A Discussion About Hybrid PLC-Wireless Communication For Smart Grids

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***Abstract*— This work outlines important characteristics of hybrid PLC-wireless systems for smart grid applications. Moreover, it discusses the hybrid wireless-PLC systems advantages in comparison to not hybrid systems. These advantages are demonstrated not only in the technical point of view, but also in the infrastructural perspective. Moreover, It addresses the environment influence on wireless and power line communications as well as relevant security aspects for a Smart Grid implementation. Computational simulations based on physical layer of IEEE P1901.2 standard and PLC and wireless channel models show that the hybrid PLC-wireless system offers a gain of signal to noise ratio when compared to only a wireless or PLC system.**

***Keywords*— Power line communication, wireless, hybrid, smart grid.**

I. INTRODUCTION

Many efforts are being made worldwide in order to transform the electric grid smarter. New ideas and process are becoming prototypes and products, but all these efforts are still limited by the data communication technologies available in the market. The target in this role is to combine reliability with the lowest cost possible. Low power radio frequency (LP-RF) and narrowband power line communication (NB-PLC) technologies are widely used for such task and both have advantages and disadvantages that depend not only on the characteristics of the application, but also on the environment they are immersed.

It is important to define the NB-PLC considered in this paper as a PLC utilizing the frequency bandwidth of 3-500 kHz and providing data rates of tens of kbps [1]. NB-PLC has been considered the best trade-off between communication distance range, low data rate requirement, and implementation cost if compared to the broadband PLC (BPL). After all, the data rates provided by NB-PLC is suitable for applications such as Automated Metering Infrastructure (AMI), Distribution Automation (DA), and Building & Industrial Automation.

In 2005 a first discussion regarding hybrid system was held [2], but it considered PLC and wireless technologies not to work at the same time. Hybrid system, at that time, was defined as the ability to join two or more access technologies (acting as communication bridge). A similar hybrid definition was shown in [3] involving in-home and vehicular applications and also in [4] for AMI application. A full-hybrid solution for AMI application, which considered PLC and wireless working at the same time in a cooperative way, was presented in [5] and [6]. The target for a full-hybrid system is to increase communication reliability. Such concept is still not widely implemented and there is a noticeable lack of contribution regarding this subject. In this context, the present work aims to discuss the usage of NB-PLC and LP-RF collaborating in a configuration to work as a full-hybrid solution for smart grid.

This work outlines important characteristics of hybrid PLC-wireless systems for smart grid applications. Moreover, it discusses the hybrid PLC-wireless systems advantages in comparison to not hybrid systems. These advantages are demonstrated not only in the technical point of view, but also in the infrastructural perspective. Moreover, It addresses the environment influence on wireless and power line communications as well as relevant security aspects for a Smart Grid implementation. Moreover, this work simulates the use of LP-RF and NB-PLC in a full-hybrid system configuration when the physical layer of IEEE P1901.2 is adopted. The results compared the full-hybrid configuration with wireless and PLC systems working alone, demonstrating a remarkable gain of signal to noise ratio (SNR) when the full hybrid arrangement is considered in a Smart Grid (SG) system implementation, which endorses the outstanding characteristic of a full-hybrid system: the extraction of the best of PLC and wireless channels.

II. THE PREFERENCE FOR RF OR PLC

It is clear that, through the years, the technical characteristics of the outdoor low voltage (LV) electric power grids were determinant for the development of data communication technology, and it is mainly based on the cost effectiveness of each solution. In USA the development was based on RF for communicating with electricity meters rather than in Europe where PLC prevails. Such situation is explained by the configuration difference of the existing outdoor LV electric power grids in USA and Europe.

In USA there are only a few houses connected to a distribution transformer (see Fig. 1), which makes the usage of PLC costly as each transformer typically needs a data concentrator [7]. The European outdoor LV electric power grids are installed underground and the distribution transformer serves in average 250-320 houses (see Fig. 2) [8], which makes the PLC an effective communication technology in terms of implementation costs.

In Latin America the LV and outdoor electric power grids have typically 60-80 consumers per transformer in average. It can be categorized as a half-way between USA and Europe, and due to this fact the relative cost of a wireless or a NB-PLC implementation is more balanced.

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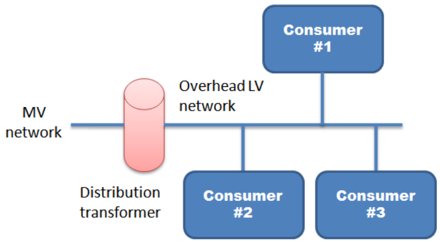

Fig. 1. Typical USA distribution network.

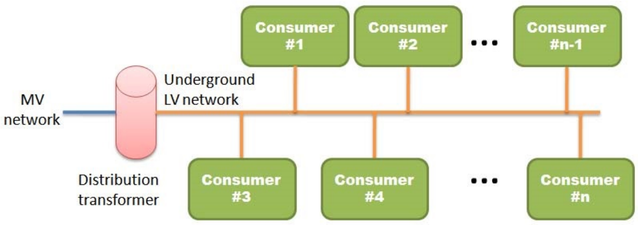

Fig. 2. Typical European distribution network.

III. Environment Influence on Communications

Wireless and power line communications suffer direct influence on the environment in which they are immersed. However, their performance is also dependent on the propagation frequency. Wireless devices emitting frequencies of 900 MHz tend to have a wider distance range if compared to higher frequencies devices, like 2.4 GHz or even 5.8 GHz, due to the wavelength associated to each frequency and how they interact with the environment obstructions, or more specifically, how these wavelengths are affected by the phenomena of reflection, refraction, diffraction, absorption, polarization, and scattering. Data communication through power cables are mainly affected by noise, multipath and impedance mismatching along the path (power cable). Cable splicing and splitting alter its impedance, as well as the aging. The amount of load over time also varies and the noise generated by switched power supplies and compact fluorescent lamps, among other loads, can produce interference on the range of frequencies used by PLC technology. There will be always favorable and unfavorable factors to support the PLC and wireless, but, in fact, they both have something in common: they do not need a new infrastructure for the communication path to be built.

IV. Security

SG provides communication infrastructure, making possible to have intelligent, reachable, and controllable devices on the field. But there is also a security risk in terms of privacy of information from Smart Meter (SM), metering theft, and external cyber attacks [9]. There is a legal concern about the information that a SM is able to provide mainly because of the energy consumption profiling capability. In [10] was demonstrated that by means of statistical methods and analysis of the data from a SM, it is possible to get electricity usage pattern of a specific consumer. From the technical point of view of the utilities this is an advantage that makes possible to compare the total usage registered by the entire LV electric power circuit with the hourly (or even lower register rate) load profile of the consumers. This ability makes possible for the utility to find out an electricity theft. However information is valuable to specific market industries like insurance companies or media and entertainment companies. There is also another negative side for the utilities about SM hacking: the meter tamper.

In 2010 a FBI report alerted about SM hacker in Puerto Rico, changing the SM settings for recording less power consumption [11]. More recently the government of Malta has revealed that a sophisticated hacking in SM making them to register less energy than what is being consumed [12]. Besides the SM itself, the communication path is also another possible entrance door for hackers to access either the SM parameters and the registered consumer information, so the security is very important as a protection against illegal and inappropriate log. There are several techniques that can be used to encrypt the data, but the system complexity can be increased and affects the performance, so a reasonable trade-off must be considered for implementation.

The SM remote communication can also helps to detect illegal load consumption reduction by tampering the current and voltage connection part that is outside of the SM as shown in [13]. This tamper was carried out in Brazil where the large-scale consumers are equipped with time-of-use (TOU) solid state current transformer (CT) meters. This type of connection requires a tests switch (also called as switch block) which is a special block that is used to disconnect CT-meter without interrupting the electricity flow to the consumer. The tamper detected consisted in built-in small relays, remote-controlling the connection and disconnection of the current portion of the tests switch, preventing these currents to be registered by the meter. The utility recognized that the meter load profile collected remotely was inconsistent and it triggers a more detailed investigation that made possible the tamper detection.

V. Environment Influence

The environment in which is immersed the communication path can highlight specific characteristics of wireless or NB-PLC. For example, a wireless Automated Meter Infrastructure (AMI) deployment in a building environment has some particularities. The usual situation is that the floors and walls are dense obstructions for wireless communication and attenuates the RF signal strongly. An alternative in some cases is the elevator pathway, which can help with the signal range performance. However, PLC technology does not depend on obstructions and the LV and in-home electric power grid capillarity is an useful characteristic such communication technology purposes. New constructions or even a tree growth can alter the communication link of deployed wireless systems, creating obstructions. In contrast, modifications in the distribution topology will affect the NB-PLC systems and can derail an existing and reliable communication path.

VI. Hybrid System

The target of a more robust communication technology can be achieved by joining LP-RF and NB-PLC in a cooperative way that both can assist, at the same time, the data transfer in the network. In fact, the idea of hybrid is not recent. In 2005 a discussion on this subject took place [2], but LP-RF and NB-PLC were considered to be working alone, each one in a section of the communication link because interconnected communication is an important key for reliability. The concept to perform a multiple and simultaneous communication through PLC and wireless parallel channels transforms the original sender-receiver dilemma in a collaborative approach. Such situation moves the main issue of a communication system which is originally designed to reach the receiver with a restrictive link into a new situation where the system can focus on the quality of the delivered data to the receiver. A hybrid system compounded by wireless and PLC at the same time has the ability to overcome with several limitations when they both cooperate to send the data to its final destination. The use of two different communication paths simultaneously enhance the reliability and extends the environment limitation rather than if they communicate individually. Obstructions or frequency interference that potentially attenuate the wireless portion will be supported by PLC in some situations and, in its turn, the PLC portion affected by additive noise or impedance mismatch will have the opportunity to be assisted by wireless portion and maintain the communication link active.

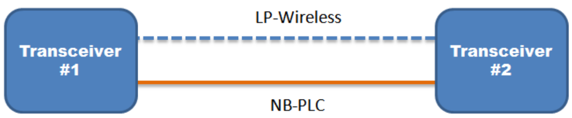

Fig. 3. Hybrid system scheme.

VII. Numerical Results

Considering the previous discussion and its assumptions, an implementation of the physical layer of the NB-PLC based on the IEEE standard for low frequency [14] was realized. This system uses multi-carrier modulation (MCM), more specifically, a special form of MCM, called HS-OFDM (Hermitian Symmetric - Orthogonal Frequency Division Multiplexing), also know as *discrete multitone* (DMT) [15]. This technique consists on carrying the data on multiple parallel channels using various closely spaced orthogonal subcarrier signals. Each subcarrier is modulated using coherent or non-coherent M-ary phase shift keying modulation. Also, the system has a forward error correction (FEC) technique (which is done concatenating Reed-Solomon, convolutional, and repetition codes) and making the interleaving process. Moreover, the energy is equally allocated among the subcarriers.

In these simulations, the total transmission power was equally distributed in both signals, i.e., PLC and wireless. After that, the power was equally distributed to all subcarriers. Additionally, DBPSK modulation was used in every single subcarrier to transmit data.

Based on [14], the frequency representation of a PLC channel is given by

$$H(f) = \sum_{i=1}^{N_p} g_i e^{(-a_0+a_1 f^k)d_i} e^{-j2\pi\frac{d_i}{v_0}}, \quad (1)$$

where N_p is the number of different paths that interferes between transmitter and receiver; g_i is a weighting factor that summarizes the reflection and transmission loss along a propagation path. It is a Gaussian random variable with zero mean and variance 1, which is scaled by 10,000; $a_{0,1}$ are attenuation parameters that depend on the characteristics of the transmission line, such as impedance; k is the slope of attenuation with respect to frequency; d_i is a Gaussian random variable representing the length of propagation paths form transmitter to receiver (in meters) with mean d_a and standard deviation d_s. This value can not be smaller than d_m; and v_0 is the wave propagation speed in meters/second.

Due to the lack of models of a LP-RF operating in the frequency of 915 MHz, we adopted a well-known model from a wide-band wireless channel to a narrow-band wireless channel. This was done by filtering the wide-band channel in the frequencies of interest, suggested in [16]. The model purposed for the LP-RF channel follows 802.15.4a IEEE report [16]. Its large scale fading is given in [17] and small scale fading is given by a Nakagami-m distribution. The equation that describes the channel impulse response (CIR) is as follows:

$$h(t) = \sum_{l=0}^{\infty}\sum_{k=0}^{\infty} \beta_{kl} e^{j\theta_{kl}} \delta(n - T_l - \tau_{kl}), \quad (2)$$

where β_{kl} is a Rayleigh distribution modeling the path gains, θ_{kl} is a uniform distribution from 0 to 2π modeling the randomness of path phases and, T_l and τ_{kl} are Poisson distributions modeling the cluster (with rate Γ) and ray (with rate γ) arrival time, respectively.

Next, we give the equations that describe the model variables shown in (2)

$$p(T_l|T_{l-1}) = \Lambda e^{[-\Lambda(T_l - T_{l-1})]}, \quad (3)$$
$$p(\tau_{kl}|\tau_{(k-1)l}) = \lambda e^{[-\lambda(\tau_{kl}-\tau_{(k-1)l})]}, \quad (4)$$
$$p(\beta_{kl}) = (2\beta_{kl}/\overline{\beta_{kl}^2}) e^{(-\beta_{kl}^2/\overline{\beta_{kl}^2})}, \quad (5)$$
$$\overline{\beta_{kl}^2} = \overline{\beta^2(0,0)} e^{-\frac{T_l}{\Gamma}} e^{-\frac{\tau_{kl}}{\gamma}}, \quad (6)$$
$$\overline{\beta^2(0,0)} = (\gamma\lambda)^{-1} G(1m) r^{-\alpha}, \quad (7)$$
$$G(1m) = G_t G_r \left[\frac{c}{4f\pi}\right]^2, \quad (8)$$

where c denotes the speed of light in meters/second; G_t and G_r denote the transmitter and receiver antenna gains, respectively.

The distribution of the small-scale amplitudes is

$$pdf(x) = \frac{2}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^m x^{2m-1} e^{-\frac{mx^2}{\Omega}}, \quad (9)$$

where $m \geq 1/2$ is the Nakagami m-factor, $\Gamma(.)$ is the gamma function, and Ω is the mean-square value of the amplitude.

The parameter m is generated by independent Gaussian random variables with mean and variance given by, respectively,

$$\mu(\tau_k) = 3.5 - \tau_k/73, \quad (10)$$
$$\sigma^2(\tau_k) = 1.84 - \tau_k/160, \quad (11)$$

in which τ_k is the ray delay measured in nanoseconds. Note that, the parameters are given for a wide-band channel, after the wide-band channel is generated, it is filtered and its filtered impulse response is of our interest.

The normalized frequency responses of NB-PLC and LP-RF channels, taken individually, are shown in Figs. 4 and 5. These frequency responses were modeled following Annex B of [14] for NB-PLC channel and from IEEE 802.15.4a channel model [16] for LP-RF.

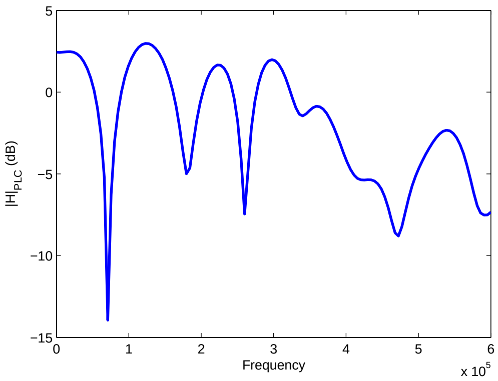

Fig. 4. Frequency response magnitude of a normalized PLC channel.

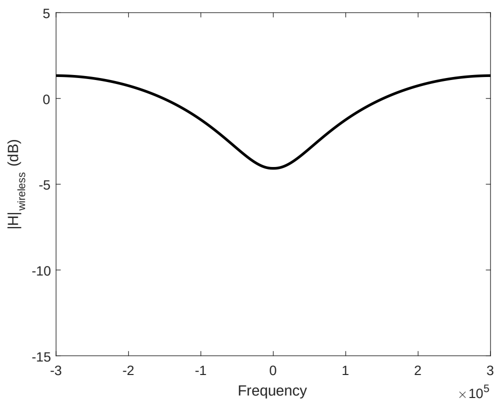

Fig. 5. Frequency response magnitude of a normalized wireless channel.

The additive PLC noise is modeled as a zero mean Gaussian random process with variance σ_P^2, i.e., $\mathcal{N}(\sigma_P^2, 0)$, while the additive wireless noise is modeled as a circularly symmetric zero mean Gaussian process ($\mathcal{N}(\sigma_W^2, 0)$). Also, $\|\mathbf{h}^W\|^2 = \|\mathbf{h}^P\|^2 = 1$ and $\sigma_W^2 = \sigma_P^2$ to guarantee a fair comparison. Note that, $\mathbf{h}^P = [h_0^P, h_1^P, \ldots, h_{L_h^P-1}^P]^T$ and $\mathbf{h}^W = [h_0^W, h_1^W, \ldots, h_{L_h^W-1}^W]^T$ are the vectorial representation of the discrete-time channel impulse response for PLC and wireless channel models and $\|.\|^2$ denotes 2-norm.

At the receiver, the SNRs were estimated for each subcarrier (corresponding to a frequency range). These estimations were made based on the estimated channel frequency response (using the preamble) and variance of the noise taken on silence period.

Following FCC-above-CENELEC specification, the allowed data communication is at the frequency range from 154.69 to 487.50 kHz and its respectively subcarriers are indicated by the index from 34 to 105, totalizing 72 subcarriers per OFDM symbol. A OFDM symbol has a length of 286 samples at the output of the transmitter, this symbol is composed of a 256-point IFFT appended by cyclic prefix (CP) corresponding to 30 samples, used for eliminating the intersymbol interference (ISI) occasioned by channel spreading effect.

One of the main characteristics of the hybrid system is to use the best of the PLC and wireless channels. In Fig. 6, it is possible to see that the hybrid system gets the best of both channels, in the frequencies in which the PLC channel has high attenuation (undesirable) and the wireless channel has low attenuation (desirable) and vice versa, the hybrid system keeps with the lowest attenuated transmitted signal in both cases. It happens due to the technique that calculate and select the best subchannels at the receiver, called selection combining (SC).

Again, Fig. 6 shows that the hybrid system has subcarrier SNR equal to the maximum of PLC and wireless channels subcarriers SNRs, considering the entire transmitting frequency band. In the case showed in this figure, the multichannel SNR (mSNR) of the PLC channel subcarriers was 2.05 dB and for the wireless channel, 3.07 dB. For the hybrid system, the mSNR was 5.09 dB, showing a mSNR gain slightly greater than 2 dB in relation to other channels. As a result, the system owner can select either having a lower bit error rate (BER) (transmitting data more reliably without reducing the total transmission power) or reducing the total transmission power, proportionally to the SNR gain, while maintaining the same BER of not hybrid system.

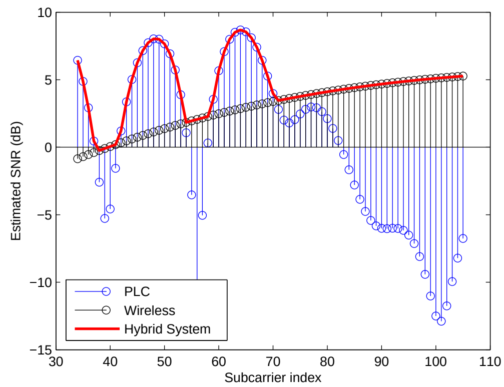

Fig. 6. Estimated SNR at the receiver for the PLC, wireless and hybrid (red curve) systems.

Performance analysis based on BER were also performed. Fig. 7 shows the bit error rate versus mSNR for PLC, wireless and PLC-wireless channels. As can be seen, it is possible to transmit data having mSNR $= 3$ dB with a BER $\approx 10^{-6}$

using hybrid system. When using only PLC channel this value of mSNR corresponds to a BER $\approx 2 \times 10^{-1}$. Since mSNR is proportional to the total transmission power, this plot confirms the fact that data communication using the same total transmission power tends to be less affected by errors when using the hybrid system.

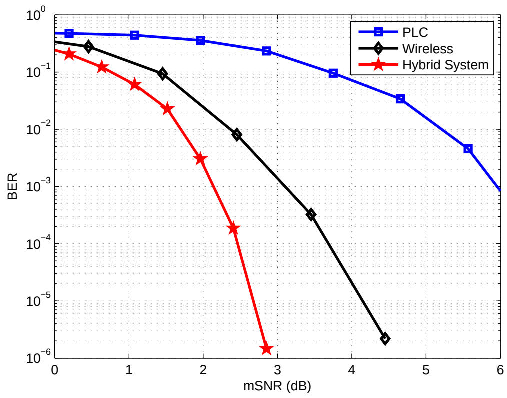

Fig. 7. Bit error rate versus multi-channel SNR.

Also, in Fig. 7, it is easy to see that, data can be transmitted with a BER $\approx 10^{-6}$, having mSNR $= 3$ dB when using hybrid channel or, having mSNR $= 4.5$ dB using solely wireless channel. In this case, having the same BER, data transmission can reduce total transmission power using the hybrid system.

It can be noticed that wireless channel has a greatly better performance than PLC channel. It happens due to the frequency selectivity characteristic of PLC channel. In fact, PLC channel has notches on frequency response and, it makes the data to be received with more errors. In opposition, LP-RF channels are almost flat, having a less hostile characteristic to data transmission.

Although, the hybrid system presents a gain when both channels are in use, it is important to point out that the advantages of hybrid systems also appear when only one of the channels are available. For example, suppose that the transmission line is not available from point A to B, i.e. the PLC could not transmit data between A and B, thus the hybrid system could keep transmitting data using only the wireless channel, making the communication system more reliable. The same holds true when wireless system is offline.

VIII. CONCLUSION

The implementation of a hybrid system is very dependent on the configuration of the LV outdoor electric power grids. As discussed previously the number of consumers connected to a distribution transformer should have to be economically reasonable considering the number of equipment on the field and the number of consumers served. That is the case of Latin America LV outdoor electric power grids, which tends to have a balanced relative cost when considering LV-PLC and LP-RF separately.

When one of the two paths is not viable to transmit data, hybrid system can use the other one to keep the communication, making it more reliable.

In addition, as showed in Section VII, hybrid system presents a gain of mSNR. Therefore, it is possible to have either a lower BER or a lower total transmission power, proportionally to the SNR gain, while maintaining the same BER in comparison to not hybrid systems.

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