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## Review Article

# A Review of Wireless and PLC Propagation Channel Characteristics for Smart Grid Environments

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Wireless, power line communication (PLC), fiber optic, Ethernet, and so forth are among the communication technologies on which smart grid communication infrastructure is envisioned to be built. Among these, wireless and PLC-based solutions are attractive considering the cost of initial deployment. Wireless communication deployment in smart grid covers a variety of environments such as indoor, outdoor, and electric-power-system facilities. Similar diversity is expected in PLC deployment as well covering low voltage (LV), medium voltage (MV), and high voltage (HV) segments of the grid. In spite of being attractive, wireless and PLC channels are very harsh posing great challenges to performance of communication systems. In proposing solutions to smart grid communication needs, two approaches are likely to be followed. One is based on the use of existing wireless and PLC technologies with some modifications, and the other relies upon developing novel communication protocols particularly addressing the smart grid needs. Both of these approaches require an in-depth knowledge of communication channel characteristics. The aim of this study is to reveal the wireless and PLC channel characteristics of smart grid environments in terms of several parameters such as path loss and attenuation, time dispersion, time selectivity, amplitude statistics, and noise characteristics.

## 1. Introduction

Utility industry has not been able to sufficiently exploit the advances in communication and information technology so far to improve the electricity grid's efficiency, reliability, security, and quality of service (QoS). Smart grid addresses all of these desired features and more by modernizing the grid with the incorporation of communication and information technologies.

Understanding of the smartness in the term "smart grid" has been rapidly expanded by the industry from smart metering, that is, more focused on advanced metering infrastructure (AMI) to true smart grid [1]. With this recently endorsed definition, objectives of the smart grid can be summarized as follows [2]:

- (1) achieving active participation of the consumers in the operations of the grid with the support of AMI,

- (2) taking advantage of all generation and storage options,
- (3) enabling the network with self-healing capability to minimize the impact of power outages on consumers,
- (4) achieving resiliency against physical and cyber attacks,
- (5) providing good quality of power considering needs of the 21st century,
- (6) enabling new products, services, and markets,
- (7) optimizing assets and operating efficiently by minimizing operations and maintenance expenses.

Objectives of the smart grid require the collection of various types of information regarding electricity generation, consumption, storage, transmission, and distribution through its communication infrastructure. Considering this requirement, smart grid communication infrastructure

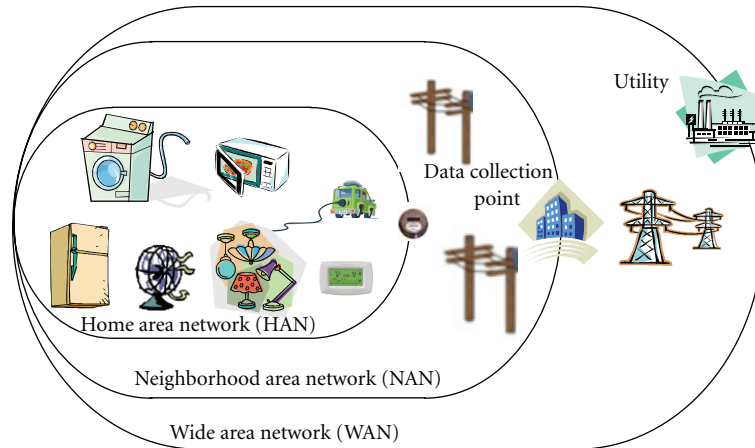


FIGURE 1: Integrating customer with smart grid.

should cover a very large geographical area that may extend from remote generation sites to densely populated residential regions and inside buildings, homes, and electricity-power-system environments. Indeed, supervisory control and data acquisition (SCADA) systems have been implemented to monitor and control electricity grid to some extent for some time [3]. However, definition of smart grid clearly necessitates the development of a more complicated two-way communication architecture beyond currently employed relatively insecure SCADA systems for a larger-scale monitoring and control.

In order to better understand the communication needs of the smart grid, it might be a good strategy to narrow down the scope and focus only on one of its objectives “integrating customers into the grid” which receives the most attention in terms of planning and investment. The underlying reason for customer integration is to maximize the efficiency of the distribution network by encouraging the customer to react to some type of stimuli coming from the utility. The opportunities with the customer integration include: (1) providing customers with new pricing options, (2) detecting power outages with automatic verification of restoration, (3) enabling customers to respond to pricing and load control signals, and (4) enabling customers to monitor, control, and schedule local energy consumption for maximizing the benefits regarding cost of electricity usage and utilization of the distribution network.

It is obvious that communication in a broader perspective lies in the core of the customer integration. First, a communication infrastructure between home devices and “smart meter” should be set up so that “smart meter” can collect information from the devices and take initiative to adjust the local consumption considering the customer preferences. Second, a communication link between “smart meters” and the utility should be established so that customers and utility can be bidirectionally notified regarding the real time electricity prices, customer behavior, and power outages. In this respect, the communication environment for the customer integration can be decomposed into three distinct communi-

cation networks as illustrated in Figure 1: home area network (HAN) for defining the interconnections between devices and the “smart meters,” neighborhood area network (NAN) for referring to the interconnections between “smart meters” and “data collection points,” wide area network (WAN) for describing the interconnections between “data collection points” and the utility. In all of these networks, a different communication technology based on a different communication medium, such as Ethernet, fiber optic, wireless, power line, satellites, and so forth, can be selected [1, 4–8]. In addition to the selection of a single communication medium, hybrid solutions (“Hybrid” in this context do not mean the use of different technologies within different network segments; rather it refers to the use of different communication technologies within the same network segment when necessary depending upon communication channel characteristics.) can also be employed [9]. Focusing only on one aspect of smart grid led us to the design of communication systems operating in three different networks most probably with different channel characteristics. Combining other aspects of the smart grid (For instance, consider communication needs for plug-in electric vehicles (PEVs) or in electric-power-system environments, such as transformation substations, power control rooms, and bulk generation plants.) with its complexity and size. (The current electricity grid in the U.S. has more than ten thousand transmission substations, two thousand distribution stations, 130 million customers, and 5600 distributed energy facilities [10].) It is not very difficult to estimate the volume of information flow and the underlying communication infrastructure for its successful realization. Similar diversity is likely to be observed in the communication applications as well with different QoS, data rate, latency, and reliability requirements ranging from simple control commands requiring low bandwidth to the transmission of video signals for the surveillance of physical assets requiring relatively larger bandwidth as outlined in Table 1 [11].

Wireless and power line communication (PLC)-based solutions are very promising and attractive compared to

the other options considering the cost of initial investment required for the smart grid communication infrastructure [7]. While addressing the communication needs of smart grid, two strategies can be followed. One of the approaches is based on integrating existing communication standards (e.g. IEEE 802.11, IEEE 802.15.1, IEEE 802.15.4, IEEE 802.16, IEEE 802.20, IEEE 1901, HomePlug (Full list of smart grid-related standards can be found in [12].)) into current electricity grid with some modifications regarding QoS, latency, reliability, and power consumption [13–16], whereas the other strategy relies upon developing novel communication protocols particularly addressing the smart grid communication needs based upon the fact that integration of existing communication standards could lead to a performance far below the expectations in a network with such heterogeneity [7, 9, 17]. Some efforts for modifying existing standards considering the requirements of smart grid are already noticeable leading to the emergence of IEEE 802.15.4 g [18–20] and HomePlug Green [21]. IEEE 802.15.4 g defines three physical layer technologies based on frequency shift keying (FSK), offset quadrature phase shift keying (OQPSK), and orthogonal frequency division multiplexing (OFDM) to address different system demands and market segments as well as some medium access control (MAC) layer modifications for lower power consumption. Similarly, HomePlug Green is based on OFDM technology with quadrature phase shift keying (QPSK) modulation for reduced cost of chip design unlike HomePlug AV which supports several modulation schemes up to 1024-quadrature amplitude modulation (QAM) as well as some other modifications for achieving lower power consumption. No matter what strategy is followed, channel characteristics of the communication environments in smart grid should be well known since they are the main determining factor in the ultimate performance of any communication system, that is, to be deployed. In addition, smart grid may need technologies over time requiring different attributes from today such as larger bandwidth paving the way to the emergence of new communication protocols [22]. It must also be noted that smart grid communication infrastructure can not be isolated from the advances in the wireless or PLC-based communication technologies while seeking communication solutions. Indeed, discussions regarding the use of white spaces in the TV spectrum that advance the state of the art in smart grid communications in a way that requires the design of smart meters with cognitive radio (CR) features already support this provision [23]. Deep understanding of the characteristics of the communication channel is a must prior to developing optimal communication solutions yet again.

In spite of being cost-effective solutions for smart grid applications, wireless and PLC environments are very harsh posing great challenges to reliability and performance of communication systems. In this respect, objective of this study is to articulate the channel characteristics of both wireless and PLC channels in smart grid environments in terms of several factors including: path loss (or attenuation which is a more frequently used term than “path loss” in PLC community), multipath characteristics (time dispersion, time selectivity, and channel amplitude statistics in

TABLE 1: Communication requirements for some smart grid applications.

Application	Data rate	Latency	Reliability
AMI	Low	High	Medium
SCADA	Medium	Low	High
Video surveillance	High	Medium	High
Mobile workforce	Low	Low	High
Distributed energy management and control	Medium	Low	High

particular), and noise characteristics. Key contributions of the study can be summarized as follows.

- (i) A comprehensive analysis and review of both wireless and PLC channel characteristics of smart grid environments are given.
- (ii) Open research topics that should be investigated further regarding wireless and PLC communication channels within the scope of smart grid communication are identified.

The remainder of the paper is organized as follows. Section 2 provides a review of propagation mechanisms effective in wireless and PLC environments. Section 3 gives the details of wireless communication characteristics of smart grid environments. Details regarding PLC channels are discussed in Section 4. Finally, the concluding remarks are given in Section 5.

## 2. Propagation Mechanism

Our discussion starts with the definition of mechanisms that govern the signal propagation within wireless and PLC channels since these propagation mechanisms form the fundamental platform for understanding the channel attributes that are to be discussed subsequently. Although propagation mechanism in wireless communication channels is relatively complex it can still be classified into three categories: *reflection*, *diffraction*, and *scattering*. *Reflection* occurs when the propagating wave impinges upon an object whose dimensions are very large compared to the wavelength of the propagating signal. *Diffraction* that explains the non-line-of-sight (NLOS) communication in wireless channels occurs when signal encounters an object with sharp edges in its path to the receiver. *Scattering*, which is the most difficult one among the others to predict, occurs when the propagating wave impinges upon an object whose dimensions are very small compared to the wavelength of the propagating signal.

The propagation in PLC channels is mostly governed by *reflections*. In PLC systems, a transmit signal propagating from one location to another suffers from *reflections* at impedance discontinuities along its path. Branching and impedance appearing at the termination points are the main source of impedance discontinuity in power line networks (PLNs) giving rise to *reflections*. These mechanisms are illustrated in Figure 2.

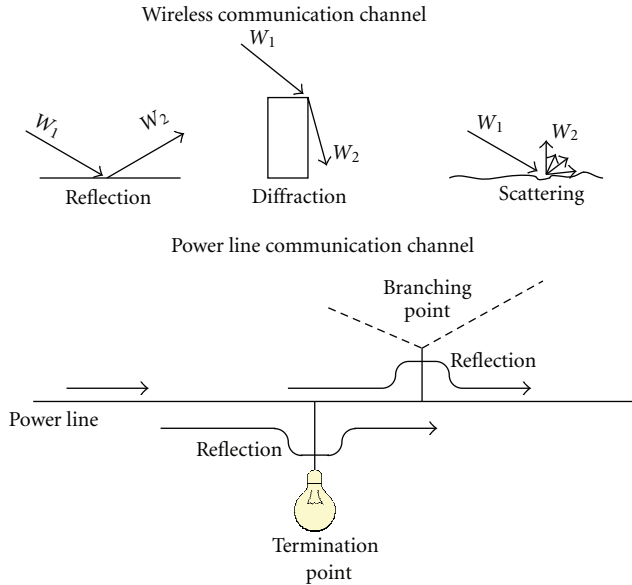


FIGURE 2: Propagation mechanisms for wireless and PLC channels.

Due to the propagation mechanisms effective in both environments, when a signal is emitted by a transmitter, the signal received at the receiver consists of attenuated, delayed, and phase-shifted replicas of the transmit signal leading to time dispersion. In communications community, significance of time dispersion is quantified by a parameter called root-mean-squared (RMS) delay spread. RMS delay spread for both communication mediums is to be discussed in a more detailed way in the subsequent sections. Besides time dispersion characteristic, both wireless and PLC channels are time selective as well. Mobility (or relative motion between transmitter and receiver from a broader perspective) is the main reason behind time selectivity of wireless channels, whereas the reason for time selectivity in PLC channels is related to the varying impedance conditions in the PLN especially at the termination points. Time selectivity is another aspect, that is to be focused on in this study. For digital communication systems, the most common figure of merit is the bit error rate (BER) which is directly related to signal-to-noise ratio (SNR). Being a function of SNR, BER can be computed by only having information regarding amplitude statistics of the received signal and the noise characteristics in the communication channel. In this respect, amplitude statistics and the noise characteristics of wireless and PLC channels are among the issues that are touched upon.

### 3. Wireless Channel Characteristics

Large-scale and small-scale fading are the two phenomena that determine the quality of received signal in wireless communication channels. Large-scale fading explains the variation in the received signal due to the motion over large areas, whereas small-scale fading is helpful in understanding the received signal characteristics as a result of small changes

(as small as a half wavelength) in the spatial domain. In explaining the large-scale fading characteristics, path loss is used for relating the transmit power to the received power in the logarithmic scale. At a particular distance  $d$  from the transmitter, path loss is expressed as

$$PL(d) = PL(d_0) + 10n \log\left(\frac{d}{d_0}\right) + X_\sigma, \quad (1)$$

where  $d_0$  is the reference distance in the far field of the transmit antenna,  $n$  is the path loss exponent, and  $X_\sigma$  denotes a real zero mean Gaussian random variable (RV) with a particular standard deviation  $\sigma$ .  $X_\sigma$  is referred to as shadowing and accounts for the impact of the terrain profile on the transmit signal. Note that possession of knowledge regarding two parameters, which are  $n$  and  $\sigma$ , while characterizing (1) is essential. Both  $n$  and  $\sigma$  are environmental dependent parameters and may change significantly depending upon communication medium profile. Smart grid communication infrastructure is likely to be deployed in a variety of communication environments. Among these deployment options are the following.

- (i) Indoor deployment: homes, offices, and so forth.
- (ii) Outdoor deployment: rural, urban, suburban areas, and so on.
- (iii) Electric-power-system facility deployment: electric-power-system environments such as transmission, distribution, and transformation substations, power control rooms, and so forth.

Note that a distinction between indoor and electric-power-system facility has been made in the classification given above. This is due to the fact that electric-power-system environments have very discriminative features compared to regular indoor environments such as prevalence of metallic structure, different noise characteristics that may stem from corona effect or switching operations, hostility in terms of temperature and humidity, and so forth. Stemming from these differences, further discussion is built upon the classification given above.

Most of the results reported in the literature regarding indoor communication environments are based on measurements carried out at around 900 MHz and 1.9 GHz. Path loss exponent ( $n$ ) for a variety of indoor propagation environments ranges from 1.2 to 6 [24–27]. Values smaller than 2 can be attributed to the waveguide effect present in the environment, whereas higher values are likely due to large attenuations introduced on the transmit signal by walls, ceilings, floors, and so forth. Regarding the standard deviation of shadowing  $\sigma$  in (1), typical values are in the range of 3 dB to 14 dB [28, 29]. In addition to the model given by (1), indoor path loss expressions that consider some other indoor environmental features such as number of walls, number of floors penetrated by the transmit signal are available in the literature as well [27, 28, 30, 31]. For instance, International Telecommunication Union (ITU) recommends a shadowing  $\sigma$  value of 12 dB for office environments along with a modified indoor path loss expression



that considers transmitter-receiver separation distance and number of floors in the transmit signal path [30].

The typical values for path loss exponent ( $n$ ) for outdoor environments range from 2.7 to 6.5 depending upon the environmental characteristics [31]. For instance, recommended value of path loss exponent by ITU is 4 for both urban and suburban areas [30]. It is also worth mentioning that rural areas with flat terrain should assume lower values of  $n$ . Shadowing  $\sigma$  for urban environments is typically 8–10 dB [32]. ITU considers a standard deviation value of 10 dB as appropriate for both urban and suburban areas [30].

The number of studies for characterizing the radio propagation medium within electric-power-system environments is very limited in the literature. An experimental study in different electric-power-system environments including a 500 kV substation, an industrial power control room, and an underground network transformer vault reports that path loss exponent  $n$  varies from 1.45 to 3.55 depending upon line-of-sight (LOS) and NLOS conditions between transmitter and receiver [33]. Shadowing  $\sigma$  values in these environments are found to be between 2.25 dB and 3.29 dB.

**3.1. Multipath Characteristics.** A complete multipath characterization of the wireless channel can be given by its complex baseband impulse response as follows [28]:

$$h(t, \tau) = \sum_{r=1}^{N(t)} a_r(t) e^{j\theta_r(t)} \delta(\tau - \tau_r(t)), \quad (2)$$

where  $N(t)$  represents the number of resolvable multipath components at time  $t$ ,  $a_r(t)$  is the amplitude of the  $r$ th multipath component,  $\theta_r(t)$  denotes the phase,  $\tau_r(t)$  represents the arrival time, and  $\delta(\cdot)$  is the Dirac delta function.

**3.1.1. Time Dispersion.** RMS delay spread is highly dependent on the wireless communication medium characteristics. A large number of studies is available in the literature for the characterization of RMS delay spread in various environments. The most straightforward conclusion that can be drawn from these studies is that the RMS delay spread values of indoor environments are smaller than those of outdoor environments [34, Chapter 2]. Typical values of RMS delay spread for residential buildings are within the range of 5 ns to 10 ns with some exceptional reported values up to 30 ns. Office environments tend to have larger values within the range of 10 ns to 100 ns. RMS delay spread values of typical urban and suburban environments are usually between 100 ns and 800 ns with some reported values up to 3  $\mu$ s. Bad urban and hilly terrain environments have much larger RMS delay spread values than these previously mentioned ones up to 18  $\mu$ s. Similar to the other propagation-related parameters, the number of studies performed in electric-power-system environments is very limited. A measurement campaign carried out in a distribution transformer revealed that the mean RMS delay spread in this environment is 85 ns [35].

**3.1.2. Time Selectivity.** Time selectivity in wireless channels manifests itself in transform domain as a spectral broadening

which is known as Doppler spread. Impact of the spread is generally evaluated through the observation of Doppler spectrum. In (2), the impact of the mobility, hence the consequence of time selectivity, is observed in the phase term, namely  $\theta_r(t)$ , for each tap (delay). Doppler spread in the received waveforms is caused by the instantaneous changes in  $\theta_r(t)$  stemming from the differences in the path distance between receiver and transmitter antennas over a very small duration of time. Doppler spectrum depends on several parameters such as operating frequency, speed, and angle of arrival (AOA) statistics at the receiver. AOA statistics mostly define the shape of the Doppler spectrum. When 3-D propagation environment is considered, shape of the Doppler spectrum may vary from classical Jakes' bath-tube-like shape to flat depending upon the AOA statistics in both azimuth and elevation planes [36, 37]. Besides these parameters, motion scenario between transmitter and receiver is another factor that defines the Doppler spectrum. In wireless communication applications, two categories can be identified to define motion scenarios: mobile receiver and fixed receiver with moving surrounding objects. It must be noted that different motion scenarios in the wireless channel lead to different Doppler spectra. Jakes' classical spectrum is commonly used in scenarios which consider the motion of the receiver antenna [32]. If transmitter is fixed and channel variation stems only from the motion of surrounding objects, then the Doppler spectrum takes a different shape from that of Jakes' with a power spectral density (PSD) approaching zero with increasing frequency [38–40]. These differences between Doppler spectra are also considered in many standards and recommendations. For instance, a flat Doppler spectrum and Classical Jakes' spectrum are recommended by ITU for indoor and outdoor propagation environments, respectively [30]. Smart grid communication infrastructure is likely to cover both mobile and fixed wireless scenarios. Wireless voice and video communication with the maintenance team in the field may correspond to the mobile receiver case, whereas the wireless communication between smart meters and home devices or within the electric-power-system facilities for monitoring and control applications may refer to the fixed receiver scenario. In this sense, the Doppler spectrum should be carefully thought for truly characterizing the communication channel. Although there is no specific study for characterizing the Doppler spread or AOA statistics within electric-power-system environments, a very rough classification can be applied, and Jakes' classical spectrum for mobile receiver case and the spectrum with a PSD approaching zero with increasing frequency for fixed receiver case are considered to be appropriate. However, it is also worth mentioning that electric-power-system environments might be located in regions or positions entirely isolated from the outside effects (e.g., underground transformer stations). Such a condition may lead to time invariance of the wireless communication channel for fixed receiver-transmitter case unlike the situation observed in indoor and outdoor communication environments in which motion of the surrounding objects such as pedestrians and vehicles results in wireless channel variation.

**3.1.3. Amplitude Statistics.** Rayleigh and Ricean probability density functions (PDFs) are widely used to describe the small scale statistics of the amplitude ( $a_r(t)$  in (2)) in wireless communication channels for NLOS and LOS conditions, respectively [28, 41]. This stems from the fact that a very large number of multipath components falls into each tap in (2) leading to the realization of complex Gaussian process as a result of central limit theorem. Besides Rayleigh and Ricean, Nakagami fading is also commonly used in order to model more variety of fading conditions. One of their interesting properties of Nakagami PDF is that it can closely approximate Rayleigh and Ricean PDF through very simple parameter manipulations [41, 42]. Finally, some other fading distributions such as Weibull are also used while defining the amplitude statistics of received signal in the literature [43]. Apart from these generalizations regarding the path amplitude statistics in wireless communication environments, it is very unfortunate not to be able to present any smart grid-specific results simply because of the immature literature in this field. In this sense, wireless fast fading modeling of smart grid environments is still an open research topic.

**3.2. Noise Characteristics.** In conventional wireless communication systems, thermal noise is usually modeled as stationary additive white Gaussian noise (AWGN). In spite of being an accurate model for most of the time, wireless communication systems are subject to impulsive noise in certain indoor and outdoor environments [44, 45]. Major sources of impulsive noise in indoor wireless channels are some devices that we frequently use in our daily lives such as photocopiers, printers, microwave ovens, hair dryers, and so forth. Impulsive noise in outdoor environments may result from some other effects such as vehicle ignition. Besides these regular environments, noise characteristics of electric-power-system environments may be dominated by the presence of impulsive noise as well [46, 47]. For instance, gap breakdown discharge phenomenon, that is, mainly caused by circuit breaker opening may result in a very strong impulsive noise in a transformer substation.

In the literature, time domain samples of the entire noise process (background noise corrupted with impulsive noise) are very frequently represented by a mixture of zero mean complex Gaussian variables with different variances and occurrence probabilities as follows:

$$f(n) = \sum_{l=0}^L p_l g(n | \sigma_l^2), \quad (3)$$

where  $p_l$ 's denote model parameters whose sum should equal unity and  $g(n | \sigma_l^2)$  is the PDF of the complex Gaussian variable with zero mean and  $\sigma_l^2$  variance. Note that (3) is a generalization of Bernoulli-Gaussian and Middleton Class-A models as noted in [48]. In spite of being widely used for the purpose of analysis, this model is memoryless and lacks representing the bursty nature of impulsive noise [49]. In order to incorporate its bursty nature into analysis, Markov model is commonly employed [49, 50]. Employing Markov model along with a persistence parameter which signifies

memory of the channel may turn this memoryless model into a bursty model forming a more realistic analysis platform.

## 4. PLC Channel Characteristics

Based on extensive measurements, frequency-distance-dependent attenuation in low voltage (LV) PLC networks is defined as [51]

$$A(f, d) = \exp\left((-a_0 - a_1 f^k) d\right), \quad (4)$$

where  $f$  and  $d$  correspond to frequency of the signal and the distance covered, respectively.  $a_0$ ,  $a_1$ , and  $k$  are all cable-dependent parameters and are mostly extracted by empirical measurements [51].

**4.1. Multipath Characteristics.** If the total number of replicas received at the receiver is considered to be limited to  $N$ , a complete characterization of the PLC channel can be given by its channel frequency response (CFR) as follows: [51]

$$H(f) = \sum_{i=0}^N \left[ \prod_{k=1}^K \Gamma_{ik} \prod_{m=1}^M T_{im} \right] A(f, d_i) \exp(-j2\pi f \tau_i), \quad (5)$$

where  $\Gamma$  and  $T$  correspond to the reflection and transmission coefficients along the propagation path, respectively,  $A(f, d_i)$  means the frequency- and distance-dependent attenuation stemming from the physical characteristics of the cable, and  $\exp(-j2\pi f \tau_i)$  refers to the phase of the  $i$ th component due to the time delay.  $K$  and  $M$  represent the number of reflection and transmission coefficients experienced by the propagating signal along a particular path denoted by the subscript  $i$ . Finally, it is worth mentioning that multiplication of  $\Gamma$ 's and  $T$ 's in (5) is referred as the reflection factor ( $|r_i|e^{j\theta_i}$ ) of a particular propagation path. Note that  $\tau_i$ , the time delay, is related to the speed of propagation within the communication medium, power line cables in our consideration as follows:

$$\tau_i = \frac{d_i \sqrt{\epsilon_r}}{c_0}, \quad (6)$$

where  $\epsilon_r$  is the dielectric constant of the insulation material and  $c_0$  is the speed of light in vacuum.

In addition to this simple and fundamental frequency domain-based PLC multipath model, there are some other characterization approaches available in the literature, that is, worth mentioning. A matrix-based approach for the calculation of multipath components based upon the aforementioned model in PLC networks is given in [52–54]. PLC channel models that are based on treating the transmission line as a two-port network are given in [55–59]. Besides these deterministic models, some statistical PLC channel characterization efforts regarding attenuation, multipath-related parameters, and so forth, that consider the PLN as a black box without dealing with its attributes such as cable characteristics, network topology, and so forth are presented in [60, 61]. Each of these channel modeling approaches has some advantages and disadvantages. For instance, all

attributes of the PLN such as the network topology, cable distance-frequency-dependent attenuation characteristics, and termination impedance conditions must all be known prior to computation if a frequency or transmission line theory-based approach is to be adopted. Statistical models can be employed if any information regarding the network attributes cannot be acquired a priori. However, an extensive measurement campaign may be required in order to draw statistically meaningful conclusions from the data sets obtained from various networks with different topologies.

*4.1.1. Time Dispersion.* Our discussion starts with the articulation of factors that define RMS delay spread in PLC channels and extends into more specific values based on measurement campaigns. One of the factors on which RMS delay spread depends in PLN is the impedance status at the termination points. Studies show that low impedance or high impedance values at the termination points yield the worst case scenario from the aspect of RMS delay spread [62–64]. Another factor is the physical attributes of the PLC medium [65]. Number of branching nodes between transmitter and receiver and distance between transmitter and receiver as well as the length statistics of the branches are among these attributes.

In spite of confusion and unclarity in RMS delay spread computation in PLC literature, values reported in [66, 67] show that it is mostly on the order of 2–3  $\mu\text{s}$  with a few exceptions as high as 5–6  $\mu\text{s}$  for a frequency range up to 30 MHz. Another very extensive study that considers the site measurements of 120 channels in the 1.8–30 MHz range reveal that the RMS delay spread is mostly below 1.31  $\mu\text{s}$  with only two exceptions of channel responses that exhibit a higher value 1.73  $\mu\text{s}$  and 1.81  $\mu\text{s}$  [68]. Similarly, RMS delay spread values reported over the same frequency range reveal that it is smaller than 0.5  $\mu\text{s}$  for 99% of the studied channels [69]. Also, a similar study conducted over a frequency range up to 30 MHz reports that 95% of the channels have an RMS delay spread value between 240 ns and 2.5  $\mu\text{s}$  [70]. Another study which considers a larger frequency band up to 100 MHz finds out that 80% of the channels exhibit RMS delay spread values between 0.06  $\mu\text{s}$  and 0.78  $\mu\text{s}$  with a mean value of 0.413  $\mu\text{s}$  upon conducting extensive measurement campaigns by obtaining 144 transfer functions collected from 7 sites [61]. In conclusion, typical RMS delay spread values in LV PLC channels are on the order of few microseconds.

*4.1.2. Time Selectivity.* Even for a fixed PLN topology, response of the PLC channels cannot be considered as time invariant. Time variation of the PLC channels is attributed to the change in the reflection factors ( $|r_i|e^{j\theta_i}$ ) of the propagation paths. It can be examined in two main categories: long-term and short term. Long-term variation stems from the fact that impedance status of the termination points constantly changes as the devices connected to the PLN are switched on/off. Change in the impedances seen at the termination points leads to a change in the reflection and transmission coefficients of some paths giving rise to the variation of the channel response. It is worth mentioning

that the impedance values seen at the termination points are also dependent on the state of the connected electrical load: unplugged, plugged but inactive, and plugged and active [71]. In addition to this long-term change in the impedance status of the termination points, impedance of most of the electrical loads is dependent on the Alternating Current (AC) mains cycle giving rise to a cyclic short-term variation in the channel response [72]. Coherence time that refers to the duration of time over which channel can be considered invariant of the LV PLC channel due to the short-term impedance variations in the PLN is reported to be no smaller than 600  $\mu\text{s}$  [72]. It is worth mentioning that studies show that separation distance between transmitter and receiver plays an important role in the significance of the channel variation due to the impedance dependency of the electrical loads on the mains AC cycle [73]. It is also shown that if a certain feature is always present in the PLN, then the PLC channel becomes a more deterministic medium than commonly believed [56].

*4.1.3. Amplitude Statistics.* Studies show that path amplitudes in LV PLC networks can be characterized with log-normal PDF merely resembling the shadow fading in wireless channels [64, 68, 74–76]. Besides frequently used log-normal distribution, use of some other PDF such as Rayleigh and Rician is also recommended for defining path amplitudes in PLC channels [66, 77, 78]. Statistics of signal amplitude in PLC environments are not well established compared to the wireless communication case and need further investigation and verification.

*4.2. Noise Characteristics.* Noise in PLC channels is classified into three main categories that are colored background noise, narrow band noise, and impulsive noise. Colored background noise results from the summation of different noise sources of low power present in the network and is usually characterized with a PSD decreasing with the frequency. Narrow band noise stems from the existence of radio broadcasters in long, middle, and short wave ranges. Colored background noise and narrow band noise are mainly considered to constitute the background noise since their amplitudes vary very slowly over the time. In addition to the background noise, impulsive noise, generated mostly by electrical appliances, is the most significant among the noise types present in PLC networks. It is considered to be the main reason behind the errors in the data transmission over the PLC channels. Analysis of the impulsive noise proposes that it can be further categorized into three categories as follows:

- (1) periodic impulsive noise asynchronous to the mains AC cycle, which is generated mostly by switched-mode power supplies,
- (2) periodic impulsive noise synchronous to the mains AC cycle, which is caused by rectifier diodes used in some of the electrical appliances,
- (3) asynchronous impulsive noise, which results from the electrical motors, drills, and on/off switching transients present in the network.

TABLE 2: Outline of wireless and PLC channel characteristics.

Channel param.	Wireless	Powerline
Path loss/attenuation	Highly dependent on the propagation environment of interests with extensive results reported in the literature	Dependent on the characteristics of cable used in the PLN
Time dispersion/Freq. selectivity	Governed by reflection, diffraction, and scattering	Governed by reflections mainly due to impedance discontinuities along the propagation path
Time selectivity/Freq. dispersion	Mobility of transmitter/receiver pairs or motion of surrounding objects	Impedance variations over both long and short term
Path amplitudes	Mostly assumed Rayleigh or Ricean depending on NLOS/LOS condition	Merely resembles shadowing effect in wireless channels and mostly assumed to obey log-Normal PDF
Noise	Mostly assumed AWGN, presence of impulsive noise in certain environments	More complicated noise structure: colored background noise, narrow band noise and impulsive noise very effective

Models proposed regarding the noise categories mentioned above are all based on empirical measurement campaigns. The main approach undertaken while modeling the background noise is based on its frequency domain characterization. One of the methods to characterize the background noise is to express it as a function of frequency by using its fitted PSD [79]. The major downside of this approach is that the random behavior of the noise process is not considered at all. In order to incorporate its random nature into analysis, background noise variation at a particular frequency value should be characterized by a certain PDF. Among these PDF proposed in the literature are sum of two Rayleigh PDF [80], log-normal [81], and Nakagami-m [82]. With regards to impulsive noise, common methodology is based on characterizing it in time domain in terms of several parameters such as impulse amplitude, impulse width, and impulse interarrival times [50, 83, 84]. In spite of the fact that impulsive noise results from entirely different sources in wireless and PLC channels, models employed in the literature are very similar to each other. Hence, the model given by (3) is widely employed in PLC community as well for the purpose of communication system analysis.

Notice that most of the preceding discussions are dedicated to the LV PLC channels. However, this does not necessarily imply that other segments of the PLN can not be considered for the purpose of communication in spite of some reliability-related concerns (Ensuring the continuation of power line cable in medium-voltage (MV) and high-voltage (HV) segments for end-to-end communication is a relatively more difficult issue than in LV segment.) [85–87]. However, although HV power lines serve as a communication medium for voice for a long time dating back to 1920s [88], the literature defines its channel characteristics as almost nonexistent. Regarding the communication channel characteristics of MV channels, although there is not much study in the literature, some general conclusions can still be drawn. Similar to LV PLC channels, MV lines exhibit time dispersion. RMS delay spread values of MV PLC channels are on the order of  $10 \mu\text{s}$ . Time variation of the channel is very weak, and the amplitude statistics obey Nakagami-m distribution [89]. In addition to these multipath-related

parameters, noise components of MV power lines are usually very similar to those of LV power lines with some discriminative features such as the dominance of corona discharges in the background noise [90].

Finally, besides the existence of impulsive noise and ingress of narrow-band noise in PLC networks as discussed earlier, electromagnetic compatibility (EMC) is another issue, that is, of paramount importance while deploying PLC-based communication systems. Similar to narrow band disturbance to PLC signals coming from radio broadcasters, the PLC signal itself can be a source of interference for the nearby transmitters that operate as a part of some other communication protocols. Specific emission limits as an indication of interference to the nearby transmitters for PLC networks are subject to national and local regulations, and the level of emission itself is highly dependent on the cable characteristics and network structure [91, 92].

## 5. Conclusion

Smart grid is a challenging project that requires the establishment of a very extensive communication infrastructure. PLC and wireless-based solutions seem very attractive considering the cost of initial investment. Being cost-effective solutions, two approaches are likely to emerge: integration of already existing PLC and wireless technologies into the grid with some modifications regarding QoS, latency, reliability, power consumption, and so forth, or developing novel communication protocols particularly addressing the smart grid communication needs. No matter what approach is taken, a deep understanding of the communication channel characteristics of smart grid environments is essential. In this study, communication channel characteristics of both PLC and wireless environments were discussed in details as summarized in Table 2. Smart grid wireless deployment options were classified roughly as indoor, outdoor, and electric-power-system environments. Similar methodology was followed in PLC environments as well by classifying them as LV, MV, and HV.

Among the communication channel characteristics discussed were path loss and attenuation, time dispersion, time



selectivity, path amplitudes, and noise characteristics. These parameters are of great importance from the perspective of communication system design for smart grid communication infrastructure. To sum up these characteristics, path loss and attenuation profile of wireless and PLC channels significantly vary with respect to communication environment, and several model parameters are available in the literature for different environment types. RMS delay spread which indicates the significance of time dispersion of a communication channel is on the order of a few microseconds in LV PLC channels. MV lines exhibit a larger RMS delay spread values on the order of 10  $\mu$ s. Similarly, typical values of RMS delay spread for indoor wireless environments are usually less than 100 ns, whereas outdoor wireless propagation environments have larger values on the order of microseconds. Regarding electric-power-system environments, RMS delay spread of wireless propagation channel in a distribution transformer is found to be 85 ns. Both wireless and PLC channels are time variant. Doppler spread is observed in order to evaluate the consequences of time selectivity in wireless channels. While discussing the Doppler spectra of different wireless communication environments, a rough classification with respect to motion scenarios was performed. Jakes' classical spectrum seems to be a suitable model for mobile receiver scenarios, whereas the spectrum with a PSD approaching zero with increasing frequency is considered to be appropriate for fixed receiver case. However, time variation of the wireless communication channel in certain electric-power-system environments could be very insignificant since these environments might be completely isolated from the outside effects. Although no specific model is available regarding the time selectivity of PLC channels, time selectivity is related to the long and short term varying impedance conditions in the PLN. Coherence time of the LV PLC channel is no less than 600  $\mu$ s in the short term. Log-normal distribution is widely used while defining amplitude statistics in LV PLC channels, whereas Rayleigh and Rician PDF are commonly employed in wireless channels for NLOS and LOS conditions, respectively. Structure of the noise in PLC channels is relatively more complex than that of wireless channels. Impulsive noise stemming from electrical loads connected to the PLN is the major source of data errors in PLC channels. Impulsive noise is observed in certain wireless indoor, outdoor, and electric-power-system environments as well. Photocopiers, printers, microwave ovens, hair dryers, and vehicle ignition are some of the sources of impulsive noise in indoor and outdoor environments. In electrical-power-system environments, especially in transformer substations, impulsive noise as a result of gap breakdown discharge phenomenon could significantly impact wireless communication.

It is worth mentioning that some aspects of the smart grid need further investigation in terms of communication channel characteristics. Some of the key open issues are as follows.

- (i) A more in-depth understanding of the radio propagation characteristics in electric-power-system environments is essential for the design of reliable wireless communication systems in the smart grid.

- (ii) Most of the research efforts in PLC channels are dedicated to the LV side of the PLN, and lack of literature in MV and HV PLC channels suggests a more comprehensive look at these environments.

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