Channel Estimation Based on Frame Control Symbol Re-encoding and Re-Mapping

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***Abstract*—This work focuses on channel estimation in power line communications (PLC) systems. Considering the IEEE Standard 1901-2010 frame structure, data-aided channel estimation is performed on the preamble sequence. However, resolution of the preamble symbols compared to the Frame Control (FC) symbol and payload symbols (256 vs. 2048 subcarriers) leads to interpolation errors that tend to increase in presence of narrow-band interference (NBI). This work addresses channel estimation in standard IEEE 1901-2010 by re-encoding and re-mapping the FC symbol. The main contribution on this paper is to show that re-estimation of only the noise power spectral density (PSD) (and not the channel frequency response (CFR)) significantly improves system performance by using FC symbol as a new reference. This conclusion provides a feasible implementation in practical systems because the proposed solution does not lead to delays nor additional computational costs. Gain obtained by this update compared to preamble based channel estimation is substantial and system behavior, especially in the presence of NBI, improves considerably. A PLC system according to the standard IEEE 1901-2010 is used to evaluate our proposal. System performance is tested on multipath channels and narrow-band noise.**

***Index Terms*—channel estimation, noise power estimation, frame control symbol, narrow-band noise, IEEE Std. 1901-2010**

I. INTRODUCTION

The use of power distribution networks for data communications systems is at the same time the main advantage and Achilles' heel of power line communications (PLC). As transmission occurs on a wired network not designed for high-speed communications, PLC suffers from one of the most aggressive communication channels. The diversity and relatively high power level of noise, as well as strong fading caused by multipath effects represent a major concern in order to guarantee robust data transmission in electrical grids. In this regard, channel estimation is still a challenge concerning the development of PLC systems [1], [2].

The IEEE Standard 1901-2010 uses a preamble sequence inserted by transmitters for supporting frame detection, synchronization and channel estimation [3]. Channel estimation is necessary for equalization, soft-demaping, soft-decoding and signal-to-jamming power ratio (SJR) as well as signal to noise power ratio (SNR) estimation. Also adaptive bit-loading demands on robust channel estimation techniques [4]. In this work, the preamble sequence is considered as prior knowledge to the receiver in order to perform data-aided channel frequency response (CFR) estimation. For that purpose, the linear minimum mean square error (LMMSE) and the least square (LS) estimators are used.

On the other hand, noise power spectral density (PSD) estimation is frequently overlooked in many channel estimation works [5], [6], [7]. When additive white Gaussian noise (AWGN) is considered, noise power is simply obtained by averaging the instantaneous noise power estimates over the whole band [8], [9], [10]. Nevertheless, AWGN cannot be assumed in power lines [1]. Colored background noise (CBN), strongly related to a variety of devices connected to the line, and narrow-band interference (NBI) caused by broadcasters in the long, middle and short wave range as well as different radio services affect data transmission over electrical grids.

The authors in [11] evaluate the impact of pilot symbol *vs.* pilot tone channel estimation. Stating that interpolation introduces errors in CFR estimation, but no mention is made about noise power estimation. In [12], Bueche et al. also analyze the interpolation error in channel estimation, concluding that the interpolation kernel has no notorious impact on CFR estimation. However, noise power estimation is not addressed in this work either, even though it is considered a colored noise model. The authors in [13] propose to use the FC symbol in a Multi-Input Multi-Output (MIMO) PLC system to mitigate interpolation errors in CFR estimation. Nevertheless, none of these works address the impact of interpolation error and possible solutions regarding the noise PSD estimation.

Hence, a major concern regarding noise power estimation in the IEEE Standard 1901-2010 preamble sequence is the broadening of noise power to the unobserved neighbor subcarriers when a 256-frequency point noise PSD is interpolated to obtain a 2048-frequency point noise PSD estimate. This inaccurate estimation of noise causes incorrect compensation of the signal at the input of the turbo decoder. To the best

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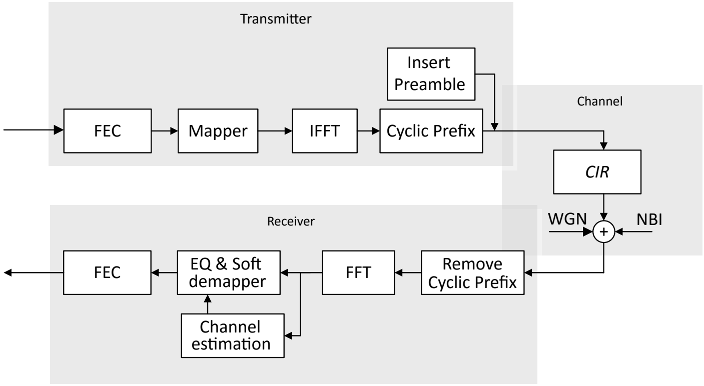

Fig. 1. IEEE Std. 1901-2010 OFDM transceiver.

of the authors' knowledge, no reports have been published to evaluate performance of this approach in presence of NBI. In the following this is analyzed through simulations.

The remainder of this paper is organized as follows. OFDM transceiver, power line channel and noise models are described in Section II. Preamble-based and proposed channel estimation methods are addressed in Section III. System performance is investigated in Section IV through simulations. Finally, conclusions are drawn in Section V.

II. OFDM TRANSCEIVER AND CHANNEL MODEL

A. IEEE Standard 1901-2010 Transceiver

Transceiver model to be used is designed to meet the specifications of IEEE Standard 1901-2010 [3]. Fig. 1 shows a block diagram of the system. On the transmitter side, the forward error correction (FEC) block is comprised by a data scrambler, a turbo convolutional encoder and a channel interleaver. A mapper followed by an inverse fast Fourier transform (IFFT), generates the time domain symbols. Phase-shift keying (PSK) and quadrature amplitude (QAM) modulations are employed by the mapper block. Then, a cyclic prefix (CP) is inserted to cancel intersymbol interference (ISI) and to allow further simple frequency-domain processing. Besides, a preamble sequence is added as header of every frame. At the receiver, symmetrical operations are performed to recover information data.

According to [3], PHY protocol data units (PPDU) carrying payload data consist of a preamble sequence, at least one frame control (FC) symbol and payload symbols [3, Table 13-3]. The preamble consists of 10 OFDM symbols divided on positive synchronization symbols (SP) and negative synchronization symbols (SM = SP). SP and SM span 256 subcarriers while the FC symbol and the payload symbols span 2048 subcarriers.

Remark that, the 1901 FFT preamble and at least one 1901 FFT FC symbol are always present in each PPDU. The FC symbol, carrying control information data, must be perfectly recovered by the receiver to correctly process the payload symbols. Hence, the FC symbol comprises a frame control check sequence which is used to check the integrity of the FC information. If cyclic redundancy code (CRC) validation of the FC data fails, the frame is immediately discarded. Therefore, a new perfectly-known reference regarding channel estimation can be created at the receiver from the FC symbol. This characteristic is used in this work to improve noise PSD estimation.

B. Channel and Noise Models

Throughout this work we use the multipath model proposed by Zimmerman in [14]. Additive white Gaussian noise (AWGN) and narrow-band noise (or narrow-band interference, NBI) are considered as the channel noise model; this is depicted in Fig. 1. Other noise sources that affects PLC are out of the scope of this work. Assuming that effective channel impulse response (CIR) is shorter or equal to the guard interval length, and removing CP, the signal at the output of the FFT block is described by:

$$Y[k] = X[k]H[k] + V[k], \tag{1}$$

where $k = 1, 2, \cdots, N$ is the sub-carrier index and Y, X, H and V are the received signal, the transmitted signal, the channel frequency response (CFR) and the channel noise in the frequency domain, respectively. $V[k]$ is the Fourier transform of the additive noise composed by AWGN and NBI. N represents the total number of subcarriers of an OFDM symbol.

NBI can be modeled as a sum of multiple sine signals with random amplitudes and phases.

$$n_{NBI}[n] = \sum_{i=1}^{I} A_i[n] \cdot \sin(2\pi w_i n + \varphi_i) \tag{2}$$

Variables $A_i[n]$, φ_i and w_i refer to the i-*th* interference amplitude, frequency and phase, respectively. The total number of interference signals is represented by I.

III. CHANNEL ESTIMATION

The following two estimates are addressed in current section: CFR estimation and noise power spectral density (PSD) estimation. This to determine $H[k]$ and the noise power (square magnitude of $V[k]$) in (1).

Subsection III-A and III-B address CFR estimation and noise Power Spectral Density (PSD) estimation, respectively; based on prior knowledge of the preamble sequence. Then, the proposed method is derived in Subsection III-C.

Following, we describe two well-known methods for the CFR estimation: the linear minimum mean-square error (LMMSE) and the Least Square (LS) estimators. The former has been one of the most extensively reported since it optimizes the mean-square error metric [15], [16], [17], [6]. On the other hand, the LS estimator is widely employed because it does not require any statistical information about channel and noise [15], [16], [18], [11]. In addition, the LS estimator exhibits a very low computational cost since it only requires a division operation at the receiver.

After detection and synchronization, L preamble symbols will be available at the receiver for estimation purposes.

In vector-matrix notation the l^{th} received OFDM preamble symbol can be conveniently expressed as

$$\mathbf{Y}_{\mathrm{P},l} = \mathbf{X}_{\mathrm{P},l}\mathbf{H}_{\mathrm{P},l} + \mathbf{V}_{\mathrm{P},l} \tag{3}$$

where:

$$\begin{aligned}
\mathbf{X}_{\mathrm{P},l} &= \mathrm{diag}(\mathrm{X}_{\mathrm{P},l}[0], \cdots, \mathrm{X}_{\mathrm{P},l}[255]) && \in \mathbb{C}^{256\times256}\\
\mathbf{H}_{\mathrm{P},l} &= [\mathrm{H}_{\mathrm{P},l}[0], \cdots, \mathrm{H}_{\mathrm{P},l}[255]] && \in \mathbb{C}^{256\times1}\\
\mathbf{V}_{\mathrm{P},l} &= [\mathrm{V}_{\mathrm{P},l}[0], \cdots, \mathrm{V}_{\mathrm{P},l}[255]] && \in \mathbb{C}^{256\times1}
\end{aligned}$$

Based on the representation in (3), CFR and noise PSD estimation will be discussed on following sections.

A. CFR Estimation

Based on prior knowledge of the preamble, the LS estimator is defined as:

$$\widehat{\mathbf{H}}_{\text{LS}\mathrm{P},l} = \mathbf{X}_{\mathrm{P},l}^{-1}\mathbf{Y}_{\mathrm{P},l}. \tag{4}$$

A better estimator can be obtained by the Wiener-Hopf or LMMSE estimator. $\widehat{\mathbf{H}}_{\text{LMMSE}}$ on the l^{th} preamble symbol is given by

$$\widehat{\mathbf{H}}_{\text{LMMSE}\mathrm{P},l} = \mathbf{R}_{hh}\left(\mathbf{R}_{hh} + \sigma_v^2\left(\mathbf{X}_{\mathrm{P},l}\mathbf{X}_{\mathrm{P},l}^H\right)^{-1}\right)^{-1}\widehat{\mathbf{H}}_{\text{LS}\mathrm{P},l}. \tag{5}$$

Supra index H is the Hermitian transposed operator. Matrix $\mathbf{R}_{hh}$ is the channel correlation matrix and $\left(\sigma_v^2\left(\mathbf{X}_{\mathrm{P},l}\mathbf{X}_{\mathrm{P},l}^H\right)^{-1}\right)^{-1}$ is the average SNR at the filter input, which are used to generate the filter coefficients. Hence, in order to determine the CFR estimator, the second order statistic of the channel ($\mathbf{R}_{hh}$) and the highest expected value of SNR parameter are required prior information. To avoid exact knowledge of the $\mathbf{R}_{hh}$ and the SNR value, a generic design is proposed in [19].

Time averaging of CFR estimates performed in each preamble symbol with equal waveforms is possible and improves estimation accuracy at low SNR values [11], [20], [21], [22], independent of estimation method. Thus, having L realizations of $\widehat{\mathbf{H}}_{\mathrm{P},l}$, channel noise can be reduced by averaging over l. Where $\widehat{\mathbf{H}}_{\mathrm{P},l}$ is obtained as (4) or (5) for LS and LMMSE estimators, respectively. Note that this estimation leads to a $[256 \times 1]$ vector. Thus, it has to be interpolated to obtain a $[2048 \times 1]$ channel gains vector corresponding to the estimated CFR.

$$\widehat{H}'_{\mathrm{P}}[k] = \frac{1}{L}\sum_{l=1}^{L}\widehat{H}_{\mathrm{P},l}[k], \qquad k = 1, 2, \cdots, 256 \tag{6}$$

$$\widehat{H}_{\mathrm{P}}[k] = f_{\text{interp}}\left(\widehat{H}'_{\mathrm{P}}[k]\right), \qquad k = 1, 2, \cdots, 2048. \tag{7}$$

$f_{\text{interp}}(\cdot)$ can be any arbitrary interpolation function. However, linear interpolation is shown to perform better than Gaussian interpolation, cubic interpolation and spline interpolation for PLC channels [12]. Due to its simplicity which leads to an efficient realization, the linear interpolation method is used in this paper.

B. Preamble Based Noise PSD Estimation

In this work a variation of noise power across OFDM subcarriers is considered, i.e. an AWGN model is not assumed. Therefore, the proposed approach performs frequency dependent estimation of local noise power values. An accurate noise power estimate is critical for adaptive modulation, and optimal soft value calculation for improving channel decoder performance. Solving for $\mathbf{V}_{\mathrm{P},l}$ in (3) leads to (8):

$$\widehat{V}_{\mathrm{P},l}[k] = Y_{\mathrm{P},l}[k] - X_{\mathrm{P},l}[k]\widehat{H}_{\mathrm{P},l}[k], \tag{8}$$

The noise PSD ($R_{\mathrm{P}}[k]$) is calculated in (9) by squaring the absolute values of $\widehat{V}_{\mathrm{P},l}[k]$ to determine the periodogram [20].

$$\widehat{R}'_{\mathrm{P},l}[k] = \left|\widehat{V}_{\mathrm{P},l}[k]\right|^2 \tag{9}$$

This method of spectral estimation has a very erratic behavior and presents high variance.

In general, the variance of a sum of L independent and identically distributed (IID) random variables is $1/L$ times the variance of each of the random variables. Thus, to reduce the variance of $\widehat{R}'_{\mathrm{P},l}[k]$, we average L realizations $\widehat{V}_{\mathrm{P},l}[k]$ of the periodograms which leads to the Bartlett method as [20]:

$$\widehat{R}'_{\mathrm{P}}[k] = \frac{1}{L}\sum_{l=1}^{L}\widehat{R}'_{\mathrm{P},l}[k] \tag{10}$$

Nevertheless, if the total number of preamble symbols recovered for channel estimation (L) is not sufficient, periodogram variance could be reduced by smoothing $\widehat{R}'_{\mathrm{P}}[k]$ in the frequency domain [23], [24]. Thus, a more accurate estimate of the noise PSD is determined by:

$$\widehat{R}^{(\mathrm{S})}_{\mathrm{P}}[k] = \widehat{R}'_{\mathrm{P}}[k] * w[k]. \tag{11}$$

Where $w[k]$ is a rectangular window of length W and $*$ is the discrete convolution operator. Variables $\widehat{R}'_{\mathrm{P}}[k]$ and $\widehat{R}^{(\mathrm{S})}_{\mathrm{P}}[k]$ are vectors of $[256 \times 1]$ elements. Therefore interpolation must be performed to obtain the 2048-frequency point noise PSD estimate ($\widehat{R}_{\mathrm{P}}[k]$) from a 256-frequency point vector $\widehat{R}^{(\mathrm{S})}_{\mathrm{P}}[k]$.

$$\widehat{R}_{\mathrm{P}}[k] = f_{\text{interp}}\left(\widehat{R}^{(\mathrm{S})}_{\mathrm{P}}[k]\right), \quad k = 1, 2, \cdots, 2048 \tag{12}$$

When AWGN is considered, noise PSD interpolation does not lead to estimation errors because all frequencies have the same average noise power. However, in presence of NBI, noise PSD interpolation broadens interference power to the unobserved neighbor subcarriers, causing an incorrect compensation of the signal at the input of the turbo decoder. This is the main motivation of this work, which is analyzed in Subsection III-C.

C. Noise PSD Estimation based on FC symbol Re-encoding and Re-mapping

A more accurate channel can be estimated if a reference $X[k]$ with greater frequency resolution is used. As FC data must be perfectly recovered to further process the payload symbols, the FC symbol can be used as a new reference for data-aided estimation [3], [13]. Improvements are obtained due to the FC symbol having 8 times the resolution of the preamble symbols (e.g. 256 subcarriers per preamble symbol vs. 2048 subcarriers per FC symbol in IEEE Std. 1901-2010).

However, it has been proven that increasing interpolation order or using more complex kernels to estimate the CFR does not carry high gains to a system with error protection [7]. Thus, a more suitable alternative is to use the FC symbol for improving only the noise PSD estimation. To the best of the authors' knowledge, no reports exist in the literature where the impact of this approach is evaluated in presence of NBI, which in the following is analyzed through simulations.

Considering the update of reference $X[k]$ in (1), (3) can be rewriten as:

$$\mathbf{Y}_{\mathrm{FC},l} = \mathbf{X}_{\mathrm{FC},l}\mathbf{H}_{\mathrm{P}} + \mathbf{V}_{\mathrm{FC},l} \qquad (13)$$

Where $\mathbf{H}_{\mathrm{P}}$ is estimated from (4) to (7). Solving for $\mathbf{V}_{\mathrm{FC},l}$ in (13), the noise in FC symbol is obtained by:

$$\widehat{V}_{\mathrm{FC},l}[k] = Y_{\mathrm{FC},l}[k] - X_{\mathrm{FC},l}[k]\widehat{H}_{\mathrm{P}}[k]. \qquad (14)$$

Where $Y_{\mathrm{FC},l}[k]$ and $\widehat{H}_{\mathrm{P}}[k]$ are the received FC symbol and preamble-based CFR estimate, respectively. Note that $\widehat{V}_{\mathrm{FC},l}[k]$ is a $[2048 \times 1]$ vector, thus, no interpolation is required. The FC symbol-based noise PSD estimate is defined by:

$$\widehat{R}'_{\mathrm{FC},l}[k] = \left|\widehat{V}_{\mathrm{FC},l}[k]\right|^2. \qquad (15)$$

When 2 FC symbols are transmitted, time average operation of $\widehat{R}'_{\mathrm{FC},l}[k]$ (equivalent to (10)) leads:

$$\widehat{R}'_{\mathrm{FC}}[k] = \frac{1}{L}\sum_{l=1}^{L}\widehat{R}'_{\mathrm{FC},l}[k]. \qquad (16)$$

For a critical case where only one FC symbol is transmitted, $L = 1$, system performance degrades (specially compared to the preamble where several synchronization symbols are recovered for estimation). Thus, frequency smoothing is critical for noise estimation based on the FC symbol. This results in a smoothed noise PSD given by:

$$\widehat{R}_{\mathrm{FC}}[k] = \widehat{R}'_{\mathrm{FC}}[k] * w[k]. \qquad (17)$$

Figure 2 shows a block diagram of the proposed channel estimation method integrated in the receiver of Fig. 1. Which comprises an update of the noise PSD estimation based on re-encoding and re-mapping the FC symbol. A description of the proposed method is provided in Algorithm 1.

Algorithm 1. Proposed channel estimation method

```
1) Estimate the 256-frequency point CFR ($\widehat{H}'_{\mathrm{P}}[k]$) and the 256-frequency point noise PSD ($\widehat{R}^{(\mathrm{S})}_{\mathrm{P}}[k]$) based on preamble sequence ($k = 1, \cdots, 256$).
2) Interpolate $\widehat{H}'_{\mathrm{P}}[k]$ and $\widehat{R}^{(\mathrm{S})}_{\mathrm{P}}[k]$ to obtain the 2048-frequency point CFR ($\widehat{H}_{\mathrm{P}}[k]$) and the 2048-frequency point noise PSD ($\widehat{R}_{\mathrm{P}}[k]$) ($k = 1, \cdots, 2048$).
3) Recover FC data.
4) IF    CRC validation    THEN
5)     Discard the frame.
6) ELSE
7)     Re-encode and re-map FC bits in order to obtain a new reference ($X_{\mathrm{FC}}[k]$, $k = 1, \cdots, 2048$).
8)     Perform a second estimation of the noise PSD employing $X_{\mathrm{FC}}[k]$ as reference ($\widehat{R}_{V_{\mathrm{FC}}}[k]$) and CFR estimated from preamble $\widehat{H}_{\mathrm{P}}[k]$.
9) END
```

After channel estimation, amplitudes at the output of FFT (Fig. 2) are equalized with the estimated CFR. The noise PSD estimated within the preamble sequence is used to soft-demappe the FC symbol giving a vector of likelihood ratios (LR) or log-likelihood ratios (LLR) that feeds FEC block. Then, the FC bits are re-encoded and re-mapped in the receiver to obtain a new reference regarding noise estimation. FC symbol based noise PSD is recalculated using the new reference and then it is employed to soft-demappe the payload symbols. The LLR of payload data feeds the FEC to finally obtain the payload bits.

IV. PERFORMANCE RESULTS

In order to validate our proposal, system performance is investigated under different combinations of CFR and noise PSD estimations. Therefore, 7 different cases are defined: **Case Real** and **Case A** to **F**. **Case Real** refers to perfect CFR and noise PSD calculation. **Case A** and **Case B** use CFR estimated by LMMSE and LS method, respectively. CFR and noise PSD estimations in both cases are done within the preamble sequence. In cases C to F, we analyze performance of updating the estimations by re-encoding and remapping the FC symbol. **Case C** and **Case D** perform LMMSE and LS based CFR estimation, respectively, within the preamble; while noise PSD is estimated in the FC symbol. Finally, the last two cases (**Case E** and **Case F**) show results of performing LMMSE and LS based CFR estimation, respectively, and noise PSD estimation, by using the FC symbol.

In this section, two multipath channels (reference channel 2 and 4 of OPERA deliverable D4 [25]) are used. The reference channels are depicted in Fig. 3.

Immunity to narrow-band interference specified in IEEE Std. 1901-2010, Section 13.11.3 [3], is evaluated through simulations. For that purpose, system performance is tested under one NBI and three NBI. In both experiments, the signal-to-jamming power ratio (SJR) is equal to -25dB.

Transceiver was configured from IEEE Standard 1901-2010 specifications: physical blocks of 520 octets, code rate equals to $\frac{1}{2}$, all carriers are mapped by QPSK, 4096-point IFFT/FFT, guard intervals of FC symbol and payload symbols of 1832 and 756 samples, respectively. Recovered number of preamble symbols after synchronization is assumed to be 4, which is an achievable value in a practical systems. In addition, we consider that sampling frequency offset is already corrected before performing channel estimation. Also, transmission of only one FC symbol is considered, which is the worst case regarding performance. Subcarriers from 0 to 81 and 1865 to 2048 are masked to avoid edge effects.

From the analysis of the estimated CFR, **Case F** is excluded from BER simulations because the recovered $H[k]$ is too

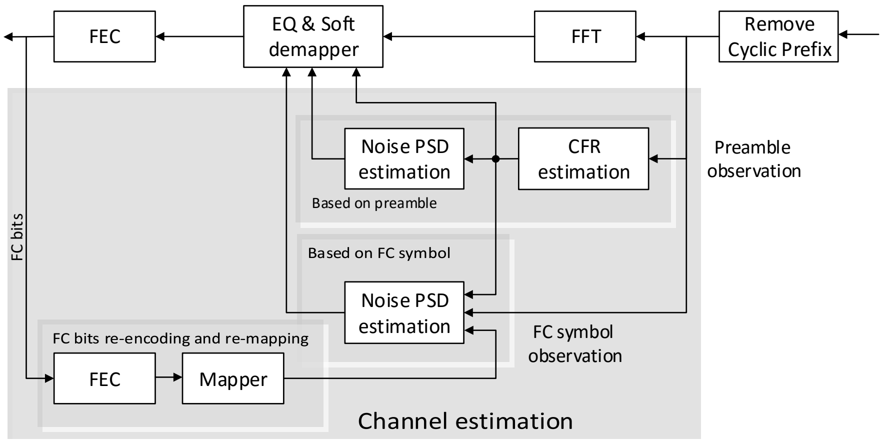

Fig. 2. Proposed receiver with noise PSD estimation based on FC symbol re-encoding and re-mapping.

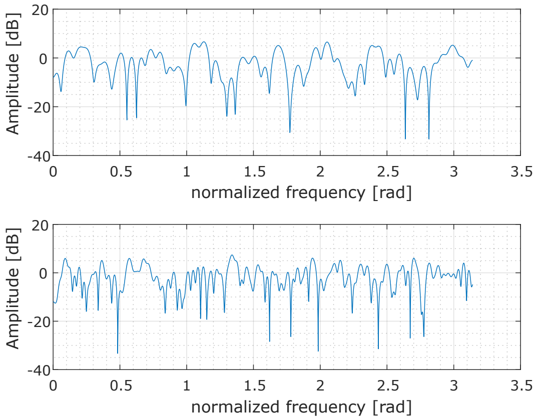

Fig. 3. Multipath reference channel 2 (top) and 4 (bottom) (OPERA deliverable D4 [25]).

inaccurate. As $\widehat{H}[k]$ is used to estimate the noise power (according to (8) and (14)), an inaccurate estimation of its magnitude gives a wrong estimation of $\widehat{V}[k]$ and $\widehat{R}[k]$. This is an expected result since LS performs worse than LMMSE estimator, and Case F does not average over several preamble symbols.

Fig. 4 shows the estimated noise PSD (**Case A** to **Case E** in colored lines) compared to the real noise PSD (**Case Real** in dark line) in presence of one NBI and tree NBI. **Case A** and **Case B** show how the interpolation broadens the interference power to the unobserved neighbor subcarriers. While **Cases C**, **Case D** and **Case F** obtain a more accurate noise PSD estimation.

BER curves are simulated for the valid cases, resulting Fig. 5 and Fig. 8. It is apparent that system performance improves substantially when FC symbol reference is used. However, it is not convenient to update CFR estimate provided that $\widehat{H}[k]$ might result highly noisy as long as only one symbol is employed. In addition, system complexity substantially increase when a second LMMSE estimation is performed. A proper compromise is to choose the proposed method (depicted by **Case C** and **Case D**), which perform CFR estimation within the preamble sequence and get improvements from time averaging. While interpolation errors are avoided in noise PSD estimation, by updating the estimation reference with the FC symbol.

In presence of 3 NBI (Fig. 8), our proposed solution improves BER from 0.3 to less than 10^{-7} for $SNR = 12$ dB. And it is expected that, the more colored the noise is, the greater the gain obtained by this proposal compared to preamble based channel estimation.

And it is expected that the more colored the noise, the greater the gain obtained by this proposal compared to the channel estimate based on the preamble.

V. CONCLUSIONS

In this work, performance of CFR and noise PSD estimation is addressed for PLC systems. For that purpose, IEEE Std. 1901-2010 transceiver model is employed. LMMSE estimator is shown to perform better than LS estimator. However, results achieved by LS estimation are not negligible. A new channel estimation method is proposed for the IEEE Std. 1901-2010 receiver. Results show that system performance can be substantially enhanced by utilizing the FC symbol to improve noise power spectral density estimate in the presence of NBI. Obtained gains are due to the higher frequency resolution of the FC signal observation as compared to the preamble symbols. A further result is that re-estimation of only the noise PSD (and not the CFR) is sufficient to get correct performance of the system. This proposal has the advantage of being feasible for practical systems and will not lead to high computational costs or delays. Experiments are done with the aim of verifying system immunity to NBI as established in

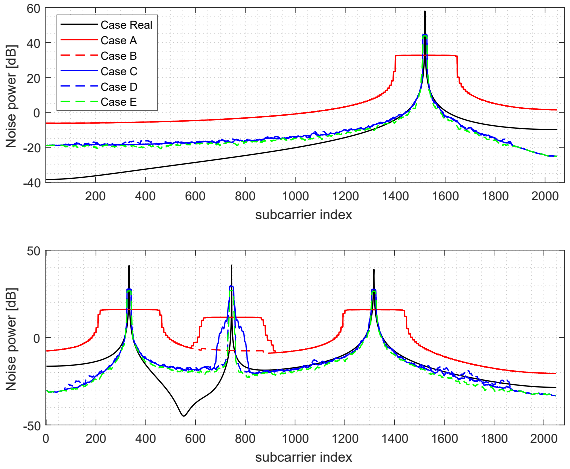

Fig. 4. Estimated noise PSD in presence of 1 NBI (top) and 3 NBI (bottom).

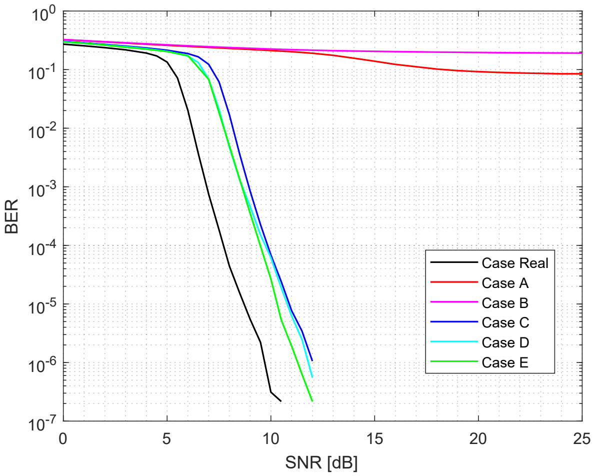

Fig. 5. BER for one NBI on reference channel 2.

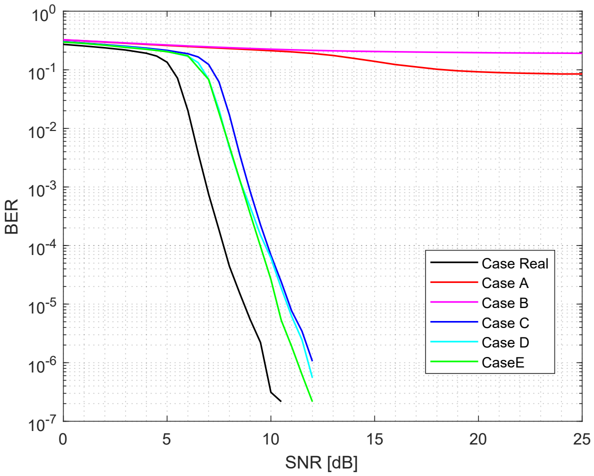

Fig. 6. BER for tree NBI on reference channel 2.

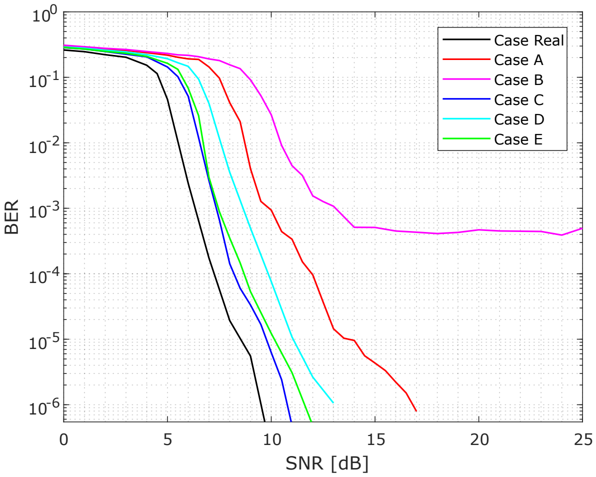

Fig. 7. BER for one NBI on reference channel 4.

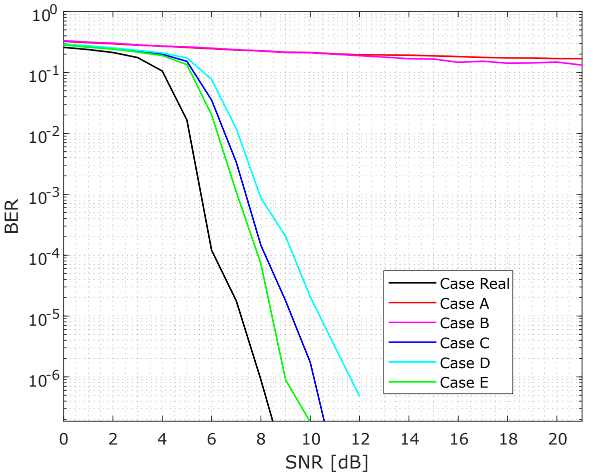

Fig. 8. BER for tree NBI on reference channel 4.

[3, Section 13.11.3]. Our proposed method performs about 2 or 3dB better than conventional channel estimation methods based on preamble sequence in the low SNR region. However, as SNR increases, system performance drastically improves by using our proposed solution.

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