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Theoretical Analysis of Transmission Parameters and Interference Issues in Power Line Communication Systems

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Abstract: *Communication over the wireless network is becoming increasingly saturated as a result of global proliferation of wireless and mobile devices. Coupled with the requirement for in-home devices and appliances to share information in real-time, powerline communication (PLC) systems are gaining rapid popularity as a cost-effective alternative to wireless and other wire communication techniques. In this work, the salient properties of PLC systems including mechanism of signal propagation, channel and noise characteristics, as well as signal interference within the PLC network are expounded. Furthermore, the effect of interference of PLC signals with signals from other existing communication channels are emphasized.*

Keywords: *Power line communication (PLC), signal propagation, channel, noise, interference*

1. INTRODUCTION

The concept of communication over the powerline is not a new one; power companies have always used PLC technique to send low-data control and monitoring signals over the power network [1], [2]. Smart grid and smart metering are evolving technologies that rely on PLC for their functioning. While smart grid allows devices and appliance connected to the electrical network to share information, and ensure performance optimisation, smart metering helps to reduce power wastage by constantly learning and monitoring power behaviour and consumption pattern of appliances on a network [3], [4]. With these technologies, remote monitoring and fault detection on the network as well as automated billing are achieved [4]. Given the successful deployment of PLC for the above technologies, it has become a strong consideration for providing reliable and affordable in-home (or in-building) communication services. Powerline networks are ubiquitous in nature i.e. they exist virtually everywhere across the globe; this makes PLC a cheaper alternative to other existing communication techniques [3]. The deployment of PLC does not require installation of any major infrastructure of software; PLC couplers or adapters and only a few other accessories are needed [3], [4]. Also, they display strong resilience against natural hazards, and are still capable of transmitting low-voltage communication signals even with the occurrence faults that render them incapable of transmitting high-voltage electric power [1]. However, the use of powerline cables as a channel/medium for information and data transfer is fraught with some challenges [6]. First, powerline networks were originally designed to carry high-voltage (relative to data signal voltage) signal, which are typically at a low frequency of 50/60Hz, while data signals are low-voltage signals at frequencies in the MHz range [6], [13]. This frequency mismatch makes the powerline network a harsh communication channel for transmitting higher-frequency data signals [9], [13]. Thus, the propagation mechanism, channel and noise characteristics of PLC channels are slightly different from those of wireless and other commonplace wire communication channels like coaxial cables, optic-fibre cables and twisted-pair cables [7]. Secondly, interference in PLC – mainly due to leakage of radio frequency (RF) signals propagating the powerline cables. This interference may occur among devices that share data within the PLC network, resulting in undesirable degradation of transmitted signals and reduction in throughput [18] or leakages from several devices may combine to form a strong signal that can totally distort other signals transmitted on same range of frequencies [19].

Because of similarities in many aspects of wireless and PLC signal propagation and channels, references to wireless systems will be made when necessary within this write-up. The subsequent sections of this paper give an overview of signal propagation behaviour, channel and noise characteristics, and interference in PLC systems.

2. SIGNAL PROPAGATION MECHANISM IN PLC NETWORKS

Like any other communication channel, it is important to discuss extensively, the signal propagation mechanism of PLC channels, as this will enhance better understanding of the channel and noise behaviour of the channel. While reflection, diffraction, and scattering are the main mechanisms of propagation in wireless channels, propagation in PLC channels is primarily based on reflection [11]. When a signal propagates the PLC channel from the transmitter to the receiver, the signal experiences reflections at impedance discontinuities along the path. These discontinuities mainly result from line branching and load terminations on the network as shown in figure 1 [7], [8], [12].

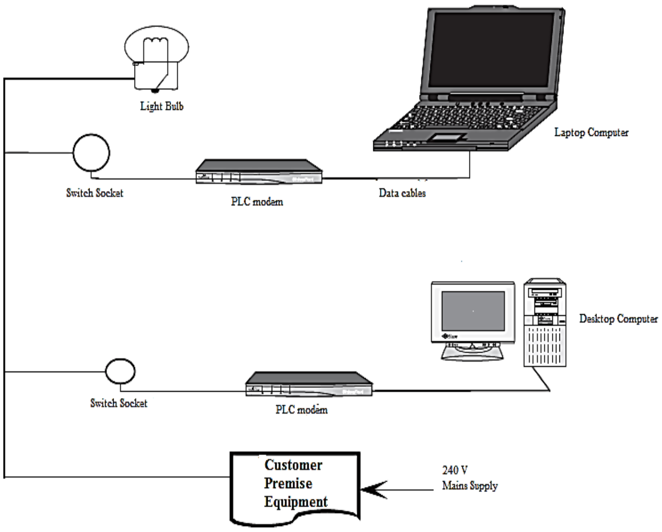

Figure 1: Customer Premise PLC Network

As a result, the received signal comprises of several attenuated, delayed, and phase-shifted copies of the transmitted signal, leading to time dispersion [7], [25]. Generally, in communications parlance, a parameter known as root-mean-squared (RMS) delay spread is measure of the extent of time dispersion [7]. Several factors on the PLC network determine the extent of the RMS delay spread [7], [30]. These include the number and length of branching nodes between the transmitter and receiver, the separating distance between the transmitter and receiver, as well as the impedance values of terminal loads. It has been observed that worst values of RMS delay spread are obtained for low and high terminal load impedances [16], [17]. Several studies and measurements on RMS delay spread values in the frequency range of 30 MHz for low-voltage PLC networks have shown that it ranges between 2 and 6 microseconds [18], [19].

Asides time dispersion, wireless and PLC channels vary with time i.e. are time-selective [9], [25]. Time-selectivity in wireless channels is due to relative mobility between the transmitter and receiver [9], [11]. In PLC channels, it is primarily due to impedance variations at load terminations on the network [7]. Time variation in PLC channels are induced by changes in the reflection factors of the propagation paths, and are categorised into long-term and short-term variation [7], [17]. The former is caused by constantly-changing impedance status of the PLC network termination points from switching on/off of connected devices. This changing impedance values at termination points induce a change in the reflection and transmission coefficients of some propagation paths, resulting in variation of the channel response. Long-term impedance variations also depend on the state of the connected electrical load – plugged and active, plugged but inactive or unplugged [7], [26]. Short-term impedance variation on the other hand stems from the cyclic nature of the mains alternating current (AC) [24]. The separation distance between transmitter and receiver determines the extent of channel variation from impedance dependency of the electrical loads on the mains cycle [31]. Short-term impedance variation in low-voltage PLC channels has a coherence time of at least 600 microseconds [17], [24]. Coherence time in communication is the duration of time over which the channels remains time-invariant [7].

3. PLC CHANNEL CHARACTERISTICS

3.1 Multipath Propagation

In wireless propagation environments, the presence of natural and man-made objects like trees, buildings, hills, atmospheric moisture e.t.c., along the signal path causes the transmitted signals undergo the effects of reflection, diffraction, and scattering. This results in multiple copies of the transmitted signals being received at the receiver i.e. multipath propagation [9], [11]. These signals comprise the direct path signal and many other attenuated and delayed copies of the signal. These signal copies will induce deep nulls at certain frequencies as a result of destructive interference between signal paths. This phenomenon is referred to as frequency-selective fading [9], [11], [13]. Similar to wireless channel environments, the powerline channel is an unstable transmission environment due to impedance variations from the characteristic impedance of the cable, the topology of the network, and the nature of the connected electrical appliances [7], [8]. This time-variation of the PLC channel causes signals propagating it to experience multipath propagation effects. The multipath in PLC depends on the physical topology as well as the physical characteristics of the channel [4], [7]. Hence the PLC channel becomes frequency selective mainly from reflections and transmissions caused by impedance mismatches at branch discontinuities and network terminations. Thus, the transmitted signals will arrive the receiver with varying attenuation and delay [7], [10]. From Fourier analysis, a delay in the time domain will result in a periodic a phase-shift in the frequency domain. At the receiver, the direct signal and the phase-shifted signals combine to produce notches/nulls at certain frequencies, resulting in frequency-selective fading [7].

According to Zimmermann and Dostert [10], the PLC channel can be completely characterised by its channel frequency response as:

$$H(f) = \sum_{i=1}^{N}\left[\prod_{k=1}^{K}\Gamma_{ik}\prod_{m=1}^{M}T_{im}\right]A(f,d_i) \qquad (1)$$

where Γ and T are the reflection and transmission coefficients along the propagation path respectively; K and M represent the number of reflection and transmission coefficients experienced by the propagating signal along a particular path i; $A(f, d_i)$ is the frequency- and distance-dependent attenuation arising from the physical characteristics of the cable; $\exp(-j2\pi f\tau_i)$ represents the phase of the ith component due to the time delay τ. The time delay, τ_i, is related to the speed of propagation within the communication channel (here, powerline cables) as:

$$\tau_i = \frac{d_i\sqrt{\epsilon_r}}{c_0} \tag{2}$$

where ϵ_r is the dielectric constant of the insulation material; and c_0 is the speed of light in a vacuum.

3.2 Attenuation

In wireless channels, signal attenuation is regarded as path loss, determined by transmission frequency and propagation distance [9]. In a similar manner, the electrical characteristics of the powerline cable and the transmission frequency band determine the extent of signal attenuation in PLC channels [4]. The signal attenuation in PLC systems is a result of the loss of power as the signal propagates the powerlines, transformers, couplers, e.t.c. From transmission line theory, four parameters that describes the electric characteristics of a cable segment include resistance, capacitance, conductivity, and inductance [13], [22]. Equation (3) shows that the resistance of a unit-length cable increases proportionally with the square-root of transmitting frequency, hence the attenuation in PLC channels is more pronounced at higher frequencies [13].

$$R' = \sqrt{\frac{\pi\mu_0}{kr^2}f} \tag{3}$$

where μ_0 is the free-space permeability; k and r are the conductivity and radius of powerline cable respectively.

Also, from extensive measurements carried out on low-voltage PLC networks, it has been shown that the attenuation varies directly with frequency and distance, and is given by the equation:

$$A(f, d) = \exp((-a_0 - a_1 f^k)d \tag{4}$$

where f is the frequency of the signal; d is the distance covered by the signal; $a_0, a_1,$ and k are cable-dependent parameters that are derived from empirical measurements [10].

From equations (3) and (4), it can be deduced that the attenuation experienced by signals propagating a powerline channel increases as the transmitting frequency and distance increase [7], [10].

4. PLC NOISE CHARACTERISTICS

Unlike wireless communication systems and most other communication systems, where noise is modelled as an additive white Gaussian noise (AWGN), noise on PLC systems are complex in nature, consisting of a slow-varying coloured background noise, narrowband noise, and a fast-changing impulsive noise [8], [13]. The coloured background noise stems from the sum total of the harmonics of the mains cycle as well as other low-power noise sources within the PLC system. This noise has a very low power spectral density that varies directly with frequency. Narrowband noise is in the form of sinusoidal signals with modulated amplitudes; it is mainly induced by interference from nearby short and medium wave broadcast radio signals. Since their amplitudes vary very slowly over time, both coloured background noise and narrowband noise make up the background noise in PLC systems [7], [13], [27]. Impulsive noise is regarded as the most significant noise in PLC systems; it is the major cause of errors in data transmission over PLC channels. It is mainly generated by intermittent and random interference on the supply signal [27], caused by electrical appliances connected to the PLC network. These noises are of three different types [7] [8], [18]:

1) *Periodic impulsive noise:* This class of noise is synchronous to the mains frequency, and is induced by the power supplies within the PLC network.
2) *Periodic impulsive noise asynchronous to the mains cycle*: This noise is mainly generated from switching on/off power supplies.
3) *Aperiodic impulsive noise:* This noise is induced by switching transients within the PLC network, this type of noise usually has a power spectral density significantly above the background level.

5. INTERFERENCE IN PLC

5.1 Electromagnetic Compatibility of Wireless and PLC Systems

Electrical signals travelling along a wire or cable causes some radiation of the signals into the surrounding. These radiated signals could interfere with nearby electronic equipment, resulting in malfunctioning of such equipment [15], [28]. This is referred to as Electromagnetic Interference (EMI) [20], [28]. Other cable types - coaxial, optic-fibre, twisted-pair cables – by design are meant to transmit data signal while limiting potential antenna effects, powerline cables inherently tend to double as unintentional antennas [15], [20]. Hence, when the powerline network is used to transmit radio frequency (RF) signals (in the range of 10 kHz – 30 MHz), some of these signals may leak, interfering with signals from other devices that are connected on the PLC network [18], [28], [29]. This results in undesirable degradation of transmitted signals and reduction in throughput [20], [21]; Some of the connected appliances my also inject noise into powerline cables, contributing further to performance degradation of the PLC network [29]. Of greater concern is the interference with signals propagating other communication channels like short-wave, medium-wave, FM and DAB radio [28], [29]. RF signals leaking from several devices on the PLC network in nearby buildings may combine to form a composite signal significant enough to interfere with, and distort signals transmitted over these channels [28]. Unfortunately, most of the regulations on PLC are restricted to a single device under monitoring and testing [18]. In a widespread PLC scenario, where numerous sources are unintentionally radiating in parallel, the wire structures that transmit the PLC signals form an antenna array thereby contributing to the far field. Expectedly, certain portion of the transmitted power are radiated through ground and sky wave, affecting highly sensitive short-wave radio services like amateur radios, wireless security services, and military surveillance stations [28].

In a nutshell, when PLC signal overlay frequency ranges of wireless services, occurrence of interference becomes unavoidable; the extent of this interference depends largely on the transmission power and distance, as well as on the structural layout of wires [21[, [28]. The network and cable symmetry determine the fraction of the injected signal power that will be emitted by radiation [28]. Symmetry is defined in terms of the impedance between a conductor and ground. For a two-wire power line, if the impedances between each conductor and ground are equal, the line is regarded as being balanced or symmetrical. For symmetrical lines, signal propagation in the desired differential mode is possible, while non-symmetrical lines results in an undesired common-mode propagation [28]. For a common-mode cable pair, current signals flow in the same direction on both conductors, where the return portions follow the ground path. Differential mode on the other hand, ensures that current signals flow in opposite directions on the cable pair. Thus, a highly symmetrical line implies a large ratio of differential to common mode current flow, and by extension, very weak radiation, while a non-symmetrical line results in common-mode current flow, inducing high radiation [28].

5.2 Mitigating Radiation Effects in PLC

As discussed in the preceding section, wireless signals transmitting on short-wave, high-frequency spectrum are susceptible to interference and in the worst case, blockage from PLC signals. In light of this, it is highly expedient to minimise radiation and unwanted radiation from PLC. The following steps are recommended to achieve this:

1) Network conditioners need to be incorporated into PLC adapters or networks. These conditioners will help reduce radiation significantly by maintaining the symmetrical balance in the power line cables.

2) Installing high-frequency filters at line ends keeps the PLC signals on the intended propagation paths and also prevents them from entering attached devices or conductors with high radiation efficiency. These filters are very effective in limiting PLC radiation to acceptable levels, but are also costly [28].

3) Using appropriate power supply cable configuration that exploits the “natural” symmetry inherent in certain configurations. For example, for a three-phase four-wire configuration, the PLC signals may be injected between two of the phases. This will generate a significantly higher symmetry than injecting the signal between the phase and neutral of a single-phase two-wire configuration [28]. This technique, however, is better suited for outdoor access network and not for indoor networks. Indoor networks cannot exploit the natural symmetry since PLC signals are only injected between phase and neutral lines [28].

4) Reducing the power spectral density of PLC signals: Since PLC signal emissions are measured within a limited bandwidth, shrinking the power spectral density immediately lowers the radiation levels, while maintaining the same transmitted power. This technique will facilitate the use of broadband multicarrier modulation schemes (like Orthogonal Frequency-Division Multiplexing or OFDM) that will spread the transmitted power across large ranges of frequencies.

6. CONCLUSION

In this article, the salient physical attributes that characterize power line networks have been outlined. First, the signal propagation mechanism was shown to be primarily by reflection, that induces a phenomenon termed RMS delay spread. This RMS delay spread depends on the impedance values of connected loads. Multipath propagation and attenuation in PLC were also presented; different factors that induce multipath propagation were identified while the transmission distance and frequency were shown to determine attenuation in PLC. The complex noise nature of PLC was also highlighted. Interference issues in PLC, especially with signals that share the same frequency was considered, and techniques of mitigating against it were suggested.

Research efforts on the effects of interference of PLC signals with other signals that share the frequency spectrum, to the best of our knowledge, remains scanty in literature. Therefore, concerted research efforts need to be directed towards analysis of interference effects of PLC signal on other signals propagating other communication channels. It is also imperative that international regulators consider embedding PLC into existing electromagnetic compatibility (EMC) rules. This will go well to resolve any interference concerns with other spectrum users, and ensure faster adoption of PLC globally as a standard communication technology.

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