Efficient Diversity Technique for Hybrid Narrowband-Powerline/Wireless Smart Grid Communications

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***Abstract*—Narrowband powerline communications (NB-PLC) and unlicensed wireless communications are considered as two leading communications technologies for emerging Smart Grid applications. The diversity provided by the simultaneous transmission of the same information over powerline and wireless links can be exploited to enhance the overall system reliability. In this paper, we propose an efficient technique to combine the received signals of the NB-PLC and wireless links considering the impulsive nature of the noise and interference on both links. We derive an expression for the average bit-error-rate of the proposed technique. In addition, we present simulation results that quantify the performance gains achieved by our proposed combining technique compared to conventional techniques.**

I. Introduction

The Smart Grids will be supported by heterogeneous networks that employ both wireless and powerline communication (PLC) technologies since no single solution fits all scenarios [1]. In particular, the two leading contenders for smart-meter two-way wireless communications in the unlicensed $902-928$ MHz in the US are the IEEE 802.15.4g standard and the emerging IEEE 802.11ah standard [2]. In addition, several PLC standards have been developed for the Smart Grid based on narrowband powerline communication (NB-PLC) in the $3-500$ kHz band (e.g. PRIME, G3, IEEE 1901.2, ITU-T G.hnem). NB-PLC is used for last-mile communications between smart meters at the customer sites and data concentrators, which are deployed by local utilities on medium-voltage (MV) or low-voltage (LV) powerlines [3], [4].

A major design challenge in Smart Grid communications is the presence of strong interference. For instance, in the unlicensed $902-928$ MHz band, the wireless interference is primarily generated from uncoordinated transmissions. Non-interoperable neighboring devices interfere with each other due to coexistence issues among existing standards. Such uncoordinated interference is impulsive in nature and can be characterized by statistical models such as the Gaussian mixture (GM), Middleton Class A (MCA) and symmetric alpha stable (SαS) models [5]. In NB-PLC, over the unlicensed $3-500$ kHz band, the dominant interference is a combination of narrowband interference and periodic impulsive noise that is synchronous to half of an AC cycle. Typical sources of the interference include non-linear power electronic devices such as inverters, DC-DC converters, and long-wave broadcast stations whose energy is coupled to the power lines in the $3-500$ kHz band.

Different from conventional spatial diversity scenarios (e.g. antenna diversity in wireless systems), simultaneous PLC and wireless transmissions experience interference signals with independent and non-identical characteristics. This motivates the need for new diversity combining techniques that take into account the asymmetric nature of the interference over the diversity branches. Initial investigations into this problem were reported in [2] where a diversity technique with combining metrics based on the instantaneous interference power, or equivalently the instantaneous SNR, was proposed. However, this technique requires higher pilot overhead than what is supported by current PLC standards. Other previous studies on PLC/wireless diversity combining include [6], and [7]. However, their investigations considered in-home BB-PLC transmissions in the $2-30$ MHz and wireless transmissions in the 2.4 GHz band, assuming MCA noise for the BB-PLC link and additive white Gaussian noise (AWGN) for the wireless link, which have different noise and interference characteristics from those encountered by NB-PLC and wireless communications in the unlicensed $902-928$ MHz band.

In this paper, assuming orthogonal frequency division multiplexing (OFDM) transmission, we propose an efficient technique for NB-PLC/wireless diversity combining with combining metrics based on the interference power spectral density (PSD), or equivalently the average SNR per OFDM sub-channel. The proposed technique does not require any pilot overhead and achieves a considerable performance gain over conventional combining techniques that use average SNR-based metrics for signal combining. In addition, we analyze the average BER of the proposed diversity combining technique and present numerical simulations that corroborate the analytical results.

The remainder of this paper is organized as follows. In the next section, we present the system model including the noise and the channel assumptions. In Section III, we describe our proposed NB-PLC/wireless diversity combining technique. In

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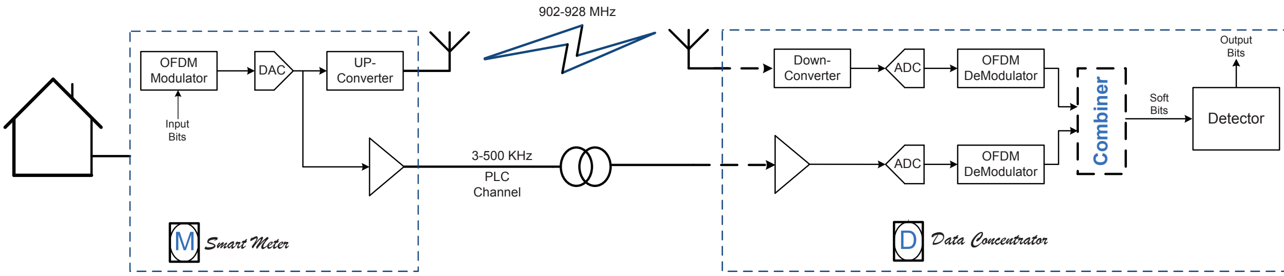

Figure 1. System block diagram for PLC and wireless diversity for communication between smart meter and data concentrator.

Section IV, we derive an expression for the average BER performance of the proposed combining technique. Numerical results are presented in Section V to quantify the performance gain of the proposed PLC/Wireless combining technique. Finally, the paper is concluded in Section VI.

II. System Model and Assumptions

As shown in Figure 1, we assume OFDM transmission for both NB-PLC and wireless links. At the transmit side, the same information is sent over both links simultaneously. At the receive side, the received signals from the two links are combined by first calculating the log-likelihood ratios (LLRs or soft bits) for each branch and then adding them using appropriate weights. The combined soft bits are then fed to a detector that makes hard decision to provide estimates for the transmitted information bits. It is worth noting that the combining is performed at the bit (LLR)-level in order to allow the two links to use different constellation sizes, FFT sizes, cyclic prefix lengths or different sampling rates, as long as both links have exactly the same average bit rate at the combiner input.

The received symbols at the combiner input for the l-th OFDM block and the k-th subchanel for the NB-PLC link, denoted as $Y^l_{p,k}$, and the wireless link, denoted as $Y^l_{w,k}$, have the following complex baseband representation

$$Y^l_{p,k} = H^l_{p,k} X^l_k + Z^l_{p,k}, \quad Y^l_{w,k} = H^l_{w,k} X^l_k + Z^l_{w,k}, \qquad (1)$$

where X^l_k is the transmitted symbol, $Z^l_{p,k}$ and $Z^l_{w,k}$ are complex random variables with zero mean and variances σ_p^2 and σ_w^2, respectively, that represent the noise and interference on the NB-PLC and wireless links, respectively. $H^l_{p,k}$ and $H^l_{w,k}$ represent the frequency-domain complex channel coefficients of the PLC and wireless links, respectively. Next, we state and justify our assumptions regarding the noise and the channel models for the NB-PLC and wireless links.

A. NB-PLC Link Noise Model

The generation of the impulsive noise process that best fits actual measurements is presented in [8], and summarized in Figure 2. $S(n)$ is a Gaussian process with zero mean and unit variance, i.e. $S(n) \sim \mathcal{N}(0,1)$. The output noise process in NB-PLC is a cyclostationary noise process that can be divided into N_R temporal regions over which the noise can be assumed a stationary process. Each region is characterized by a discrete-time linear time-invariant (LTI) filter $h_j(n)$. The noise power

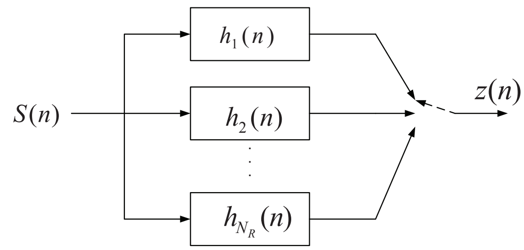

Figure 2. NB-PLC cyclostationary noise model.

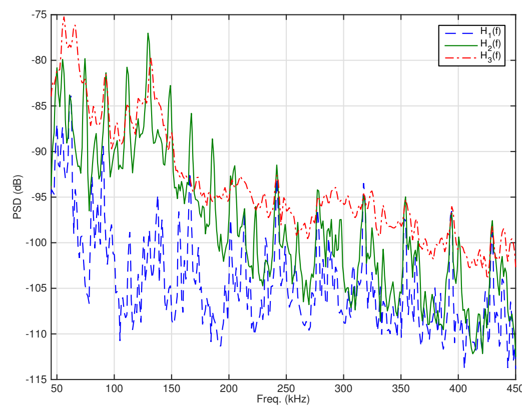

Figure 3. Noise PSD.

in each region is expressed as $\mathrm{E}\{|z(n)|^2\} = ||h_j(n)||^2, \ n \in \mathcal{R}_j$, where $\mathrm{E}\{.\}$ denotes the expectation operation. The noise model is then parameterized by: the number of stationary regions N_R, the region intervals $\{\mathcal{R}_i : 1 \le j \le N_R\}$, and the LTI filters $\{h_i(n) : 1 \le j \le N_R\}$, which are usually represented by their corresponding noise PSDs obtained from field measurements. An example for the filter PSDs used in the simulations is shown in Figure 3 for the case of $N_R = 3$, where the ratios of the average noise powers over the three regions are $-6.59 : 1.93 : 5.15$ dB with time durations of 5, 2 and 1.3 ms, respectively.

B. Wireless Link Noise Model

Various statistical models have been proposed to capture the statistics of the interference that affects the uncoordinated wireless transmissions in the unlicensed frequency bands. The main statistical models proposed are the GM, the MCA, and the SαS models. Given that the MCA probability density function (PDF) is a special case of the GM PDF and that the SαS random variable can also be approximated by a GM random variable, we consider the noise and interference in the wireless link to be modeled as a GM random process [5]. Next, we present the time-domain and frequency-domain statistics of the noise and interference in the wireless link.

1) Time-Domain Noise Statistics: The PDF of the GM distribution is a weighted sum of a set of Gaussian PDFs. The PDF of a GM random variable z is given by $p(z) = \sum_{m=0}^{M-1} \frac{\alpha_m}{\pi \sigma_m^2} \exp\left(\frac{-|z|^2}{\sigma_m^2}\right)$, where α_m is the probability of the m-th Gaussian state, and M is the number of states. Each state has a noise variance σ_m^2 where the average noise variance over all states is σ_w^2. We assume that the state with index $m = 0$ represents the thermal noise component. In practice, only two terms of the GM PDF are enough to fit the impulsive interference to the GM model [5].

2) Frequency-Domain Noise Statistics: The noise in the frequency domain can be expressed as $Z_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} \zeta_{kn}, \;\; k = 0, \ldots, N-1$, where N is the FFT size and $\zeta_{kn} = z_n \mathrm{e}^{-j\frac{2\pi}{N}kn}$. Given the state of the n-th noise sample, the PDF of ζ_{kn} is Gaussian with mean σ_m^2, i.e. $\zeta_{kn}|m \sim \mathcal{N}\left(0, \sigma_m^2\right)$. Hence, for the special case of $M = 2$, the PDF of Z_k can be written as $Z_k \sim \sum_{i=0}^{N} \binom{N}{i} \alpha_0^i \alpha_1^{N-i} \mathcal{N}\left(0, \bar{\sigma}_i^2\right)$, where $\bar{\sigma}_i^2 = \frac{1}{N}\left[i\sigma_0^2 + (N-i)\,\sigma_1^2\right]$. Hence, we conclude that the PDF of the frequency-domain noise also follows a GM distribution with $N + 1$ states.

C. NB-PLC Link Channel Model

We adopt a channel model based on measurements that we conducted in the laboratory for a LV power line cable connected with various loads. We measured the channel impulse response (CIR) by sending a known periodic training sequence with a period of 512 μs on one end of the cable and then estimating the CIR from the received signal at the other end of the cable. The measured CIR is shown in Figure 4 to be periodic with a period of around one quarter of the AC cycle where each period consists of 7 channel realizations with the amplitudes of their largest taps following a sinusoidal profile. Figure 5 shows the CIR and the channel frequency response (CFR) of the channel realizations within one period, where we observe that the realizations are quite similar except for those which coincide with the sinusoidal zero crossing.

D. Wireless Link Channel Model

We assume a Rayleigh fading model for the wireless link since it is widely used to capture small-scale fading effects on signal propagation in wireless environments.

III. Proposed NB-PLC/Wireless Combining Technique

We investigate a maximal-ratio-combining (MRC)-based technique where the combining weights are to be optimized according to the noise characteristics in the the NB-PLC and wireless links. Given that the noise statistics on both links

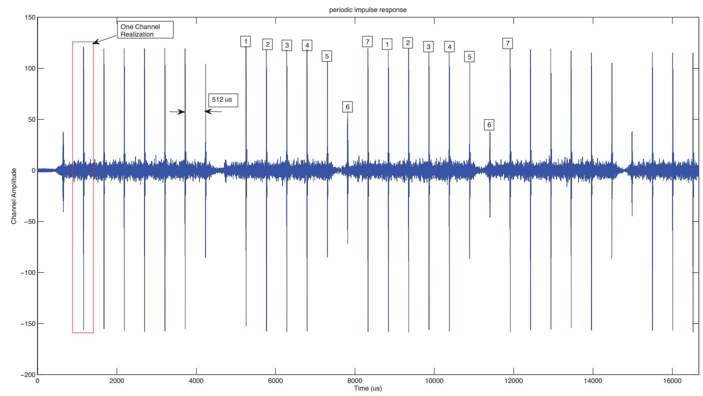

Figure 4. Multiple realizations of the channel impulse response over time.

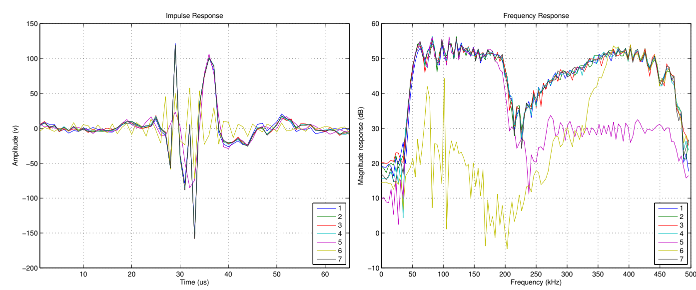

Figure 5. Channel impulse response and frequency response of one period.

are not identical and that the NB-PLC noise model is non-stationary and based on field measurements, it is challenging to derive the optimal MRC scheme analytically. Furthermore, the optimal sufficient statistic for signal detection in the presence of GM noise is computationally intensive[9]. A sub-optimal implementation of the MRC scheme assumes the noise to be Gaussian on both the NB-PLC and wireless links with variances σ_p^2 and σ_w^2, respectively. In this case, the log-likelihood (LL) function can be expressed as

$$\begin{aligned} LL(X_k^l) &= \mathrm{Log}\left[p\left(Y_{p,k}^l|H_{p,k}^l X_k^l\right) \times p\left(Y_{w,k}^l|H_{w,k}^l X_k^l\right)\right] \\ &= -\frac{|Y_{p,k}^l - H_{p,k}^l X_k^l|^2}{\sigma_p^2} - \frac{|Y_{w,k}^l - H_{w,k}^l X_k^l|^2}{\sigma_w^2} \end{aligned} \quad (2)$$

Hence, considering BPSK modulation, the LLR of the MRC scheme can be expressed as

$$\begin{aligned} LLR &= LL(X_k^l = 1) - LL(X_k^l = -1) \\ &= LLR_w + LLR_p. \end{aligned} \quad (3)$$

From (2) and (3), we note that the contribution of each link to the combined LLR is inherently weighted by the inverse of the average noise power on that link. However, given the impulsive nature of the noise on both the NB-PLC and wireless links, the average noise power cannot be assumed constant over time or frequency. The instantaneous noise power over frequency subchannels across multiple OFDM blocks is depicted in Figure 6. It is clear from Figure 6 that the noise power level shows rapid variations over the OFDM data symbols where it actually suffers drastic changes on a symbol-by-symbol basis, especially in the PLC link. Moreover, the noise power

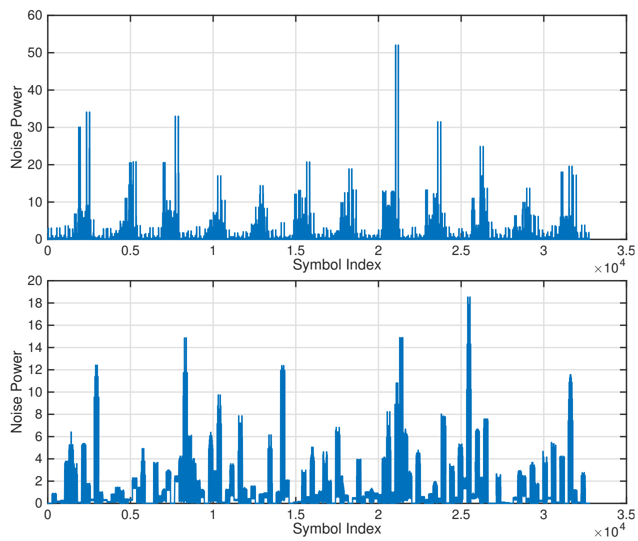

Figure 6. Noise Power in PLC link (above) and wireless link (below).

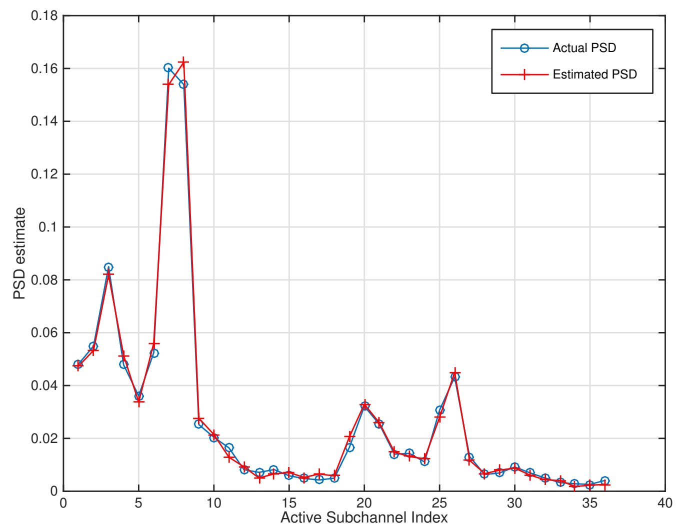

Figure 7. Actual and Estimated Noise PSD.

is shown to have a high peak-to-average ratio, which is higher on the PLC than on the wireless link. Hence, to capture the instantaneous noise variations, the LLR combining weights must be based on the instantaneous noise powers. However, the estimation of the instantaneous noise powers requires either high pilot overhead (e.g. [2]) or high computational complexity (e.g. [3]). Hence, as a practical solution to compute the combining weights, we propose using the average noise power per OFDM subchannel, or equivalently the noise PSD, to compute the MRC combining weights, as follows

$$LL(X_k^l) = -\frac{|Y_{p,k}^l - H_{p,k}^l X_k^l|^2}{\tilde{\sigma}_{p,lk}^2} - \frac{|Y_{w,k}^l - H_{w,k}^l X_k^l|^2}{\tilde{\sigma}_{w,lk}^2},$$

where $\tilde{\sigma}_{lk}^2$ is the average noise power for the l-th OFDM block at the k-th subchannel. It is worth mentioning that the noise PSD varies from one OFDM block to another in the PLC link since the noise has multiple stationary regions with different PSDs while, for the wireless link, the PSD is the same for all OFDM blocks. Next, we present an efficient technique to estimate the noise PSD from the received signal power.

A. Noise PSD Estimation

The received symbol power over the l-th OFDM symbol and the k-th subchannel index can be written as

$$|Y_k^l|^2 = |H_k^l X_k^l|^2 + |Z_k^l|^2 + 2\mathfrak{Re}\left[H_k^l X_k^l Z_k^{l*}\right].$$

Averaging over $|Y_k^l|^2$, we get

$$\begin{aligned} \mathrm{E}|Y_k^l|^2 &= \mathrm{E}|H_k^l|^2 \mathrm{E}|X_k^l|^2 \\ &+ \mathrm{E}|Z_k^l|^2 + 2\mathfrak{Re}\left[\mathrm{E}\left(H_k^l X_k^l\right)\mathrm{E}\left(Z_k^{l*}\right)\right], \end{aligned} \quad (4)$$

where E(.) denotes the expectation operator. Since $\mathrm{E}\left(Z_k^{l*}\right) = 0$, then $\mathrm{E}|Y_k^l|^2$ reduces to

$$\mathrm{E}|Y_k^l|^2 = \mathrm{E}|H_k^l|^2 \mathrm{E}|X_k^l|^2 + \mathrm{E}|Z_k^l|^2.$$

Setting $\mathrm{E}|X_k^l|^2 = 1$, we get

$$\tilde{\sigma}_{lk}^2 = \mathrm{E}|Z_k^l|^2 = \mathrm{E}|Y_k^l|^2 - \mathrm{E}|H_k^l|^2. \quad (5)$$

Hence, from (5), for a certain subchannel k, the average noise power can be estimated by subtracting the average channel power from the average received data symbol power. The averaging time duration has to be long enough in order to suppress the term $\mathrm{E}\left(Z_k^{l*}\right)$ in (4) and obtain accurate estimates. However, the receiver can start decoding the received data, using some initial combining weights, while the averaging is running and does not have to wait for averaging to converge. Furthermore, a convergence criterion can be easily set to terminate the averaging and avoid having the averaging duration as a design parameter. The estimated PSD using the proposed estimation technique is shown in Figure 7 to be very close to the actual PSD over the set of active subchannels with averaging duration of 512 OFDM blocks.

IV. Performance Analysis

In this section, assuming OFDM transmission, we first present the average BER expression for each link separately. Then, we derive an expression for the average BER of the proposed NB-PLC/wireless combining technique.

A. PLC Link

The average BER can be expressed as $P_b(E) = \sum_{j=0}^{N_R-1} R_j P_b^j(E)$, where $P_b^j(E)$ is the average BER corresponding to the j-th filter and is given by $P_b^j(E) = \frac{1}{N}\sum_{k=0}^{N-1} P_b^{jk}(E)$, where N is the FFT size and $P_b^{jk}(E)$ is the average BER corresponding to the j-th filter over the k-th subchannel. For binary phase-shift keying (BPSK) modulation, $P_b^{jk}(E)$ is given by $P_b^{jk}(E) = \mathrm{Q}\left[\sqrt{\frac{2E_b}{P_{jk}\sigma_p^2}}\right]$, where P_{jk} is the j-th filter average noise power over subchannel k.

B. Wireless Link

For $M = 2$, the BER of an OFDM system in the presence of GM noise can be readily obtained as $P_b(E) =$

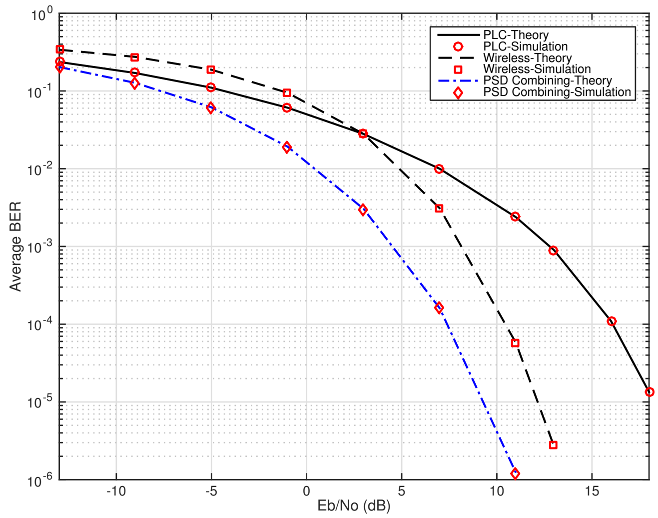

Figure 8. Average BER vs E_b/N_o in dB for PLC and wireless assuming flat channels.

$\sum_{i=0}^{N}\binom{N}{i}\alpha_0^i\alpha_1^{N-i}P_b^i(E)$, where $P_b^i(E)$ for BPSK is given by $P_b^i(E) = \mathrm{Q}\left(\sqrt{\frac{2E_b}{\bar{\sigma}_i^2}}\right)$.

C. Proposed NB-PLC/Wireless Combining

For the flat-fading case, the received symbol in the kth OFDM subchannel after combining can be represented as $Z_k^l = X_k^l + w_{p,lk}Z_{p,k}^l + w_{w,lk}Z_{w,k}^l$, where $w_{p,lk} = (1+\tilde{\sigma}_{p,lk}^2/\tilde{\sigma}_{w,lk}^2)^{-1}$ and $w_{w,lk} = (1+\tilde{\sigma}_{w,lk}^2/\tilde{\sigma}_{p,lk}^2)^{-1}$ are the combining weights for the PLC and the wireless links, respectively. Hence, the average BER for the proposed combining technique assuming perfect PSD estimates can be expressed as

$$P_b(E) = \sum_{j=0}^{N_R-1} R_j \sum_{i=0}^{N}\binom{N}{i}\alpha_0^i\alpha_1^{N-i}P_b^{ji}(E), \qquad (6)$$

where $P_b^{ji}(E)$ is the average BER corresponding to the j-th filter and the i-th noise state of the GM PDF and is given by $P_b^{ji}(E) = \frac{1}{N}\sum_{k=0}^{N-1}P_b^{jik}(E)$, where $P_b^{jik}(E)$ can be written as $P_b^{jik}(E) = \mathrm{Q}\left[\sqrt{\frac{2E_b}{w_{w,jk}^2\bar{\sigma}_i^2 + w_{p,jk}^2P_{jk}\sigma_p^2}}\right]$ for BPSK modulation. Figure 8 shows the average BER expressions derived analytically to be inline with the simulation results.

V. Numerical Results

In this section, we present numerical results for the coded performance of the proposed NB-PLC/wireless diversity combining technique compared to the combining techniques based on average SNR and instantaneous SNR.

A. Simulation Parameters

We consider transmission in the CENELEC A frequency band ($35.9375 - 90.6250$ kHz). The sampling rate is set to 400 kHz. We assume OFDM transmission with FFT size of 256 subchannels and a cyclic prefix of 22 samples. These parameters are chosen to be compliant with the IEEE 1901.2 NB-PLC standard. The noise on the wireless link is modeled as a GM process with $M=2$, $\alpha_0 = 0.99$, $\alpha_1 = 0.01$, $\sigma_0^2 = 0$ dB and $\sigma_1^2 = 50$ dB. For forward error correction (FEC), we assume convolutional coding with rate $\frac{1}{2}$ and constraint length 7 at the transmitter and a Viterbi decoder with soft decision decoding at the receiver. It is worth noting that the average SNRs of the two links are different, in general.

Figure	9	10	11	12
Gain (dB)	2.5dB	2dB	1.2dB	1.5dB

Table I
Performance gains of the proposed combining technique over average SNR combining at 10^{-5} BER.

Figure	9	10	11	12
Loss (dB)	2dB	1.5dB	1dB	0.8dB

Table II
Performance loss of the proposed technique compared to instantaneous SNR combining at 10^{-5} BER.

B. Performance Results

In this subsection, we study the performance of NB-PLC/wireless diversity using the proposed combining technique. In Figure 9, assuming a flat channel for both links, we plot the average BER for both links versus the E_b/N_o of the PLC link while fixing the E_b/N_o of the wireless link at 2 dB. On the other hand, in Figure 10, assuming a flat channel, we plot the average BER for both links versus the E_b/N_o of the wireless link while fixing the E_b/N_o of the PLC link at 2 dB. In Figures 11 and 12, we plot the average BER for both links versus the E_b/N_o of the PLC and wireless links, where both links have equal E_b/N_o in this case, for the flat and fading channel cases, respectively. The achieved performance gains of the proposed combining technique over combining based on the average noise powers is summarized in Table I. In addition, the performance loss of the proposed technique compared to using the instantaneous noise power metrics, or equivalently the instantaneous SNR metrics, is shown in Table II. It is worth mentioning that the instantaneous noise power estimation is performed using linear interpolation between comb-type pilots that are inserted periodically within the active subchannels of each OFDM block. The pilot spacing used in the simulations is 5 subchannels.

VI. Conclusion

We proposed an efficient diversity combining technique for hybrid NB-PLC and unlicensed wireless transmission that takes into account the impulsive nature of the noise and interference on both links. The proposed technique uses the average noise power per OFDM subchannel, or equivalently the noise PSD, in computing the MRC metrics. In addition, we presented a simple algorithm for noise PSD estimation that does not require any pilot overhead. We also derived an analytical expression for the average BER performance of the proposed technique and showed that it matches the simulation results. Finally, we presented numerical results that quantify the performance gains achieved by the proposed combining technique compared with conventional MRC that uses average noise power-based metrics.

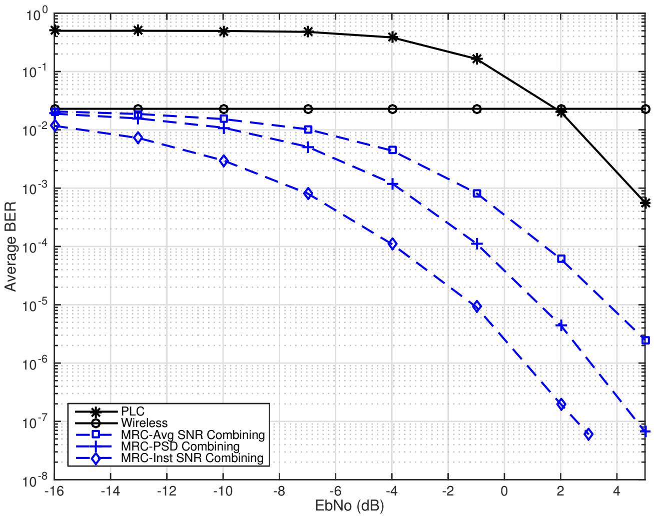

Figure 9. Average BER vs E_b/N_o of the PLC link for $E_b/N_o = 0$ dB for wireless with flat channels assumed.

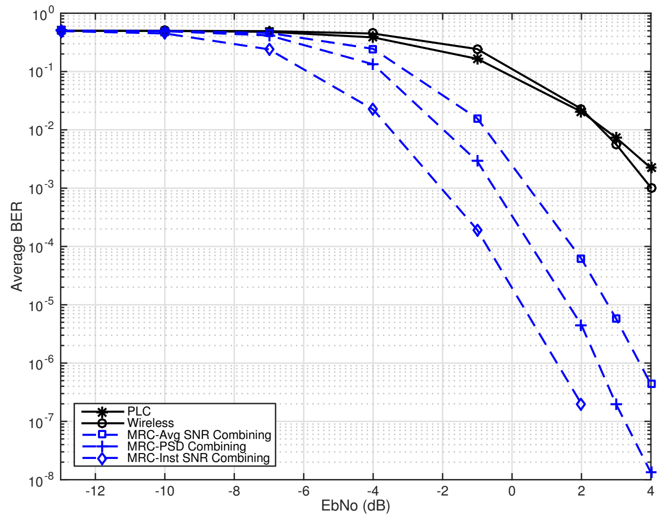

Figure 11. Average BER vs E_b/N_o of both the PLC and the wireless links with flat channels.

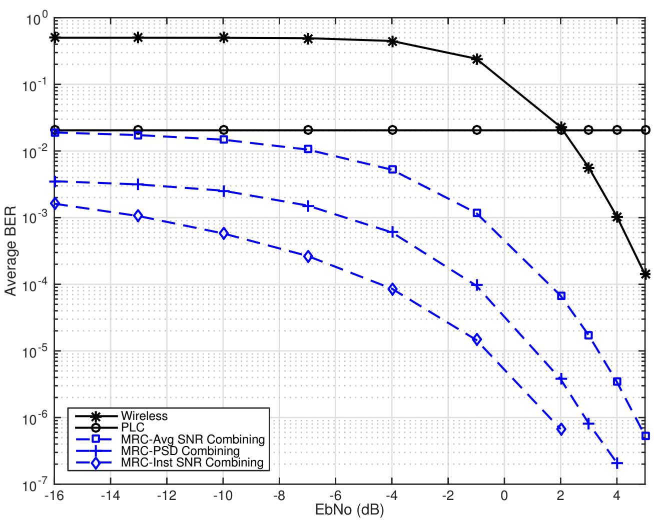

Figure 10. Average BER vs E_b/N_o of the wireless link for $E_b/N_o = 2$ dB for PLC with flat channels assumed.

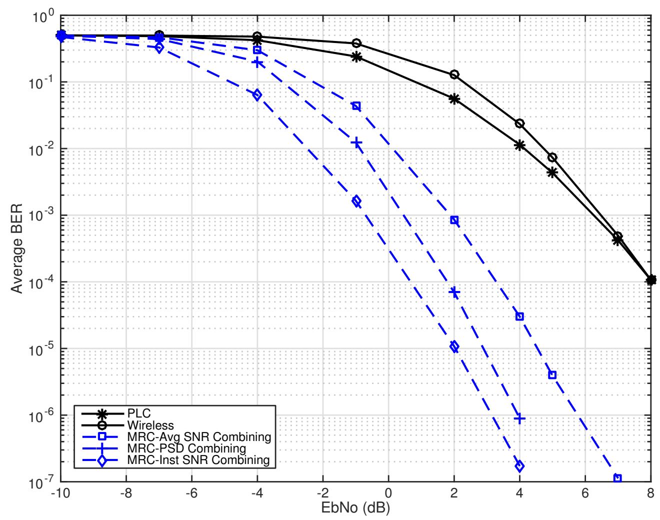

Figure 12. Average BER vs E_b/N_o of both the PLC and the wireless links with fading channels.

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