques due to the dispersive effects caused by multipath propagation [88]. Its definition includes the frequency correlation function, $R(\Delta f) = \int_{B_1}^{B_2} H(f) H^*(f + \Delta f) df$ , that is a measure of the correlation between channel response at different frequencies, spaced by a frequency shift $\Delta f$ . It is assumed $H(f) = 0$ outside the frequency range $(B_1, B_2)$ . Hence, the coherence bandwidth represents a statistical measure that provides the range of frequencies over which $R(\Delta f)$ is constant.

Table 4. Metrics derived from the frequency response of the channel.

#### 3.4. BTPLC models

Several approaches are commonly employed in order to model the transfer function and capturing its cyclical variations over short periods of time, both in the time and frequency domain. The time domain approaches are typically associated with statistical tools, like the top-down models, which involve averaging various measurements. On the other hand, frequency domain methods are linked to deterministic tools, like the bottom-up approaches. Moreover, building upon these two approaches, hybrid methods have also been employed in the literature [92,93].

Bottom-up models provide a more accurate representation of the physical propagation of PLC signals within a specific network, whereas top-down models offer the advantage of lower complexity. Deterministic bottom-up approaches allow for an a-priori estimation of the PLC network transfer function, reducing the need for extensive measurement activities for verification purposes. Instead, statistical top-down approaches express the transfer function in terms of multiple paths, obtained through measurement campaigns, and do not require knowledge of the network.

In the railway industry, the complexity of the network, its dynamic variations over time, and the high costs associated with conducting experimental campaigns put challenges for (i) incorporating different network paths into top-down models and (ii) acquiring detailed knowledge of the grid topology for bottom-up models.

The main characteristics of top-down, bottom-up and hybrid models are deepened in the following paragraphs.

#### 3.4.1. Top-down models

Top-down models represent the first models developed for characterizing the Power Line Communication (PLC) channel, taking into account the significant effects caused by network branches. These effects include the multipath nature of the line resulting from discontinuities and/or impedance mismatches. Statistical models are constructed by analyzing the outcomes of experimental campaigns or by statistically describing the

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topology of the grid. In recent years, measurement campaigns have been carried out in broadband outdoor networks [94].

One of the first top-down multipath propagation models was proposed by Zimmermann et al. [53] which proposed the transfer function model described by (3):

$$H(f) = \sum_{i=1}^{N} |g_i(f)| \ e^{\phi_{g_i}(f)} \ e^{-(a_0 + a_1 f^k)d_i} \ e^{-j2\pi f\tau_i}$$
(3)

in which, for the  $i_{th}$  line segment on N, the term  $H(f) = |g_i| e^{\phi_{g_i}(f)}$  encapsulates the transmission and reflection factors along the line,  $e^{-(a_0+a_1f^k)d_i}$  describes the attenuation, with  $a_0$ ,  $a_1$  and k constant parameters that depend on the characteristics of the line section under consideration, and, finally,  $e^{-j2\pi f\tau_i}$  describes the delay in signal transmission. The model described by (3) has been extended by Tonello et al. in [95] as:

$$H(f) = A \sum_{i=1}^{N} (g_i + c_i f^{K_2}) e^{\phi_{g_i}(f)} e^{-(a_0 + a_1 f^k)d_i} e^{-j2\pi f \tau_i}$$
(4)

where a constant coefficient *A* is added for the corrections of attenuation, and the term  $g_i(f)$  is approximated as a real-valued coefficient with an explicit frequency dependence through the constants  $K_2$ , that is constant and equal for all paths;  $g_i$  and  $c_i$  depend on the path and are modeled as random variables.

In [91], channel measurements in the time domain were made by using a signal generator, connected to the transmitting port, and a digital oscilloscope, connected to the receiving port to acquire the signal applied by the generator to the line.

Overall, top-down models, as shown in (3), do not necessitate prior knowledge of 428 the PLC grid topology, which can be challenging to obtain. However, they are unable to 429 explicitly incorporate phenomena such as resonance caused by parasitic capacitances or 430 cable characteristics present in the network. Although these models allow for the inclusion 431 of attenuation and delay parameters, determining these parameters can be complex and 432 expensive. This is because one has to consider the possible network configurations, which 433 can undergo significant changes with the addition or modification of even a single network 434 path. In real-world PLC network studies, there is typically limited knowledge regarding 435 the various potential paths within the network. 436

#### 3.4.2. Bottom-up models

Bottom-up models rely on deterministic models that necessitate comprehensive knowledge of the grid topology and cable patterns. They make use of transmission line theory to derive models that accurately depict signal propagation along the power line.

The first bottom-up models for BPLC networks were defined by Barnes et al. in [96], 441 Mang et al. in [97], and Galli et al. in [98]. The simplest way to model the frequency 442 response of the channel, according to such deterministic models, is through amplitude and 443 phase voltages that follow a log-normal distribution and a uniform distribution, respectively 444 [99]. Considering these signals, the PLC channel can then be modeled using the ratio of the 445 voltage measured at the receiving port  $V_r(f)$  to the voltage  $V_i(f)$  measured at the input 446 port of a branch, and considering the product of this ratio for each branch, appropriately 447 multiplied by a coefficient A(f) describing the factor of change in signal attenuation due 448 to the cables. The transfer function varies for each network as a function of topology, 449 cable length, number of branches, and the probability that each branch is connected to the 450 network. The channel transfer function defined by Tonello et al. in [100,101] is: 451

$$H_p(f) = A(f) \prod_{i=1}^{N} \frac{V_r(f)}{V_i(f)}$$
(5)

These bottom-up approaches for modeling the PLC channel are discussed in the literature for both indoor [102] and outdoor applications [103].

They involve an approximation of the PLC grid segments by considering it as a loaded transmission line using a relationship between input and output voltages and currents to the grid. This approximation can be made via the transmission matrix T, as shown in (6), where subscript 1 denotes the input parameters and subscript 2 denotes the receiving parameters.

$$\begin{bmatrix} V_1\\ I_1 \end{bmatrix} = T \begin{bmatrix} V_2\\ I_2 \end{bmatrix} = \begin{bmatrix} A & B\\ C & D \end{bmatrix} \begin{bmatrix} V_2\\ I_2 \end{bmatrix}$$
(6)

This characterization allows obtaining the transfer function as in (7), where  $Z_S$  and  $Z_L$  are the network input impedance and load impedance, respectively.

$$H = 20 \log_{10} \left( \frac{Z_L}{AZ_L + B + CZ_L Z_S + DZ_S} \right)$$
(7)

The coefficients of the transmission line can be evaluated as follows:

$$A = D = \cosh(\gamma l)$$
  

$$B = Z_0 \sinh(\gamma l)$$
  

$$C = Z_0^{-1} \sinh(\gamma l)$$
(8)

where the parameters l,  $\gamma$ , and  $Z_0$  are the length, propagation constant, and characteristic impedance of the cable, respectively. With regards to more complex transmission lines, the transfer function can be evaluated by (6), but using different *ABCD* parameters. As an example, Esmalian et al. studied in [104] the transfer function of a transmission line with one bridge tap. Overall, the transfer function of a generic PLC system, composed of different *n* branches, can be computed by evaluating the *n* transmission matrices  $T_i$  for i = 1, ..., n, and then the overall transmission matrix as  $T = T_1 T_2 ... T_n$  [105]. A graphical description of the transmission line represented as a 2-port network is provided in Fig. 5.



**Figure 5.** Representation of a 2-port network, along with the transmission matrix T = ABCD.

In addition to the aforementioned approaches, there are other state-of-the-art methods proposed for modeling outdoor PLC networks, like scattering parameters matrix-based approaches [106]. For a given line, the outgoing  $(\underline{B}_1, \underline{A}_2)$  and incoming waves vectors  $(\underline{A}_1, \underline{B}_2)$  are linked through the scattering parameters matrix  $\underline{S}$  according to (9). For the sake of simplicity, the frequency dependency of all the variables involved in (9) has not been reported explicitly.

$$\frac{\underline{B}_1}{\underline{A}_2} = \begin{bmatrix} \underline{S}_{11} & \underline{S}_{12} \\ \underline{\underline{S}}_{21} & \underline{\underline{S}}_{22} \end{bmatrix} \begin{bmatrix} \underline{A}_1 \\ \underline{\underline{B}}_2 \end{bmatrix}$$
(9)

The scattering matrix can be obtained by direct measurements or by a numerical model of the two port-device. Issa et al. [107] used the numerical model and the scattering matrix

to develop a simulator, later validated by experimental data acquired by measurements that were carried out on outdoor LV PLC networks in Swiss and French. They found that 479 the simulated results are in reasonable agreement with the experimental results, but with a 480 discrepancy due to impedance mismatch and radiation losses. The main advantage of this 481 model is in the independence of the matrix from the load change: when the load changes, 482 matrices don't have to be re-evaluated. In some cases, instead of the scattering matrix <u>S</u>, 483 the scattering transfer matrix  $T_W$ , which is obtained by <u>S</u>, is used. It allows the calculation 484 of the scattering transfer matrix of the overall PLC system, obtained as product of the 485 individual matrices  $T_{Wi}$  of each branch. 486

Bottom-up models have computational complexity independent of grid topology, as they aggregate the effects of discontinuities and multipath into synthetic parameters. However, the major disadvantage of these models is that the grid topology and the type of cables and their parameters need to be accurately known in order to obtain a model as reported in (7).

# 3.4.3. Hybrid models

To overcome the limitations and leverage the advantages of both top-down and 493 bottom-up models, different proposals combine them into hybrid models. This hybrid approach utilizes a set of representative topologies that are common in most PLC grids to 495 derive a transfer function. Esmailian et al. [104] made one of the initial attempts to define a 496 model for generating PLC network topologies. They employed a statistical representation 497 of the topology within the bottom-up model, incorporating constraints on the number of branches, distances between nodes, and other characteristic parameters of the network. 499 This model was later extended to account for the cyclostationary nature of the channel 500 [108] and characterized for the European region [109]. Barmada et al. [52] proposed the 501 use of the scattering transfer parameters matrix to obtain an equivalent matrix through 502 the cascade connection of multiple circuits. By multiplying the respective matrices, this 503 method allows estimating the uncertainty of the parameters of each sub-circuit through 504 a variational approach. Consequently, the bounds of the response, influenced by the 505 parameters uncertainty, can be determined through a Monte Carlo procedure involving 506 multiple simulations with random variations of the loads. This method combines aspects 507 of both the top-down and bottom-up approaches, as it can be used whether the topology is 508 known or unknown, but it requires measurements of the scattering parameters. 509

For the sake of comprehensiveness, Table 5 summarizes the three mentioned modeling approaches. 510

Top-down	Based on statistical models built to analyze the outcomes of the conducted experimen-
	tal campaigns.
Bottom-up	Based on deterministic models that necessitate complete knowledge of the grid topol-
	ogy and cable patterns.
Hybrid	Based on the combination between top-down and bottom-up modeling strategies.
	It employs a set of representative topologies to derive the transfer function of the
	communication channel.

Table 5. Summary of the modeling strategies.

#### 4. Literature analysis and discussion

Based on the literature from which the body of knowledge given in the previous 513 Section has been extracted, the key contributions and advancements in the specific field of 514 BTPLC are here discussed. The specific time frame considered for this review was from 515 2006 onward, while the inclusion criteria for the considered papers centered primarily 516 around articles written in English and published in scientific journals that provided a clear 517 indication of the essential functional components of BTPLC. This methodology allowed 518 selecting nine papers that put forth improved models or methods to characterize the BTPLC 519 channel. Furthermore, their architectures align with the functional blocks defined in Fig. 3. 520

With regard to the frequency response characterization of the PLC line, 6 studies out of 9 employed bottom-up approaches, as shown in Tab. 6; the remaining three studies 522 employed top-down approaches. In the knowledge of the Authors, no relevant study 523 adopted hybrid approaches as of July 2023. The frequency interval most used in all the

Table 6. Details of the works considered for discussion in terms of frequency response approach, frequency range, and application scenario.

Work	Year	Approach	Freq. Range (MHz)	Application Scenario
Tang et al. [110]	2006	Top-down	4.5 - 21.0	Railway simulation and characterization
Barmada et al. [111]	2008	Bottom-up	0 - 30	UIC Cables modeling
Barmada et al. [112]	2009	Bottom-up	0 - 30	UIC Cables modeling
Tang et al. [113]	2011	Top-down	4.3 - 20.9	Railway simulation and characterization
Francis et al. [114]	2011	Bottom-up	0 - 100.0	Channel capacity evaluation
Barmada et al. [115]	2016	Bottom-up	0 - 30	UIC Cables modeling
Barmada et al. [77]	2019	Bottom-up	0 - 30	UIC Cables modeling
Belhassen et al. [25]	2020	Top-down	0 - 35	Railway to wayside communication
Gheth et al. [15]	2020	Bottom-up	10 - 30	Train speed influence in data transmission

considered works is included in the frequency range suggested by the standard *HomePlug* AV (1.8 - 30.0 MHz). In addition, 6 works out of 9 (reported in Tab. 6) expanded their 526 study also in the narrowband and ultra-narrowband fields.

Only in [114], a frequency range up to 100 MHz was considered: this may be due to 528 the choice of the authors to plot the channel capacity (expressed in bits/s), over frequency 529 by showing his trend tending to zero, roughly approximately at 100 *MHz*. 530

#### 4.1. Top-down approaches

According to the top-down approaches, Tang et al. in [110] established an electrical 532 railway model made up of a locomotive model on a railroad, and a BPLC system, developed 533 on the track-powered module by using graphite brushes with springs to simulate the 634 pantograph. The communication, in the frequency range of 4.5 - 21.0 MHz, was provided between two laptops on the PLC channel. One laptop was placed on the locomotive as a 536 mobile device, and the other one on the ground as a network service; each of them was 537 endowed with an adapter. Different scenarios in which the communication between the 538 laptop was once from the train to the ground, and then vice-versa for different speeds of the locomotive in the range 25 - 70 cm/s were investigated. The success rate of the transmission 540 was independent of the locomotive speed and there was no significant difference between 541 the different flows of communication, from ground to train and vice versa. However, 542 the short speed interval was considered not sufficient to generalize the results to a real 543 environment. 544

For this reason, in [113] the previous railway model was updated with different 545 graphite brushes, motor, and structure of the system in order to guarantee the simulation 546 of a high-speed train, with a speed up to 209 km/h, for a BTPLC system in 4.3 – 20.9 MHz. 547 There was a discrepancy between the two scenarios of communication flow (from ground 548 to train and vice versa), with a significant difference in success rate, which was better in the 549 scenario from ground to train. However, in both scenarios, the success data rate decreased 550 over train speed, and the highest data rate was equal to 14 *Mbps*. 551

Finally, Belhassen et al. [25] developed a top-down approach in order to investigate the use of the BTPLC in a tramway train-to-infrastructure context with the aim of developing a 553 BTPLC-based Closed Circuit TV (CCTV), working in the frequency range 4.0 – 34.0 MHz. 554 The authors carried out the experimental campaigns within a public transport network in 555 Lyon (France), an LV-DC distribution system, on a 15-km line. The developed infrastructure consists of one onboard PLC system, a static PLC system, and different modems with one 557 or two capacitive couplers on the PLC network, spaced at 350 *m* each other. The EMC 558 measurements showed no EMC interference between the PLC and railway signals as these 559 signals operate on separate frequency bands without overlapping, while the NIEs have 560 a higher average value for running trams than for stationary trams, with  $-40 \, dB \, (1 \, mW)$ 561

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level for frequencies less than 24.0 MHz, and a peak at 13.6 MHz. The line impedance 562 measurements showed a strong variation of the input impedance of the line seen from 563 the coupler to which the PLC modems are connected. According to the Signal-to-Noise 564 Ratio (SNR) measurements, the average value of SNR increases over the frequency, with a 565 downward peak at 22.0 MHz due to the EMC values. Therefore, the operative band was selected in the range 10.0 - 20.0 MHz. Due to the unstable link between transmitter and 567 receiver with the movement of the tram, the authors created an adaptive system with an 568 extra on-board PLC modem, a switch, and a device for the available link research. In this 569 way, the system managed to automatically detect the PLC modems around the tramway, 570 and compare the bit rate of the available links in order to establish the most stable and fast 571 link. With such a system, the channel capacity increased to 80 *Mb/s* with a typical latency 572 up to 62 *ms*. 573

#### 4.2. Bottom-up approaches

Barmada et al. in [111] explored the possibility of using single and 16-conductor cables 575 as BTPLC channel; specifically, the considered cable were UIC onboard cables [116]. The 576 authors used the two-port model in order to model the frequency transfer function of the 577 line composed by a series of two 20-m lines, the last closed on a 50  $\Omega$  resistance, and the relative FEM model in order to obtain the per-unit-length parameters of the UIC cable. 579 Then, they used the Time-Domain Wavelet Expansion [117] for obtaining the simulation of the frequency response in the range (0-30) MHz by means of the evaluation of the impulse 581 response. The simulations indicated similar responses for the two cables, so the possibility 582 to use them in an equivalent manner. In addition, as shown in the literature, they observed 583 an increasing attenuation over frequency in the range of interest. The work was further 584 extended in [112] by comparing the previous simulated per-unit-length parameters of the 585 UIC cables with those obtained by measurements carried out on a 6-m UIC cable provided 586 by Trenitalia s.p.a., again in the frequency range (0-30) MHz, and obtaining a relative error 587 below 10 %. In addition, a series of six 20-m cables with connections of 5 m between them, 588 all terminating with an open circuit, as in [111], or with a 50  $\Omega$  resistance was simulated. 589 Both cases showed a high-quality channel for BTPLC in the range (2-30) MHz, without a 590 significant influence of the 50  $\Omega$  resistance as end load. The cross-talk was also evaluated 591 by considering the effects of the data signal in a conductor on the others of the same cable: 592 according to the obtained results, the cross-talk showed negligible effects. 593

Instead, in [115], it was simulated the frequency response for a different number of cables, from one to seven, in the frequency range (2-30) MHz, by observing an increasing attenuation over distance and frequency. By considering a maximum attenuation of -30 dB for practical uses, it was highlighted the need for a repeater every 75 m. By evaluating the channel capacity (see Tab. 4) using trapezoidal interpolation, and considering the channel affected by additive white Gaussian noise, a channel capacity value of 80 Mbit/s for a 20 dB SNR was obtained. As well known, shorter distances are more adequate for high-speed transmissions in the considered frequency range.

The same research group, in [77], evaluated the delay spread, the cumulative distribution function of the frequency response attenuations, and the bit error rate over distance. It was considered a transmission power of 55 dBm/Hz over the entire frequency band as it is typical for PLC devices, obtaining a capacity of 1.6 Mbit/s. Values of RMS-DS (see Tab. 4 -RMS), which ranged from 52.1 ns for 25 m lines to 411 ns for 175 m lines, in accordance with the literature were reported [88]. The bit error rate increases over the distance and decreases over the SNR, ranging from 0 % for a transmission with 60-dB SNR on a 25 m line, to 0.4 % for a transmission with 25 dB on a 175 m line.

Francis et al., in [114], used the bottom-up approach with the two-port model in order to model the overhead power line referring to the Indian railways, which use single-phase double lines in copper or aluminum. These operate with 50 Hz supply power, provided by substations distant from each other about 32-64 km, which is collected by pantographs and converted to DC. In order to obtain the channel frequency response as in (7), they evaluated the transmission matrix as in (6) for a 100 m line composed of two cables from 0.125 to 615 0.750 m apart, with per-unit-length parameters ranging in different intervals for copper 616 and aluminum, according to power cable standards. With simulations in the frequency 617 range (0-10) MHz, it is shown attenuation at high frequencies, gain increments upon 618 diameters, channel capacity increments at low frequencies with a maximum of 10 Mbps at 619 approximately 1.5 MHz. Finally, the capacity decreased over distance for all frequencies in 620 the range of interest. 621

Gheth et al. in [15] proposed a simplified system of the overhead power line for the two-622 port network model in order to represent its frequency response. The simulation considered 623 the length variation of the transmission line according to the train movement. The length 624 of the line, a characteristic of the ABCD matrix (6), is updated in the simulation according 625 to the train speed and acceleration in a time period, according to the law of uniformly 626 accelerated motion. For a 25 km railway section, the frequency response is evaluated as in 627 (7) within the frequency range (1-30) MHz for different train speeds. It is shown that the amplitude of H(f) decreased over line length and frequency with attenuation increasing 629 over train speed, traveling time, and frequency. For a small distance, i.e. when the train is 630 close to the substation, the attenuation variation over frequency was negligible. 631

#### 4.3. Overall considerations

In summary, the selected works primarily investigated the relationship between 633 frequency response, attenuation, and their dependence on frequency and distance. Each 634 work aimed to assess how these factors influence the performance of the system. Each 635 scenario examined in the works was unique, consequently, the achieved channel capacity varied, ranging from 1.6 Mbps up to 80 Mbps. 637

# 5. Conclusion

The survey has considered broadband power line communications for railway traction 639 lines (BTPLC). The readers interested in the field has been provided with useful infor-640 mation related to the theoretical and empirical approaches that have been experimented 641 to characterize the transmission channel. Specifically, thanks to a thorough analysis of 642 pivotal works published since 2006, the relevant challenges related to the implementation of 643 BTPLC have been highlighted, and the progresses made in the field have been figured out. 644 It has been shown that the employed strategies essentially match two approaches, named 645 top-down and bottom-up. The top-down approach, despite its theoretical robustness, is 646 less prolific due to resource-intensive demands. In contrast, the bottom-up one gains more 647 prominence, particularly in the context of channel modeling and simulation across various 648 operational scenarios. The study has then underlined the unbalanced attention payed in 649 the scientific literature to these approaches. Also an intriguing void at the state of the art 650 has been put into evidence, which involves the absence of hybrid approaches merging the 651 strengths of both top-down and bottom-up ones; the scientific literature presents just some 652 modelling attempts. This research gap offers an opportunity for researchers to contribute 653 to a better understanding of BTPLC systems with innovative proposals aimed at improving 654 the possibilities of the essential characterization approaches.

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A review of cyber-physical system research relevant to the emerging IT trends: industry 4.0, IoT, big data, and cloud 677 computing. Journal of industrial integration and management 2017, 2, 1750011. 678 Dilberoglu, U.M.; Gharehpapagh, B.; Yaman, U.; Dolen, M. The role of additive manufacturing in the era of industry 4.0. Procedia 6. 679 manufacturing 2017, 11, 545-554. 680 Angrisani, L.; Arpaia, P.; De Benedetto, E.; Duraccio, L.; Lo Regio, F.; Tedesco, A. Wearable Brain-Computer Interfaces 7. 681 based on Steady-State Visually Evoked Potentials and Augmented Reality: a Review. IEEE Sensors Journal 2023, pp. 1–1. 682 https://doi.org/10.1109/JSEN.2023.3287983. 683 8. González-Ramos, J.; Uribe-Pérez, N.; Sendin, A.; Gil, D.; de la Vega, D.; Fernández, I.; Núñez, I.J. Upgrading the power grid 684 functionalities with broadband power line communications: Basis, applications, current trends and challenges. Sensors 2022, 685 22, 4348. 686 9. Majumder, A.; et al. Power line communications. IEEE potentials 2004, 23, 4-8. 687 Marumo, N. Simultaneous transmission and reception in radio telephony. *Proceedings of the Institute of Radio Engineers* 1920, 10. 688 8.199-219. 689 11. Mannan, A.; Saxena, D.; Banday, M. A study on power line communication. international journal of scientific and research publications 690 2014.4.1-4. 691 Fraga-Lamas, P.; Fernández-Caramés, T.M.; Castedo, L. Towards the Internet of smart trains: A review on industrial IoT-connected 12. 692 railways. Sensors 2017, 17, 1457. 693 Fokum, D.T.; Frost, V.S. A survey on methods for broadband internet access on trains. IEEE communications surveys & tutorials 13. 694 2010, 12, 171-185. 695 14. Gheth, W.; Rabie, K.M.; Adebisi, B.; Ijaz, M.; Harris, G. Communication systems of high-speed railway: a survey. Transactions on 696 *Emerging Telecommunications Technologies* **2021**, 32, e4189. 697 15. Gheth, W.; Rabie, K.M.; Adebisi, B.; Ijaz, M.; Harris, G.D. Channel modeling for overhead line equipment for train communication. 698 In Proceedings of the 2020 IEEE International Symposium on Power Line Communications and its Applications (ISPLC). IEEE, 699 2020, pp. 1-6. 700 Slacik, J.; Mlynek, P.; Fujdiak, R.; Musil, P.; Voznak, M.; Orgon, M.; Hlavnicka, J. Capabilities and visions of broadband power-line 16. 701 in smart grids applications. In Proceedings of the 2019 20th International Scientific Conference on Electric Power Engineering 702 (EPE). IEEE, 2019, pp. 1–5. 703 Franceschinis, M.; Mauro, F.; Pastrone, C.; Spirito, M.A.; Rossi, M. Predictive monitoring of train wagons conditions using 17. 704 wireless network technologies 2013. pp. 1-8. 705 18. Thaduri, A.; Galar, D.; Kumar, U. Railway assets: A potential domain for big data analytics. Procedia Computer Science 2015, 706 53, 457-467. 707 Núñez, A.; Hendriks, J.; Li, Z.; De Schutter, B.; Dollevoet, R. Facilitating maintenance decisions on the Dutch railways using big 19. 708 data: The ABA case study 2014. pp. 48-53. 709 20. Davari, N.; Veloso, B.; Costa, G.d.A.; Pereira, P.M.; Ribeiro, R.P.; Gama, J. A survey on data-driven predictive maintenance for the 710 railway industry. Sensors 2021, 21, 5739. 711 21. de Miranda Pinto, J.T.; Mistage, O.; Bilotta, P.; Helmers, E. Road-rail intermodal freight transport as a strategy for climate change 712 mitigation. *Environmental development* **2018**, 25, 100–110. 713 22. Greaves, R. The Single European Transport Area and sustainability of the transport industry. In Sustainable and Efficient Transport; 714 Edward Elgar Publishing, 2019; pp. 34–50. 715 23. García-Olivares, A.; Solé, J.; Samsó, R.; Ballabrera-Poy, J. Sustainable European transport system in a 100% renewable economy. 716 Sustainability 2020, 12, 5091. 717 24. Lopez, G.; Matanza, J.; De La Vega, D.; Castro, M.; Arrinda, A.; Moreno, J.I.; Sendin, A. The role of power line communications in 718 the smart grid revisited: Applications, challenges, and research initiatives. IEEE Access 2019, 7, 117346–117368. 719 25. Belhassen, H.; Verney, E. Proof of concept of Vehicle to Infrastructure Power Line Communication link for tramway CCTV. IEEE 720 Intelligent Transportation Systems Magazine 2020, 13, 89–98. 721

- Schwartz, M.; Batchelor, C. The origins of carrier multiplexing: Major George Owen Squier and AT&T. IEEE Communications Magazine 2008, 46, 20–24.
- Artale, G.; Cataliotti, A.; Cosentino, V.; Di Cara, D.; Fiorelli, R.; Guaiana, S.; Panzavecchia, N.; Tinè, G. A new low cost power line communication solution for smart grid monitoring and management. *IEEE Instrumentation & Measurement Magazine* 2018, 21, 29–33.
- Cano, C.; Pittolo, A.; Malone, D.; Lampe, L.; Tonello, A.M.; Dabak, A.G. State of the art in power line communications: From the applications to the medium. *IEEE Journal on Selected Areas in Communications* 2016, 34, 1935–1952.
- Schwartz, M. Carrier-wave telephony over power lines: Early history [history of communications]. IEEE Communications Magazine 2009, 47, 14–18.
- Du, J.; Wu, J.; Wang, R.; Lin, Z.; He, X. DC power-line communication based on power/signal dual modulation in phase shift full-bridge converters. *IEEE Transactions on Power Electronics* 2016, 32, 693–702.
- 31. Standard, B.; et al. Voltage characteristics of electricity supplied by public distribution networks. BS EN 2007.
- Berger, L.T.; Schwager, A.; Galli, S.; Pagani, P.; Schneider, D.M.; Lioe, H. Current power line communication systems: A survey, 2014.
- de Oliveira, R.M.; Vieira, A.B.; Latchman, H.A.; Ribeiro, M.V. Medium access control protocols for power line communication: A survey. *IEEE Communications Surveys & Tutorials* 2018, 21, 920–939.
- Blazek, V.; Slanina, Z.; Petruzela, M.; Hrbáč, R.; Vysocký, J.; Prokop, L.; Misak, S.; Walendziuk, W. Error Analysis of Narrowband Power-Line Communication in the Off-Grid Electrical System. *Sensors* 2022, 22. https://doi.org/10.3390/s22062265.
- 35. IEEE Standard for Medium Frequency (less than 12 MHz) Power Line Communications for Smart Grid Applications. IEEE Std 1901.1-2018 2018, pp. 1–192. https://doi.org/10.1109/IEEESTD.2018.8360785.
- Ndjiongue, A.R.; Ferreira, H.C. Power line communications (PLC) technology: More than 20 years of intense research. *Transactions* on *Emerging Telecommunications Technologies* 2019, 30, e3575.
- Song, J.; Ding, W.; Yang, F.; Yang, H.; Yu, B.; Zhang, H. An indoor broadband broadcasting system based on PLC and VLC. *IEEE Transactions on Broadcasting* 2015, 61, 299–308.
- Colen, G.R.; Marques, C.A.; Oliveira, T.R.; de Campos, F.P.; Ribeiro, M.V. Measurement setup for characterizing low-voltage and outdoor electric distribution grids for PLC systems. In Proceedings of the 2013 IEEE PES Conference on Innovative Smart Grid
   Technologies (ISGT Latin America). IEEE, 2013, pp. 1–5.
- Righetti, F.; Vallati, C.; Anastasi, G.; Masetti, G.; Di Giandomenico, F. Failure management strategies for IoT-based railways systems. In Proceedings of the 2020 IEEE international conference on smart computing (SMARTCOMP). IEEE, 2020, pp. 386–391.
- 40. Power Line Communication Market. https://www.gminsights.com/industry-analysis/power-line-communication-plc-market. 751 Accessed: 2023-03-10. 752
- Ninth IRG-Rail Market Monitoring Report. https://www.irg-rail.eu/irg/documents/market-monitoring/312,2021.html. Accessed: 2023-06-19.
- Cañete, F.; Dostert, K.; Galli, S.; Katayama, M.; Lampe, L.; Lienard, M.; Mashayekhi, S.; Michelson, D.; Nassar, M.; Pighi, R.; et al. Channel characterization. Power Line Communications: Principles, Standards and Applications from Multimedia to Smart Grid 2016, pp. 8–177.
- 43. Garczynski, J. Les Transmissions Par Courants Porteurs Sur Les Lignes a Haute Tension. L'Onde Electrique 1933, 12, 140–141.
- Solaz, M.; Simon, J.; Sendin, A.; Andersson, L.; Maurer, M. High Availability solution for medium voltage BPL communication retworks. In Proceedings of the 18th IEEE International Symposium on Power Line Communications and Its Applications. IEEE, 2014, pp. 162–167.
- Giraneza, M.; Abo-Al-Ez, K. Power line communication: A review on couplers and channel characterization. AIMS Electronics and Electrical Engineering 2022, 6, 265–284.
- Sibanda, M.P.; van Rensburg, P.A.J.; Ferreira, H.C. Passive, transformerless coupling circuitry for narrow-band power-line communications. In Proceedings of the 2009 IEEE International Symposium on Power Line Communications and Its Applications. IEEE, 2009, pp. 125–130.
- Yang, S.; Li, H.; Goldberg, M.; Carcelle, X.; Onado, F.; Rowland, S. Broadband impedance matching circuit design using numerical optimisation techniques and field measurements. In Proceedings of the 2007 IEEE International Symposium on Power Line Communications and Its Applications. IEEE, 2007, pp. 425–430.
- da Silva Costa, L.G.; de Queiroz, A.C.M.; Adebisi, B.; da Costa, V.L.R.; Ribeiro, M.V. Coupling for power line communications: A survey. *Journal of Communication and Information Systems* 2017, 32.
- Vines, R.M.; Trussell, H.J.; Shuey, K.C.; O'Neal, J.B. Impedance of the residential power-distribution circuit. *IEEE Transactions on Electromagnetic Compatibility* 1985, pp. 6–12.
- Kikkert, C.J. MV to LV transformer PLC bypass coupling networks for a low cost Smart Grid rollout. In Proceedings of the 2011 IEEE PES Innovative Smart Grid Technologies. IEEE, 2011, pp. 1–6.
- Ferreira, H.C.; Lampe, L.; Newbury, J.; Swart, T.G. Power line communications: theory and applications for narrowband and broadband communications over power lines; John Wiley & Sons, 2011.
- 52. Barmada, S.; Musolino, A.; Raugi, M. Innovative model for time-varying power line communication channel response evaluation.
   778 IEEE journal on selected areas in communications 2006, 24, 1317–1326.
   779
- 53. Zimmermann, M.; Dostert, K. A multipath model for the powerline channel. *IEEE Transactions on communications* 2002, 50, 553–559. 780

- Galli, S.; Scaglione, A.; Wang, Z. Power line communications and the smart grid. In Proceedings of the 2010 First IEEE International Conference on Smart Grid Communications. IEEE, 2010, pp. 303–308.
- Corripio, F.J.C.; Arrabal, J.A.C.; Del Río, L.D.; Munoz, J.E. Analysis of the cyclic short-term variation of indoor power line channels. *IEEE Journal on selected areas in communications* 2006, 24, 1327–1338.
- Picorone, A.A.; de Oliveira, T.R.; Sampaio-Neto, R.; Khosravy, M.; Ribeiro, M.V. Channel characterization of low voltage electric power distribution networks for PLC applications based on measurement campaign. *International Journal of Electrical Power & Teorgy Systems* 2020, *116*, 105554.
- Artesyn Technologies: Boca Raton, FL, U. Directive 2014/30/EU of the European Parliament and of the Council of 26 February 2014 on the Harmonization of the Laws of the Member States Relating to Electromagnetic Compatibility. 2014.
- Richards, J.C. Potential interference from broadband over power line (BPL) systems to federal government radiocommunications at 1.7-80 MHz-Phase 2 Study. Technical report, Institute for Telecommunication Sciences, 2007.
- Li, Y.; Dawalibi, F.; Raymond, R. Electromagnetic compatibility analysis of power line and railway sharing the same right-of-way corridor: a practical case study. In Proceedings of the 2010 International Conference on Future Power and Energy Engineering. IEEE, 2010, pp. 103–106.
- Vick, R. Radiated emission caused by in-house PLC-systems. In Proceedings of the IEEE Int. Symp. on Power Line Commun.
   795 and Its Applications (ISPLC), 2001.
- Amirshahi, P.; Kavehrad, M. Medium voltage overhead power-line broadband communications; transmission capacity and electromagnetic interference. In Proceedings of the International Symposium on Power Line Communications and Its Applications, 2005. IEEE, 2005, pp. 2–6.
- Barros, L.A.; Tanta, M.; Martins, A.P.; Afonso, J.L.; Pinto, J. STATCOM evaluation in electrified railway using V/V and Scott power transformers. In Proceedings of the Sustainable Energy for Smart Cities: First EAI International Conference, SESC 2019, Braga, Portugal, December 4–6, 2019, Proceedings 1. Springer, 2020, pp. 18–32.
- Barros, L.A.; Martins, A.P.; Pinto, J.G. Balancing the Active Power of a Railway Traction Power Substation with an sp-RPC. Energies 2023, 16, 3074.
- 64. Song, S.; Liu, J.; Ouyang, S.; Chen, X. A modular multilevel converter based Railway Power Conditioner for power balance and harmonic compensation in Scott railway traction system. In Proceedings of the 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia). IEEE, 2016, pp. 2412–2416.
- Barros, L.A.; Tanta, M.; Martins, A.P.; Afonso, J.L.; Pinto, J. Opportunities and challenges of power electronics systems in future railway electrification. In Proceedings of the 2020 IEEE 14th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG). IEEE, 2020, Vol. 1, pp. 530–537.
- Meng, H.; Guan, Y.L.; Chen, S. Modeling and analysis of noise effects on broadband power-line communications. *IEEE Transactions on Power delivery* 2005, 20, 630–637.
- Pinomaa, A.; Ahola, J.; Kosonen, A.; Nuutinen, P. Noise analysis of a power-line communication channel in an LVDC smart grid
   concept. In Proceedings of the 2013 IEEE 17th International Symposium on Power Line Communications and Its Applications.
   IEEE, 2013, pp. 41–46.
- Kawaguchi, A.; Okada, H.; Yamazato, T.; Katayama, M. Correlations of noise wavements at different outlets in a power-line network. 2006 IEEE International sysposium on Power Line Communications and its Applications 2006.
- Sabolic, D.; Bazant, A.; Malaric, R. Signal propagation modeling in power-line communication networks. *IEEE Transactions on Power Delivery* 2005, 20, 2429–2436.
- European Committee for Electrotechnical Standardization: Brussels, B. EN 55032:2016; Electromagnetic Compatibility of Multimedia Equipment—Emission Requirements. 2016.
   820
- EN 50561-3:2016; Power Line Communication Apparatus Used in Low-Voltage Installations-Radio Disturbance Characteristics-Limits and Methods of Measurement-Part 3: Apparatus Operating Above 30 MHz. European Committee for Electrotechnical Standardization: Brussels, Belgium, 2016. 2016.
- Ma, Y.; So, P.; Gunawan, E. Performance analysis of OFDM systems for broadband power line communications under impulsive noise and multipath effects. *IEEE transactions on power delivery* 2005, 20, 674–682.
- Andreadou, N.; Pavlidou, F.N. Modeling the noise on the OFDM power-line communications system. *IEEE Transactions on Power* Delivery 2009, 25, 150–157.
- 74. Liang, D.; Guo, H.; Zheng, T. Real-time impedance estimation for power line communication. IEEE Access 2019, 7, 88107–88115. 829
- 75. Gotz, M.; Rapp, M.; Dostert, K. Power line channel characteristics and their effect on communication system design. *IEEE* Communications Magazine 2004, 42, 78–86.
   831
- Yang, S.; Franklin, G.A. Effects of segmented shield wires on signal attenuation of power-line carrier channels on overhead transmission lines—Part I: Modeling method. *IEEE Transactions on Power Delivery* 2012, 28, 427–433.
- Barmada, S.; Tucci, M.; Romano, F. Transmission Channel Analysis for Broadband Communication over Multiconductor UIC
   Cables Onboard Regional Trains. *Energies* 2019, 12, 497.
- Tonello, A.M.; Pittolo, A. Considerations on narrowband and broadband power line communication for smart grids. In Proceedings of the 2015 IEEE International Conference on Smart Grid Communications (SmartGridComm). IEEE, 2015, pp. 13–18.
- 79. Kikkert, C.J.; Perutka, D. Calculating radiation from power lines for power line communications. In MATLAB for Engineers-Applications in Control, Electrical Engineering, IT and Robotics; Intech, 2011.

- Kiedrowski, P.; Saganowski, Ł. Method of Assessing the Efficiency of Electrical Power Circuit Separation with the Power Line Communication for Railway Signs Monitoring. *Transport and Telecommunication Journal* 2021, 22, 407–416.
- Araneo, R.; Celozzi, S.; Lovat, G. Design of impedance matching couplers for power line communications. In Proceedings of the 2009 IEEE International Symposium on Electromagnetic Compatibility. IEEE, 2009, pp. 64–69.
- Versolatto, F.; Tonello, A.M. PLC channel characterization up to 300 MHz: Frequency response and line impedance. In Proceedings of the 2012 IEEE Global Communications Conference (GLOBECOM). IEEE, 2012, pp. 3525–3530.
- Fernández, I.; Arrinda, A.; Angulo, I.; De La Vega, D.; Uribe-Pérez, N.; Llano, A. Field trials for the empirical characterization of the low voltage grid access impedance from 35 kHz to 500 kHz. *IEEE Access* 2019, 7, 85786–85795.
- Antoniali, M.; Tonello, A.M.; Versolatto, F. A study on the optimal receiver impedance for SNR maximization in broadband PLC. Journal of Electrical and Computer Engineering 2013, 2013.
- 85. Galli, S. A novel approach to the statistical modeling of wireline channels. *IEEE Transactions on Communications* 2011, 59, 1332–1345.
- Oliveira, T.R.; Picorone, A.A.; Netto, S.L.; Ribeiro, M.V. Characterization of Brazilian in-home power line channels for data communication. *Electric Power Systems Research* 2017, 150, 188–197.
- Picorone, A.A.M.; Neto, R.S.; Ribeiro, M.V. Coherence time and sparsity of Brazilian outdoor PLC channels: A preliminary analysis. In Proceedings of the 18th IEEE International Symposium on Power Line Communications and Its Applications. IEEE, 2014, pp. 1–5.
- Tlich, M.; Avril, G.; Zeddam, A. Coherence Bandwidth and its Relationship with the RMS delay spread for PLC channels using Measurements up to 100 MHz. In Proceedings of the Home Networking: First IFIP WG 6.2 Home Networking Conference (IHN'2007), Paris, France, December 10–12, 2007. Springer, 2008, pp. 129–142.
- Liu, W.; Widmer, H.P.; Aldis, J.; Kaltenschnee, T. Nature of power line medium and design aspects for broadband PLC system. In Proceedings of the 2000 International Zurich Seminar on Broadband Communications. Accessing, Transmission, Networking.
   Proceedings (Cat. No. 00TH8475). IEEE, 2000, pp. 185–189.
- Liu, H.; Song, J.; Zhao, B.; Li, X. Channel study for medium-voltage power network. In Proceedings of the 2006 IEEE International Symposium on Power Line Communications and Its Applications. IEEE, 2006, pp. 245–250.
- Versolatto, F.; Tonello, A.M.; Tornelli, C.; Della Giustina, D. Statistical analysis of broadband underground medium voltage channels for PLC applications. In Proceedings of the 2014 IEEE International Conference on Smart Grid Communications (SmartGridComm). IEEE, 2014, pp. 493–498.
- 92. Amirshahi, P.; Kavehrad, M. High-frequency characteristics of overhead multiconductor power lines for broadband communications. *IEEE Journal on Selected Areas in Communications* 2006, 24, 1292–1303.
   868
- Lazaropoulos, A.G. Broadband transmission and statistical performance properties of overhead high-voltage transmission networks. *Journal of Computer Networks and Communications* 2012, 2012.
- 94. Zhai, M.Y. Transmission characteristics of low-voltage distribution networks in China under the smart grids environment. *IEEE Transactions on Power Delivery* 2010, 26, 173–180.
- 95. Tonello, A.M.; Versolatto, F.; Béjar, B.; Zazo, S. A fitting algorithm for random modeling the PLC channel. *IEEE Transactions on Power Delivery* 2012, 27, 1477–1484.
   874
- 96. Barnes, J.S. A physical multi-path model for power distribution network propagation. In Proceedings of the Proceedings of 1875 International Symposium on Power-line Communications and its Applications, 1998, pp. 76–89.
- Meng, H.; Chen, S.; Guan, Y.; Law, C.; So, P.; Gunawan, E.; Lie, T. Modeling of transfer characteristics for the broadband power line communication channel. *IEEE Transactions on Power delivery* 2004, 19, 1057–1064.
- 98. Galli, S.; Banwell, T.C. A deterministic frequency-domain model for the indoor power line transfer function. *IEEE Journal on Selected Areas in Communications* 2006, 24, 1304–1316.
   880
- 99. Tonello, A.M.; Pittolo, A.; Girotto, M. Power line communications: Understanding the channel for physical layer evolution based on filter bank modulation. *IEICE Transactions on Communications* **2014**, *97*, 1494–1503.
- Tonello, A.M.; Zheng, T. Bottom-up transfer function generator for broadband PLC statistical channel modeling. In Proceedings of the 2009 IEEE International Symposium on Power Line Communications and Its Applications. IEEE, 2009, pp. 7–12.
- Tonello, A.M.; Versolatto, F. Bottom-up statistical PLC channel modeling—Part I: Random topology model and efficient transfer function computation. *IEEE Transactions on Power Delivery* 2011, 26, 891–898.
- 102. Galli, S.; Banwell, T. A novel approach to the modeling of the indoor power line channel-Part II: transfer function and its properties. *IEEE Transactions on Power Delivery* 2005, 20, 1869–1878.
- 103. Akinnikawe, A.; Butler-Purry, K.L. Investigation of broadband over power line channel capacity of shipboard power system cables for ship communication networks. In Proceedings of the 2009 IEEE Power & Energy Society General Meeting. IEEE, 2009, pp. 1–9.
- 104. Esmailian, T.; Kschischang, F.R.; Glenn Gulak, P. In-building power lines as high-speed communication channels: channel characterization and a test channel ensemble. *International Journal of Communication Systems* 2003, *16*, 381–400.
- 105. Paul, C.R. Analysis of multiconductor transmission lines; John Wiley & Sons, 2007.
- 106. Araneo, R.; Barmada, S.; Celozzi, S.; Raugi, M. Two-port equivalent of PCB discontinuities in the wavelet domain. *IEEE transactions on microwave theory and techniques* **2005**, *53*, 907–918.

- 107. Issa, F.; Sartenaer, T.; Marthe, E.; Rachidi, F.; Korovkin, N.; Duteau, S.; Pacaud, A. Analysis of power line communication networks using a new approach based on scattering parameters matrix. In Proceedings of the 2002 IEEE International Symposium on Electromagnetic Compatibility. IEEE, 2002, Vol. 2, pp. 1043–1047.
- Canete, F.J.; Cortes, J.A.; Diez, L.; Entrambasaguas, J.T. A channel model proposal for indoor power line communications. *IEEE Communications Magazine* 2011, 49, 166–174.
- 109. Tonello, A.M.; Versolatto, F. New results on top-down and bottom-up statistical PLC channel modeling. In Proceedings of the
   Third workshop on power line communications, 2009, pp. 1–2.
- 110. Tang, C.j.; Pan, J.M. An Experimental Model of the Mobile Power-Line Communication Systems 2006.
- Barmada, S.; Gaggelli, A.; Musolino, A.; Rizzo, R.; Raugi, M.; Tucci, M. Design of a PLC system onboard trains: Selection and analysis of the PLC channel. In Proceedings of the 2008 IEEE International Symposium on Power Line Communications and Its Applications. IEEE, 2008, pp. 13–17.
- Barmada, S.; Musolino, A.; Rizzo, R.; Tucci, M.; Gaggelli, A.; Masini, P. Modeling of UIC cables in railway systems for their use as power line communication channels. *The Applied Computational Electromagnetics Society Journal (ACES)* 2009, pp. 609–617.
- 113. Tang Jr, C.J.; Zhang Jr, W.P. SIMULATION AND ANALYSIS OF MOBILE POWER-LINE COMMUNICATION ON HIGH-SPEED 910 ELECTRICAL RAILWAY SYSTEM 2011. 911
- 114. Francis, A.; Titus, G. Channel capacity analysis of railway power lines. In Proceedings of the 2011 International Conference on Emerging Trends in Electrical and Computer Technology. IEEE, 2011, pp. 74–77.
- Barmada, S.; Tucci, M.; Romano, F. Channel Capacity Evaluation of UIC Cables for High Speed Data Transmission Onboard Regional Trains. In Proceedings of the Proceedings of the Third International Conference on Railway Technology: Research, Development and Maintenance, Cagliari, Italy, 2016, pp. 5–8.
- 116. UIC 558 Union, Ligne de telecommande et d'information. Caracteristiquest techniques unifiees por l'equipment des voitures RIC.
   917
   918
   918
- Barmada, S.; Raugi, M. Transient numerical solutions of nonuniform MTL equations with nonlinear loads by wavelet expansion in time or space domain. *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications* 2000, 47, 1178–1190.

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