Null Subcarriers Assisted Impulsive Noise Mitigation for In-Vehicle Power Line Communication in the Presence of Narrowband Interference

Jun Yin, Xu Zhu, *Senior Member, IEEE,* Yi Huang, *Senior Member, IEEE,* and Yufei Jiang, *Member, IEEE*

***Abstract*—Impulsive noise (IN) is one of the crucial affecting factors of in-vehicle power line communication (PLC) systems, and therefore an effective IN mitigation scheme is required to enhance the performance significantly. Narrowband interference (NBI) from various nearby radios often has great impact on the IN reconstruction and mitigation. In this paper, IN mitigation over uncoded orthogonal frequency division multiplexing (OFDM) PLC systems is investigated considering the impact of NBI. A null subcarriers assisted IN mitigation scheme is proposed, to mitigate IN in the scenarios of NBI absence and NBI presence, respectively. The IN vector is reconstructed at the proposed receiver first, and then cancelled out from the received signal. Theoretical analysis shows that the proposed scheme outperforms the blanking method. Also, the implement of pre-joint NBI/IN mitigation with the aid of null subcarriers in the proposed scheme can combat the impact of intensive NBI, and achieve a near-optimal bit error rate (BER) performance with no iterations. The effectiveness of the proposed mitigation scheme is validated by simulation results, which is applicable to the vehicular environments under the disturbance of joint IN and NBI.**

***Index Terms*—Power line communication (PLC), impulsive noise, narrowband interference, noise cancellation, receiver operating characteristic (ROC), system performance, vehicular communications.**

I. Introduction

DUE to the increasing demand for vehicular applications, power line communication (PLC) [1] has been recognized as a cost-effective solution for in-vehicle data transmission infrastructure without new wiring facilities needed. PLC enables vehicular technologies such as intelligent driving and in-vehicle entertainment [2], and is a promising alternative to WiFi, especially in vehicle to grid (V2G) information exchange [3]. Impulsive noise (IN) is one of the main sources causing pollution to the PLC spectrum [4], which should be dealt with properly. Therefore, a thorough IN mitigation plays a crucial role in in-vehicle PLC systems.

Generally, IN can be classified as periodic and aperiodic [5]. Periodic IN either synchronous or asynchronous to the mains occurs with a low frequency and low amplitude [5], while aperiodic IN caused by ignition noise in vehicles and switching/plugging/unplugging transients of electric devices is dominant, which degrades the system performance significantly [4], [6]. Aperiodic IN often occurs randomly in a series of impulses, referred to as burst [6], for which the occurrence is statistically modeled in [7] using the tool of Markov chain (MC). It may hence result in bust errors during data transmissions. This paper focuses on mitigating aperiodic IN. Most of the existing IN mitigation schemes are executed in orthogonal frequency division multiplexing (OFDM) systems through a number of conventional nonlinear techniques, such as blanking [8], clipping/deep clipping [9] and weighted combinations of them [10], [11]. However, the conventional schemes are based on detecting the IN contaminated data tones instead of reconstructing the IN vector and cancelling it out. Hence, the performance of the conventional methods is limited by the high peak-to-average power ratio (PAPR) OFDM signals, where use of the advanced techniques with channel coding schemes [12], [13] is necessary to achieve a satisfactory bit error rate (BER) in OFDM systems [14], [15]. Some sophisticated IN mitigation schemes were developed in [16], [17], [18] with the aid of compressive sensing [19], [20] and sparse Bayesian learning [21]. However, these algorithms require matrix multiplication and inversion and also the acquisition of the *a priori* information, which are complex. The iterative IN mitigation methods [22], [23] allows a good trade-off between the performance and complexity of IN mitigation, through the setting number of iterations, which leads to a higher degree of freedom. With full iterations, the performance of IN mitigation is near-optimal and better than that of the compressive sensing based methods [22]. Moreover, a multilayer perceptron (MLP)-based approach was applied in [24] to detect IN, and the channel estimation accuracy is improved iteratively through the feedback of IN mitigation. However, there lacks a thorough validation of the algorithms in [22]-[24] since the adopted IN model cannot simulate the burst environments, and the common disturbance of narrowband interference (NBI) on the in-vehicle PLC spectrum was not considered. NBI at PLC receivers from various nearby radio applications such as broadcast radios and amateur radios [25] is considered in this paper. Since the unshielded power line can be a good antenna picking up the radios around [25], NBI may become a salient issue that degrades the PLC

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receiver performance. In [26], the technique of block sparse Bayesian learning, is utilized to estimate the NBI for the application of 5G. The authors of [27] and [28] proposed to use spatial and temporal correlations for NBI cancellation for the application of wireless MIMO channels and in-home PLC, respectively. There lacks a thorough consideration of both IN and NBI for in-vehicle PLC applications. High power spectral density (PSD) of the intensive NBI may lead a high rate of indistinguishable IN at receivers. Thus, a suitable scheme is required to qualify the IN mitigation for in-vehicle PLC systems.

In this paper, the problem of constructing an effective IN mitigation scheme for robust in-vehicle PLC receivers is addressed. Our work is different in the following aspects. First, a novel IN mitigation scheme is proposed where the feedback of IN estimation is updated iteratively for a thorough mitigation. The use of null subcarriers leads a reduced number of iterations. Unlike the conventional blanking scheme [10] executed given the test statistics of the received signal, the harmful impact of high PAPR signals on the IN reconstruction is excluded in the proposed scheme. The associated receiver operating characteristic (ROC) is derived to show the performance of IN detection for both schemes. Second, the IN mitigation in the presence of NBI from nearby radio users with different impacts of NBI environments on the proposed receiver is evaluated, which has not been fully investigated previously. The associated analytical expressions for ROC are given to show the ability of IN detection under the disturbance of NBI. In the case that the system is intensively disturbed by NBI, the IN vector reconstruction becomes ineffective, resulting in an incomplete IN mitigation. Third, null subcarriers aided pre-mitigation blocks are adopted in the proposed receiver to achieve a near-optimal performance without updating the IN estimation iteratively. The pre-mitigation significantly improves the initial IN estimation, while eliminating the impact of intensive NBI when it is present, leading to a joint NBI and IN mitigation. The thresholds for pre-NBI and pre-IN mitigation blocks are set to be sufficiently high, in order to achieve a desired low false alarm rate for outliers detection. Simulation results are provided to demonstrate an improved BER performance achievable under the proposed IN mitigation scheme compared to the conventional blanking nonlinearity, while the robustness of the proposed receiver is also validated under the intensive disturbance of NBI.

In Section II, a system model is presented to describe the overall IN mitigation scenarios for in-vehicle PLC. In Section III, the IN vector estimation in the proposed scheme is implemented over a PLC channel for NBI absence and NBI presence, respectively. The performance of the proposed scheme is compared to that of the conventional blanking approach. Simulation results are given in Section IV to validate the proposed IN mitigation approach. The conclusion is finally remarked in Section V.

Notations: The notations used in this paper are listed below.

N_ξ	Number of null subcarriers;
$\Pr(\cdot\|\cdot)$	Transition probability;
$\mathit{\Pi}_{\mathrm{II}}$	Steady state probability of IN;
μ	Disturbance ratio of NBI;
p_v	Normalized power at the NBI contaminated subcarriers;
$\boldsymbol{F}(\mathcal{M})$	The $\mathcal{M}$th received signal symbol in frequency domain;
N	Number of total subcarriers;
$\boldsymbol{F}$	N-point DFT matrix;
$\hat{\boldsymbol{N}}$	Estimated FD noise;
$\lambda^{(\mathrm{IN})}$	Threshold for IN vector estimation;
$\hat{n}_{\mathrm{i}}$	Estimated IN vector in TD;
$\tilde{r}$	Received signal after the IN mitigation;
$\hat{e}$	Error vector caused by the feedback of erroneous decisions;
$(\cdot)_\xi$	The sub-vector which has the entries indexed by the null subcarriers set ξ;
$\boldsymbol{R}_{\mathrm{pre}}^{(\mathrm{FD})}$	Output from the pre-FD nulling block;
Λ_{pre}	Threshold for the pre-FD nulling;
$r_{\mathrm{pre}}^{(\mathrm{TD})}$	Output from the pre-TD nulling block;
λ_{pre}	Threshold for the pre-TD nulling.

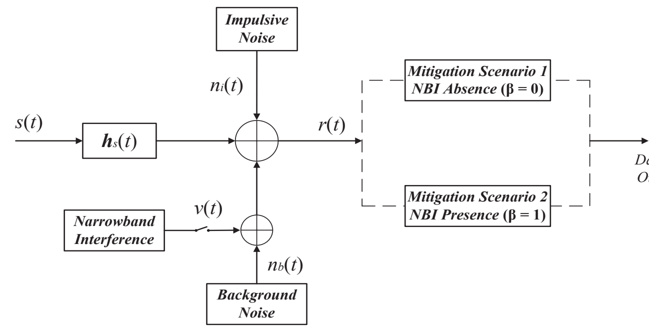

Fig. 1. Block diagram of the in-vehicle PLC system with IN mitigation.

II. System Model

The block diagram of an in-vehicle PLC system is depicted in Fig. 1, where $s(t)$ represents the transmit signal and $r(t)$ is the received signal. A hybrid of the aperiodic IN $n_{\mathrm{i}}(t)$, the NBI $v(t)$ and the background noise $n_{\mathrm{b}}(t)$ are the added disturbance at PLC receiver. While $n_{\mathrm{i}}(t)$ is caused from ignition noise in vehicles and any potential switching/plug transients of the electric devices in the system ($n_{\mathrm{i}}(t) = 0$ means no noise), and $v(t)$ is from various nearby radio applications ($v(t) = 0$ means no interference). We assume IN is present for each transmission. The dashed block indicates the proposed IN mitigation scheme at the receiver, considering two different scenarios that NBI is present and NBI is absent, respectively.

In a discrete-time system, the signal at the PLC receiver is a mixture of various noises. Let $r(m)$ denote the mth received signal sample, expressed as:

$$r(m) = \{h_{\mathrm{s}} * s\}(m) + n_{\mathrm{i}}(m) + \beta \cdot v(m) + n_{\mathrm{b}}(m) \qquad (1)$$

where $\{h_{\mathrm{s}} * s\}(m) = \sum_n h_{\mathrm{s}}(n) s(m-n)$ and h_{s} is the channel impulse response for the PLC transmit signal $s(m)$. Following OFDM modulation, the m-th sample of the transmitted signal can be expressed by $s(m) = \sum_{k=0}^{N-1} S_k e^{j2\pi km/N}$. A random

PLC channel generator in [29] is applied as the channel model. The background noise $n_{\mathrm{b}}(m)$ is assumed to be additive white Gaussian noise (AWGN) with zero mean and variance σ_{b}^2. $n_{\mathrm{i}}(m)$ is the considered IN at PLC receiver, which has a zero mean and variance σ_{i}^2. It is assumed that the variance of the background noise is much lower than that of the IN, *i.e.*, $\sigma_{\mathrm{b}}^2 \ll \sigma_{\mathrm{i}}^2$. The NBI $v(m)$ is from radio applications and occurs with probabilities. In (1), $\beta \in \{0,\ 1\}$ is the parameter indicating the occurrence states (absent or present) of the NBI, where $\Pr(\beta = 1)$ reflects the NBI occurrence probability.

As shown in Fig. 1, the IN mitigation scheme should be implemented in both scenarios of NBI absence ($\beta = 0$) and NBI presence ($\beta = 1$), with the probabilities of $\Pr(\beta = 0)$ and $\Pr(\beta = 1)$, respectively. In the following subsections, we describe the statistical models for IN and NBI. PLC systems under the IN and the NBI can be simulated applying these statistical models, and the effectiveness of the proposed mitigation scheme can be easily evaluated without carrying out any measurements.

A. Statistical IN Model

We consider the impact of aperiodic IN since it is dominant in wired communication systems [30]. Aperiodic IN occurs randomly and often refers to as burst in time domain [6], which has its occurrence probabilities dependent on the previous states, following the MC process [31]. Modeling of the time-domain (TD) occurrence-dependent IN was presented in [7], where a two-level MC-based model was proposed.

In [7], the occurrence of a burst can be described by the first level MC, and the occurrence of individual impulses within a burst are characterized by the second level MC. The first-order Markov process can be described by its transition probability matrix, which is conditioned by the previous one state. Steady-state probability (SSP) can be applied to define the occurrence probability of a event under discrete-time Markov process, where the next state probabilities have dependence on the current state probabilities and are determined by the transition probability matrix as

$$\boldsymbol{\mathit{\Pi}}_{t+1} = \boldsymbol{P}\boldsymbol{\mathit{\Pi}}_t \tag{2}$$

where $\boldsymbol{P}$ is transition probability matrix, which has the elements defined by $\Pr(\{t+1\}|\{t\})$. The probability of the next state '$\{t+1\}$' is conditioned by the current state '$\{t\}$'. $\boldsymbol{\mathit{\Pi}}_t$ is a column vector whose elements represent the state probabilities at time t. In the steady-state, we have $\boldsymbol{\mathit{\Pi}}_{t+1} = \boldsymbol{\mathit{\Pi}}_t$.

For simplicity, it is assumed that the considered in-vehicle system in Fig. 1 is hit by one burst from a single IN source during each transmission. We adopt the second level MC to reproduce the impulses in a burst. Let '$\{t\}$' indicate the state in the second level MC at the discrete-time t. The corresponding state has a value of '1' in the presence of an impulse, otherwise '0' represents the absent of IN. $\mathit{\Pi}_{\mathrm{II}}$ indicates the SSP of producing an individual impulse in the second level MC, which can be derived by solving (2) as

$$\mathit{\Pi}_{\mathrm{II}} = \frac{\Pr\left(\{t+1\} = 1|\{t\} = 0\right)}{\Pr(\{t+1\} = 1|\{t\} = 0) + \Pr(\{t+1\} = 0|\{t\} = 1)} \tag{3}$$

which is weighted by the corresponding transition probabilities.

It is assumed the IN $n_{\mathrm{i}}(m)$ with zero mean and variance σ_{i}^2 has a Gaussian process of $\mathcal{N}(0, \sigma_{\mathrm{i}}^2)$, where $\sigma_{\mathrm{i}}^2 \gg \sigma_{\mathrm{b}}^2$. Thus, the PDF of the combined noise $n = n_{\mathrm{i}} + n_{\mathrm{b}}$ is given by

$$\begin{aligned} \boldsymbol{f}_n(n) &= \left[f(n|\{t\} = 0) \quad f(n|\{t\} = 1)\right] \\ &= \left[\mathcal{N}(0, \sigma_{\mathrm{b}}^2) \quad \mathcal{N}(0, \sigma_{\mathrm{b}}^2 + \sigma_{\mathrm{i}}^2)\right] \cdot \begin{bmatrix} \Pr(0|0) & \Pr(0|1) \\ \Pr(1|0) & \Pr(1|1) \end{bmatrix} \end{aligned} \tag{4}$$

which is conditioned by the current impulse state. In the steady-state of IN, the PDF can be expressed as

$$f_n(n) = (1 - \mathit{\Pi}_{\mathrm{II}}) \cdot \mathcal{N}(n; 0, \sigma_{\mathrm{b}}^2) + \mathit{\Pi}_{\mathrm{II}} \cdot \mathcal{N}(n; 0, \sigma_{\mathrm{b}}^2 + \sigma_{\mathrm{i}}^2) \tag{5}$$

where $\mathit{\Pi}_{\mathrm{II}}$ is independent of the initial transition state.

The corresponding arrival rate of the impulses normalized to the sampling interval, follows the reciprocal value of the number of consecutive non-impulse states k between two impulses, which has the probability distribution for remaining in the non-impulse state as

$$P(k) = \Pr(0|0)^{k-1} \cdot (1 - \Pr(0|0)) \tag{6}$$

The SSP $\mathit{\Pi}_{\mathrm{II}}$ and the arrival model of the second level MC can describe the particular impulsive scenario in the considered in-vehicle PLC system accurately, which are important to evaluate the performance of the proposed IN mitigation approach.

B. Statistical NBI Model

In [32], a single level 3D MC model was proposed for the reconstruction of NBI in frequency domain (FD), considering the TD occurrence-dependence. Let $\boldsymbol{P}^{(int)}$ be the transition probability matrix for the number of active radio interferers over the total ϕ potential interferers, which can be formulated as

$$\boldsymbol{P}^{(int)} = \begin{bmatrix} P_{0,0} & P_{1,0} & 0 & \cdots & 0 \\ P_{0,1} & P_{1,1} & \ddots & \ddots & \vdots \\ 0 & P_{1,2} & \ddots & P_{\phi-1,\phi-2} & 0 \\ \vdots & \ddots & \ddots & P_{\phi-1,\phi-1} & P_{\phi,\phi-1} \\ 0 & \cdots & 0 & P_{\phi-1,\phi} & P_{\phi,\phi} \end{bmatrix} \tag{7}$$

where $P_{i,j}$ is defined as the transition probability from the number of i tone interferers to j tone interferers, with $i, j = 0, 1, 2, \ldots, \phi$.

Let the random variable $a = 1, 2, \ldots, \phi$ be the number of active radio channels (NBI) in current state. Letting b represent the possible frequency locations of the presented NBI channels, the total number of the possible locations of NBI is actually a calculation of the combinations $C(\phi, a)$, *i.e.*, $b = 1, 2, \ldots, C(\phi, a)$. Let $c = 1, 2, \ldots, C(\phi, a)$ denote the possible number of radio user distributions in the corresponding a NBI channels, respectively. The transition states are constructed by the random variables $\{a, b, c\}$. For simplicity, it is assumed the transition starts from ϕ interferers and $P_{\phi,\phi} = 1$, *i.e.*, $a = \phi$, $b = c = 1$.

IN mitigation is normally considered under the OFDM systems [15]. As specified for the OFDM in HPAV standard [33], about 40% of the total N subcarriers are set to zero to avoid interfering with other applications, referred to as null subcarriers. NBI from radio applications normally presents in those subcarriers from the total N_ξ null subcarriers [16]. Thus, it is assumed the FD sparse NBI vector with N_ξ entries has its ϕ nonzero entries located at ϕ out of all the N_ξ null subcarriers.

The initial ϕ NBI entries are randomly chosen which has the disturbance ratio $\mu = \phi/N_\xi$. The amplitude distribution for each band-limited tone interferer can be modeled by Gaussian noise as described in [16], [34] with the PSD σ_v^2, following a Gaussian distribution of $\mathcal{N}(0, \sigma_v^2)$. The NBI power normalized to the background noise power at the NBI contaminated subcarriers is $p_v = N\sigma_v^2/\phi$.

In the proposed IN mitigation scheme in Section III, null subcarriers are adopted to improve the reconstruction of IN at PLC receiving end. In the presence of NBI, the accuracy of IN estimation is affected by the NBI contaminated subcarriers, which brings challenges for IN mitigation. The environments with NBI can be simulated using the statistical model, which is important to test the proposed mitigation method under the joint impact of IN and NBI.

III. Iterative IN Mitigation

In Fig. 2, two detailed block diagrams of the proposed IN mitigation scheme at receiver are demonstrated, where the red dashed-line block illustrates a zoom-in on the IN mitigation block using an iterative approach. Basically, IN is estimated using the feedback of soft data detection, and removal of the estimated IN from the received sequence improves the data detection accordingly. Hence, both IN estimation and data detection blocks are updated iteratively until the hard decision is made for data output. The use of null subcarriers improves the iterative method significantly, but also brings challenges on accurate IN reconstruction when some of the subcarriers are contaminated by NBI. The design of pre-NBI mitigation and pre-IN mitigation blocks is to combat the impact of NBI, and further enhances the performance of the proposed mitigation scheme. In this section, the IN mitigation proposed for both scenarios as shown in Fig. 1 is described, considering the NBI absence ($\beta = 0$) and the NBI presence ($\beta = 1$), respectively.

A. IN Mitigation in the Absence of NBI

In this subsection, the environment of IN only is considered, which is widely applied to test the existing mitigation algorithms. First, we look into the conventional blanking scheme reported in the literature. Then, the proposed IN mitigation scheme is studied, where the performance is also analysed to show the benefit of using null subcarriers.

1) Conventional Blanking Approach: In the case of $\beta = 0$ in (1), where NBI from radio applications is absent. The received signal in (1) is then simplified to

$$r(m) = \{h_\mathrm{s} * s\}(m) + n_\mathrm{i}(m) + n_\mathrm{b}(m) \tag{8}$$

which is usually applied as the received sequence for various vehicular communication systems [15], [18]. Thus, most of the existing IN mitigation methods such as [22], [35], are verified through the basic system model in (8).

The conventional nonlinear techniques are widely used to mitigate IN at the receiver, including blanking, clipping and weighted combinations of them [9], [11]. The blanking nonlinearity is defined as [10]

$$\bar{r}(m) = \begin{cases} r(m), & |r(m)| \le \lambda^{(\mathrm{blank})} \\ 0, & |r(m)| > \lambda^{(\mathrm{blank})} \end{cases} \tag{9}$$

where $\lambda^{(\mathrm{blank})}$ denotes the blanking threshold and $\bar{r}(m)$ is the blanked sequence, with $m = 0, 1, \ldots, N-1$.

As described in (5), each noise term has a Gaussian PDF. In a large number N of OFDM subcarriers, the transmit signal $s(m)$ filtered by power line channel follows a Gaussian distribution of $\mathcal{N}(0, \sigma_\mathrm{s}^2)$. Thus, the PDF of the received signal $r(m)$ in (8) can be expressed as

$$f_r(r) = (1 - \mathit{\Pi}_\mathrm{II}) \cdot \mathcal{N}(r; 0, \sigma_\mathrm{s}^2 + \sigma_\mathrm{b}^2) + \mathit{\Pi}_\mathrm{II} \cdot \mathcal{N}(r; 0, \sigma_\mathrm{s}^2 + \sigma_\mathrm{b}^2 + \sigma_\mathrm{i}^2) \tag{10}$$

The basic principle for the threshold-based techniques is actually to use signal detection theory, where the ROC can be analyzed on the test signal statistics [36]. ROC curves explore the trade-offs between the probability of detection $\mathcal{P}_d$ and the probability of false alarm $\mathcal{P}_f$ for a range of varied thresholds. By comparing the test statistics $|r(m)|$ to a given threshold λ, the associated probabilities $\mathcal{P}_f$ and $\mathcal{P}_d$ are expressed as

$$\mathcal{P}_f = \mathrm{erfc}\left(\frac{\lambda}{\sqrt{2(\sigma_\mathrm{s}^2 + \sigma_\mathrm{b}^2)}}\right) \tag{11}$$

$$\mathcal{P}_d = \mathrm{erfc}\left(\frac{\lambda}{\sqrt{2(\sigma_\mathrm{s}^2 + \sigma_\mathrm{b}^2 + \sigma_\mathrm{i}^2)}}\right) \tag{12}$$

where erfc is the complementary error function [37].

The corresponding optimal threshold can be determined with respect to a pair of best trade-off probabilities, which can be selected for specific system requirements, and varied according to different criteria [15].

2) IN Estimation Using Data Subcarriers: Under the proposed IN mitigation scheme as shown in Fig. 2, IN samples are estimated first and then suppressed from the received signal individually, rather than set the IN contaminated signal samples to zero as described in the conventional blanking approach. The basic principle for the IN estimation is to cancel out the data term at the channel output from the received signal, and then reconstruct the IN from the remaining mixed noise terms.

For the considered system in (1) with $\beta = 0$, the received signal $r(m)$ is initially passed through the FFT module at the conventional OFDM receiver, yielding

$$\boldsymbol{R}(\mathcal{M}) = \{\boldsymbol{H}_\mathrm{s} \cdot \boldsymbol{S}\}(\mathcal{M}) + \boldsymbol{F} n_\mathrm{i}(\mathcal{M}) + \boldsymbol{F} n_\mathrm{b}(\mathcal{M}) \tag{13}$$

where $\boldsymbol{F}$ denotes the FFT block of size N and $\boldsymbol{H}_\mathrm{s}$ is the channel frequency response matrix, with the subcarrier index $\mathcal{M} = 0, 1, \ldots, N-1$.

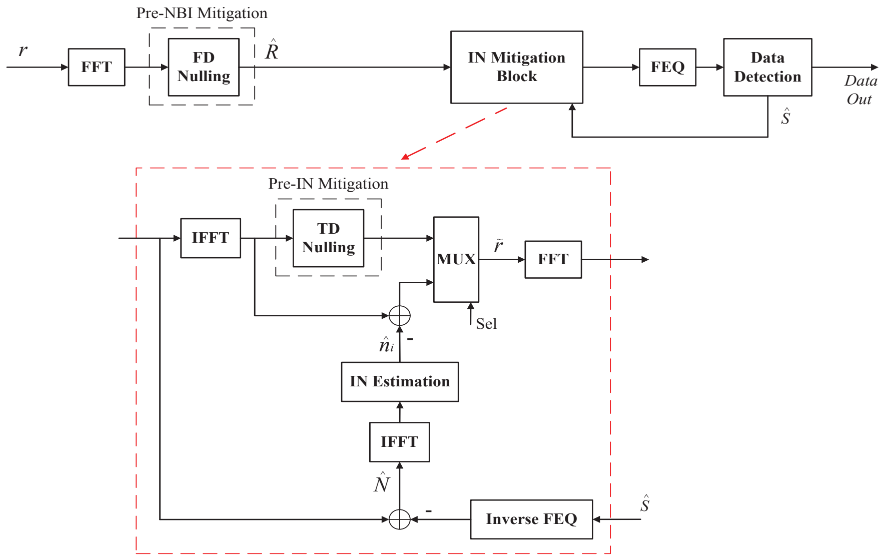

Fig. 2. Block diagram of the null subcarriers assisted receiver for IN mitigation (FEQ-frequency domain equalization; FD-nulling is applied when NBI is present; TD-nulling is applied when IN is present).

Then, the signal can be simply compensated by a frequency-domain equalizer (FEQ) on each subcarrier independently. Assuming perfect channel estimation and using a zero-forcing equalizer, the tentative soft decision $\hat{\boldsymbol{S}}(\mathcal{M})$ can be obtained, which is then cancelled out from the received signal in order to find the estimation of noise terms as

$$\hat{\boldsymbol{N}}(\mathcal{M}) = \boldsymbol{R}(\mathcal{M}) - \{\boldsymbol{H}_{\rm s} \cdot \hat{\boldsymbol{S}}\}(\mathcal{M}) \tag{14}$$

To reconstruct the IN vector in TD, IFFT is performed on $\hat{\boldsymbol{N}}(\mathcal{M})$ in order to obtain the mixed TD noise terms $\hat{n}(m)$. In the proposed scheme, the IN vector can then be estimated by

$$\hat{n}_{\rm i}(m) = \begin{cases} 0, & |\hat{n}(m)| \leq \lambda^{(\rm IN)} \\ \hat{n}(m), & |\hat{n}(m)| > \lambda^{(\rm IN)} \end{cases} \tag{15}$$

where $\hat{n}_{\rm i}(m)$ denotes the estimated IN vector and $\lambda^{(\rm IN)}$ is the corresponding threshold.

An accurate detection of the nonzero entries in $\hat{n}_{\rm i}$ leads a good estimation of the IN vector, and hence improves the performance of the according mitigation techniques. A perfect detection may lead to a thorough IN mitigation. Unlike the conventional blanking approach in (9) which takes the detection on IN entries given the received signal vector, the detection in the proposed scheme is performed given the noise terms only. Thus, the impact of high PAPR signals on the threshold-based detection is eliminated. According to (15), the test statistics $|\hat{n}(m)|$ is compared to a given threshold λ, resulting in the detection probabilities as

$$\mathcal{P}_f = \text{erfc}\left(\frac{\lambda}{\sigma_{\rm b}\sqrt{2}}\right) \tag{16}$$

$$\mathcal{P}_d = \text{erfc}\left(\frac{\lambda}{\sqrt{2(\sigma_{\rm b}^2 + \sigma_{\rm i}^2)}}\right) \tag{17}$$

which outperforms the conventional blanking in classifying between the zero and nonzero entries of the IN vector, especially in the high SNR region. For a given false alarm rate $\mathcal{P}_f$ in (16), the non-adaptive threshold λ can be simply calculated by the inverse complementary error function.

Then, the estimated IN vector $\hat{n}_{\rm i}$ can be used as a feedback to obtain a cleaner received signal $\tilde{r}(m)$ as

$$\tilde{r}(m) = r(m) - \hat{n}_{\rm i}(m) \tag{18}$$

where the estimated impulses are suppressed individually from the initially received signal samples and a multiplexer is used to select the updated received signal for further data processing of the proposed receiver.

3) IN Estimation Using Data and Null Subcarriers: In practical, the estimate of the IN vector $\hat{n}_{\rm i}$ in TD is imperfect, which is affected by the accuracy of $\hat{n}(m)$ estimation and the trade-off thresholding. The tentative soft decision $\hat{S}(\mathcal{M})$ may contain many errors without doing iterations. Thus, after performing the IFFT on (14), the estimated noise terms can be expressed by considering decision errors as

$$\hat{n}(m) = \hat{e}(m) + n_{\rm i}(m) + n_{\rm b}(m) \tag{19}$$

where $\hat{e}(m)$ is caused by the feedback of wrong decisions. In the high SNR region, decision errors are rare and negligible. While in the low SNR region, lots of wrong decisions are made, and $\hat{e}(m)$ can be assumed as Gaussian distributed due to the IFFT operation. Thus, the PDF of $\hat{n}(m)$ in (19) can be expressed by

$$f_{\hat{n}}(\hat{n}) = (1-\mathit{\Pi}_{\rm II}) \cdot \mathcal{N}(\hat{n}; 0, \sigma_{\rm \hat{e}}^2 + \sigma_{\rm b}^2) + \mathit{\Pi}_{\rm II} \cdot \mathcal{N}(\hat{n}; 0, \sigma_{\rm \hat{e}}^2 + \sigma_{\rm b}^2 + \sigma_{\rm i}^2) \tag{20}$$

where $\sigma_{\rm \hat{e}}^2$ is the variance of $\hat{e}(m)$, which should be lowered to improve the IN estimation. According to the proposed receiver in Fig. 2, it normally costs several iterations to minimize $\sigma_{\rm \hat{e}}^2$.

Most of the power line systems do not use the whole spectrum for data transmission, in order to avoid interfering with other applications. A spectrum mask for HPAV is implemented to stay clear from transmission on some frequencies [38]. This ability can be easily performed at the OFDM transmitter by setting the corresponding subcarriers to zero, referred to as null subcarriers.

At the receiver, the wideband IN spreads its power over all frequencies, which has its components in the null subcarriers. Let ξ be the index set of the null subcarriers, where the total number $N_\xi = |\xi|$ of null subcarriers is considered. In the absence of NBI ($\beta = 0$ in (1)), the noise terms from the null subcarriers can be observed at the receiver as

$$\boldsymbol{R}_\xi(\mathcal{M}) = \boldsymbol{F}_\xi n_{\rm i}(\mathcal{M}) + \boldsymbol{F}_\xi n_{\rm b}(\mathcal{M}) \tag{21}$$

where $(\cdot)_\xi$ indicates the sub-vector which has the entries indexed by the null subcarriers set ξ, *i.e.*, $\mathcal{M} \in \xi$.

The noise terms in null subcarriers are from nature with no decision errors, resulting in a more accurate initial estimate of the IN vector. Hence, the receiver performance can be improved with a certain number of iterations by adopting the null subcarriers. The performance of detecting the nonzero entries in the IN vector given $\hat{n}(m)$ in (19) can be evaluated by comparing the test statistics $|\hat{n}(m)|$ to a given threshold λ, yielding the detection probabilities as

$$\mathcal{P}_f = \text{erfc}\left(\frac{\lambda}{\sqrt{2(\sigma_{\hat{\rm e}}^2 + \sigma_{\rm b}^2)}}\right) \tag{22}$$

$$\mathcal{P}_d = \text{erfc}\left(\frac{\lambda}{\sqrt{2(\sigma_{\hat{\rm e}}^2 + \sigma_{\rm b}^2 + \sigma_{\rm i}^2)}}\right) \tag{23}$$

where the mean squared error $\sigma_{\hat{\rm e}}^2$ is lowered by using null subcarriers since $\boldsymbol{F}_\xi \hat{e} = 0$. After few iterations, $\sigma_{\hat{\rm e}}^2$ is negligible and equals zero in the high SNR region.

For a maximum allowed false alarm rate $\mathcal{P}_f$ in (22), the threshold can be derived as

$$\lambda = \sqrt{2}\sigma_{\hat{\rm n}} \cdot \text{erfc}^{-1}(\mathcal{P}_f) \tag{24}$$

where $\sigma_{\hat{\rm n}} = \sum_m |\hat{n}(m)|$ is the standard derivation of the noise $\hat{n}(m)$ in (19) and erfc^{-1} denotes the inverse complementary error function. The chosen threshold is adaptive since the value of $\sigma_{\hat{\rm e}}^2$ varies with SNR.

With the assistance of null subcarriers and adaptive thresholding, feedback of the improved IN estimation $\hat{n}_{\rm i}$ can be obtained to mitigate the IN thoroughly by costing a reduced number of iterations.

4) Pre-TD Processing Using Null Subcarriers: To further improve the IN mitigation algorithm, the feedback of an accurate initial estimated IN vector $\hat{n}_{\rm i}$ is the key to achieve a satisfactory performance of the proposed receiver, without updating $\hat{n}_{\rm i}$ iteratively.

A pre-processing block is applied to improve the tentative soft decision $\hat{\boldsymbol{S}}(\mathcal{M})$ before the initial IN estimation. Hence, a lower mean squared error $\sigma_{\hat{\rm e}}^2$ caused by wrong decisions can be obtained to achieve a better initial IN estimation. The pre-processing term can be reconstructed by using the null subcarriers as

$$\boldsymbol{R}_{\rm pre}(\mathcal{M}) = \begin{cases} \boldsymbol{R}_\xi(\mathcal{M}), & \mathcal{M} \in \xi \\ 0, & \mathcal{M} \in \bar{\xi} \end{cases} \tag{25}$$

where $\bar{(\cdot)}$ indicates the set complement. Let $r_{\rm pre}(m)$ denote the IFFT counterpart of (25), with $m = 0, 1, \ldots, N-1$.

In the absence of NBI, the pre-TD processing is meant to remove the strong portion in $r_{\rm pre}(m)$ from the received signal $r(m)$, which can be formulated by

$$r_{\rm pre}^{\rm (TD)}(m) = \begin{cases} r(m), & |r_{\rm pre}(m)| \le \lambda_{\rm pre} \\ r(m) - r_{\rm pre}(m), & |r_{\rm pre}(m)| > \lambda_{\rm pre} \end{cases} \tag{26}$$

where $\lambda_{\rm pre}$ denotes the threshold for pre-TD processing, which can be determined using the standard derivation of $r_{\rm pre}(m)$ through (24). The threshold $\lambda_{\rm pre}$ is non-adaptive to SNR since the test statistics $|r_{\rm pre}(m)|$ only includes the noise terms from nature.

Instead of the received signal $r(m)$, the vector $r_{\rm pre}^{\rm (TD)}$ in (26) is passed through the conventional OFDM receiver in order to obtain an improved initial feedback of the tentative decision $\hat{\boldsymbol{S}}(\mathcal{M})$. Thus, the initial IN estimation using (14) and (15) can be refined accordingly.

B. IN Mitigation in the Presence of NBI

The previous subsection demonstrates the proposed IN mitigation scheme in the absence of NBI. With the aid of null subcarriers, the initial estimate of the IN vector can be significantly improved. According to the system model in Fig. 1, NBI is a common event for in-vehicle PLC where the NBI contaminated subcarriers bring challenges for the IN reconstruction. In this subsection, first, the proposed receiver performance in the presence of NBI is analysed, and then a joint mitigation of the NBI and IN before the estimate of the IN vector is applied, in order to combat the effect of NBI as shown in Fig. 2.

1) IN Estimation Using Data and Null Subcarriers: The NBI from radio applications such as emergencies, amateur and mobile-radios often happens to in-vehicle scenarios. The use of null subcarriers for the OFDM PLC avoids interfering with other applications, and on the other hand, improves the proposed IN estimation when NBI is absent as learned in Subsection III-A. In the case of $\beta = 1$ in (1), the IN estimation should be performed in the presence of NBI, where the IN observed in null subcarriers are polluted by the NBI. Thus, the noise terms added at receiver from the null subcarriers can be formulated as

$$\boldsymbol{R}_\xi(\mathcal{M}) = \boldsymbol{F}_\xi n_{\rm i}(\mathcal{M}) + \boldsymbol{F}_\xi v(\mathcal{M}) + \boldsymbol{F}_\xi n_{\rm b}(\mathcal{M}) \tag{27}$$

where the subcarrier index $\mathcal{M} \in \xi$. Let the complement set $\bar{\xi}$ denote the index set of the data subcarriers where $\boldsymbol{F}_{\bar{\xi}} v(\mathcal{M}) = 0$. Thus, the received signal from the data subcarriers can be represented by (13) with $\mathcal{M} \in \bar{\xi}$.

According to the proposed receiver in Fig. 2, the received signal before the FFT operation equals

$$r(m) = \{h_{\rm s} * s\}(m) + n_{\rm i}(m) + v(m) + n_{\rm b}(m) \tag{28}$$

which can be adopted after FFT to obtain the estimated noise terms as in (14). Hence, the IFFT counterpart of (14) can be expressed as

$$\hat{n}(m) = \hat{e}(m) + n_{\rm i}(m) + v(m) + n_{\rm b}(m) \tag{29}$$

where the amplitude distribution for the NBI $v(m)$ follows the random Gaussian of $\mathcal{N}(0, \sigma_v^2)$. Thus, the PDF of $\hat{n}(m)$ in (29) can be expressed by

$$f_{\hat{n}}(\hat{n}) = (1 - \varPi_{\mathrm{II}}) \cdot \mathcal{N}(\hat{n}; 0, \sigma_{\hat{\mathrm{e}}}^2 + \sigma_{\mathrm{b}}^2 + \sigma_v^2) + \varPi_{\mathrm{II}} \cdot \mathcal{N}(\hat{n}; 0, \sigma_{\hat{\mathrm{e}}}^2 + \sigma_{\mathrm{b}}^2 + \sigma_v^2 + \sigma_{\mathrm{i}}^2) \quad (30)$$

where the estimated IN vector $\hat{n}_{\mathrm{i}}(m)$ can be obtained in (15) by comparing the test statistics $|\hat{n}(m)|$ modelled in (30) to a given threshold. In the presence of NBI, the performance of detecting the nonzero entries in the IN vector can be evaluated by

$$\mathcal{P}_f = \mathrm{erfc}\left(\frac{\lambda}{\sqrt{2(\sigma_{\hat{\mathrm{e}}}^2 + \sigma_{\mathrm{b}}^2 + \sigma_v^2)}}\right) \quad (31)$$

$$\mathcal{P}_d = \mathrm{erfc}\left(\frac{\lambda}{\sqrt{2(\sigma_{\hat{\mathrm{e}}}^2 + \sigma_{\mathrm{b}}^2 + \sigma_v^2 + \sigma_{\mathrm{i}}^2)}}\right) \quad (32)$$

where the ingress of the intensive NBI ($\sigma_v^2 \gg \sigma_{\mathrm{b}}^2$) can cause a harmful impact on the detection performance. For a maximum allowed false alarm rate $\mathcal{P}_f$ in (31), the associated threshold λ can be calculated using (24) given the standard derivation of $\hat{n}(m)$ in (29).

In the presence of intensive NBI, although the mean squared error $\sigma_{\hat{\mathrm{e}}}^2$ can be reduced iteratively, the high PSD σ_v^2 can still disturb the reconstruction of the IN vector, leading an incomplete IN mitigation in (18). The intensive NBI in null subcarriers should be removed in advance to enhance the performance of the proposed IN mitigation scheme.

2) Pre-Joint FD/TD Nulling: The presence of NBI with high PSD σ_v^2 brings challenges for the IN detection given the vector $\hat{n}(m)$ in (29), where the entries with weak IN would be indistinguishable from the entries with the combined terms of background noise, NBI and decision errors only.

A pre-joint mitigation on the intensive NBI and IN is required to improve the reconstruction of IN in the presence of NBI, which is indicated by the dashed blocks in Fig. 2. The pre-FD nulling is meant to detect and null the NBI contaminated subcarriers, which can be formulated by

$$\boldsymbol{R}_{\mathrm{pre}}^{(\mathrm{FD})}(\mathcal{M}) = \begin{cases} \boldsymbol{R}_{\xi}(\mathcal{M}), & |\boldsymbol{R}_{\xi}(\mathcal{M})| \leq \Lambda_{\mathrm{pre}} \\ 0, & |\boldsymbol{R}_{\xi}(\mathcal{M})| > \Lambda_{\mathrm{pre}} \end{cases} \quad (33)$$

where $\boldsymbol{R}_{\mathrm{pre}}^{(\mathrm{FD})}$ is the output from the pre-FD nulling block with $\mathcal{M} \in \xi$, and Λ_{pre} denotes the threshold for the pre-FD nulling. Detection of the NBI contaminated subcarriers would be accurate since it has much higher intensity of the FD component compared to that of the IN and background noise. Hence, the chosen threshold can be sufficiently high to keep a low rate of false alarm. For a sufficiently low false alarm rate $\mathcal{P}_f$, the threshold Λ_{pre} is given by

$$\Lambda_{\mathrm{pre}} = \sqrt{2(\sigma_{\mathrm{b}}^2 + \varPi_{\mathrm{II}}\sigma_{\mathrm{i}}^2)} \cdot \mathrm{erfc}^{-1}(\mathcal{P}_f) \quad (34)$$

where Λ_{pre} is non-adaptive to the SNR. The refined received signal $\hat{\boldsymbol{R}}(\mathcal{M})$ can be reconstructed by

$$\hat{\boldsymbol{R}}(\mathcal{M}) = \begin{cases} \boldsymbol{R}_{\mathrm{pre}}^{(\mathrm{FD})}(\mathcal{M}), & \mathcal{M} \in \xi \\ \boldsymbol{R}_{\bar{\xi}}(\mathcal{M}), & \mathcal{M} \in \bar{\xi} \end{cases} \quad (35)$$

which excludes the influence of NBI and has its IFFT counterpart $\hat{r}(m)$, with $m = 0, 1, \ldots, N-1$.

Following the pre-FD nulling, it is possible to detect the IN from TD more accurately. The pre-TD nulling is meant to detect and null the strong portion in $\hat{r}(m)$, which is defined as

$$r_{\mathrm{pre}}^{(\mathrm{TD})}(m) = \begin{cases} \hat{r}(m), & |\hat{r}(m)| \leq \lambda_{\mathrm{pre}} \\ 0, & |\hat{r}(m)| > \lambda_{\mathrm{pre}} \end{cases} \quad (36)$$

where $r_{\mathrm{pre}}^{(\mathrm{TD})}$ indicates the output from the pre-TD nulling block. λ_{pre} denotes the threshold for the pre-TD nulling, which can be set for a maximum allowed false alarm rate $\mathcal{P}_f$ as

$$\lambda_{\mathrm{pre}} = \sqrt{2}\sigma_{\hat{\mathrm{r}}} \cdot \mathrm{erfc}^{-1}(\mathcal{P}_f) \quad (37)$$

where $\sigma_{\hat{\mathrm{r}}}$ is the standard derivation of the refined received signal $\hat{r}(m)$ by the pre-FD nulling. At this stage, a sufficiently low $\mathcal{P}_f$ is expected that λ_{pre} should be high enough, and the impact of strong IN would be mitigated. The chosen threshold varies with $\sigma_{\hat{\mathrm{r}}}$, which is adaptive to the SNR value.

With the benefit of pre-joint FD/TD nulling, an improved tentative soft decision $\hat{\boldsymbol{S}}(\mathcal{M})$ can be obtained before the IN reconstruction. Meanwhile, the estimation on noise terms is given by

$$\hat{\boldsymbol{N}}(\mathcal{M}) = \hat{\boldsymbol{R}}(\mathcal{M}) - \{\boldsymbol{H}_{\mathrm{s}} \cdot \hat{\boldsymbol{S}}\}(\mathcal{M}) \quad (38)$$

which eliminates the influence of NBI by using $\hat{\boldsymbol{R}}(\mathcal{M})$ instead of the received signal $\boldsymbol{R}(\mathcal{M})$ as in (14). Therefore, after the IFFT process, even the initial IN estimation through (15) can be fairly good.

IV. Simulation Results and Discussions

The performance of the proposed IN mitigation scheme is evaluated through extensive simulations over the in-vehicle PLC system in Fig. 1, where both scenarios of NBI absence and NBI presence are considered. Since there lacks a commonly used standard for in-vehicle PLC, a conventional uncoded OFDM system has been simulated. Moreover, it brings an intuitive comparison between the proposed method and the existing approaches, since the performance of some existing methods takes the advantage of channel coding, *e.g.*, 20 dB gain over no coding at BER of 0.01 in turbo-coded OFDM systems. The proposed approach can be easily combined with channel coding to improve the performance. Without loss of generality, we assume binary phase-shift keying (BPSK) modulation. We assume $N = 256$ subcarriers for OFDM, among which $N_\xi = 112$ are set to be null subcarriers [33]. A random PLC channel generator in [29] is applied to obtain the class-9 PLC channel which is assumed perfectly estimated at the receiver. The PLC channel model is classified according to Shannon's capacity. The channel magnitude model generates the transfer functions statistically around the average attenuation $H_s(f) \sim -13 + 7\cos((f/4.5e7) - 0.5)$ for the frequency band of 1 MHz-100 MHz, while the channel phase model includes the group delay characteristics [29]. The IN environment is generated statistically using the arrival model in (6) with $\Pr(0|0) = 0.98$, where $\varPi_{\mathrm{II}} = 0.1$ and $\sigma_{\mathrm{i}}^2 = 1000\sigma_{\mathrm{b}}^2$. Three different NBI scenarios are considered:

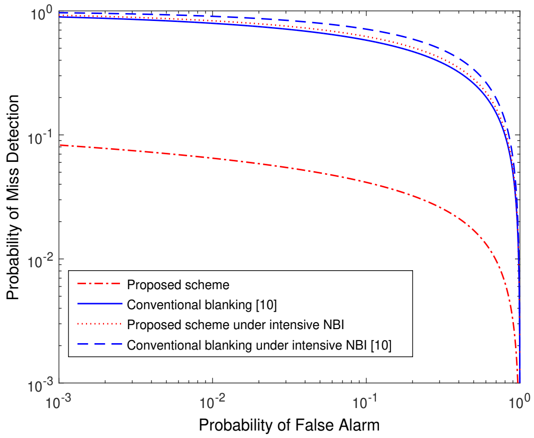

Fig. 3. Complementary ROC curves for different IN detection schemes.

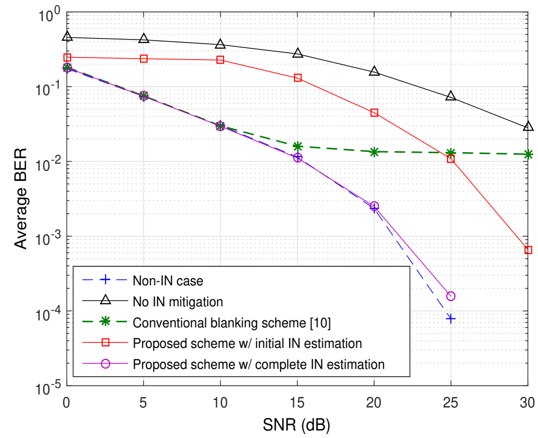

Fig. 4. BER performance comparison of different mitigation schemes using data subcarriers only ($\beta = 0$).

weakly disturbed ($\mu = 0.01$; $p_v/\sigma_{\mathrm{b}}^2 = 20$ dB), strongly disturbed ($\mu = 0.9$; $p_v/\sigma_{\mathrm{b}}^2 = 20$ dB) and intensively disturbed ($\mu = 0.1$; $p_v/\sigma_{\mathrm{b}}^2 = 40$ dB). Strongly disturbed scenario is reflected by the extremely high occurrence probability of the NBI environment, while the intensively disturbed scenario is indicated by large variance of the NBI environment. The intensively disturbed scenario is critical and considered in particular in this paper, as it brings a harmful impact on IN reconstruction. Figs. 4, 5 and 6 are carried out in the absence of NBI ($\beta = 0$), while the BER performance in Figs. 7 and 8 is evaluated in the presence of NBI ($\beta = 1$). Moreover, the results obtained from the proposed scheme are compared to those from the previous IN mitigation methods with the optimal blanking threshold in [10].

In Fig. 3, the performance of detecting the nonzero entries in the IN vector of the proposed scheme is evaluated, in comparison with the conventional detection-based blanking scheme, using the complementary ROC ($1 - \mathcal{P}_d$ versus $\mathcal{P}_f$) over the non-NBI and intensive NBI scenarios. The curves are illustrated for SNR = 25 dB, which is high enough to achieve a negligible $\sigma_{\hat{\mathrm{e}}}^2$ for the proposed scheme. It can be seen in Fig. 3 that the proposed scheme which can achieve a sufficiently high detection rate by causing a negligible false alarm rate, outperforms the conventional blanking in terms of the ability of IN entries detection. According to the test statistics for the blanking nonlinearity, the associated threshold-based IN detection is disturbed by the high PAPR, resulting in a poor ROC performance. Meanwhile, the curves reveal that when the system is intensively disturbed by added NBI, the rate of indistinguishable IN becomes quite high for both schemes under the impact of high NBI power.

Fig. 4 shows the BER performance comparison between the proposed IN mitigation scheme and the conventional blanking scheme using data subcarriers only. Let P_e indicate the average received signal PSD. The horizontal axis denotes the average signal-to-background noise power ratio, *i.e.*, SNR = $P_e/\sigma_{\mathrm{b}}^2$, which varies from 0 dB to 30 dB. For a maximum allowed false alarm rate $\mathcal{P}_f = 10^{-3}$ defined in (22), the corresponding threshold value normalized to $\sigma_{\hat{\mathrm{n}}}$ defined in (24) is set to 3.29. It can be observed that the proposed scheme with complete IN

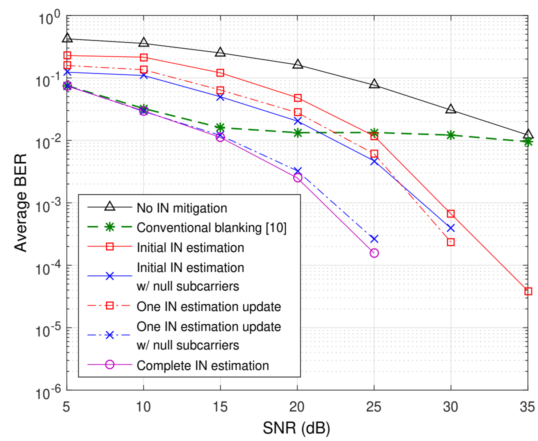

Fig. 5. BER performance comparison of different mitigation schemes to show the benefit of using null subcarriers in the proposed scheme ($\beta = 0$).

estimation clearly exhibits a much better performance than the conventional blanking scheme especially in high SNR region, where the curve for blanking illustrates an error floor over various SNR values. According to (9) and (15), high SNR would disturb the IN detection for blanking nonlinearity, which however provides benefits on the proposed scheme by causing a fairly low mean squared decision error $\sigma_{\hat{\mathrm{e}}}^2$. Thus, even with initial IN estimation, the curves reveal that the proposed IN mitigation outperforms the blanking nonlinearity when the SNR value achieves 25 dB or above. The complete IN estimation using data subcarriers only normally costs four or five iterations, where the soft decision $\hat{\boldsymbol{S}}$ cannot be improved any more and should serve as the hard decision for data output.

The benefit of adopting null subcarriers in the proposed mitigation scheme is learned in Fig. 5 in terms of BER performance. According to (21), use of the null subcarriers containing no decision errors results in a lower $\sigma_{\hat{\mathrm{e}}}^2$, yielding an improved IN estimation. Hence, the IN can be thoroughly mitigated using the feedback of the estimated IN as in (18) with a reduced number of iterations. The results show that with the aid of null subcarriers, only one iteration of the estimated

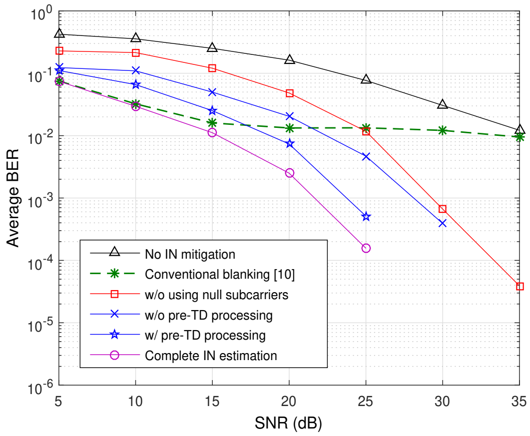

Fig. 6. BER performance comparison under the proposed scheme with initial IN estimation to show the benefit of adopting the pre-TD processing ($\beta = 0$).

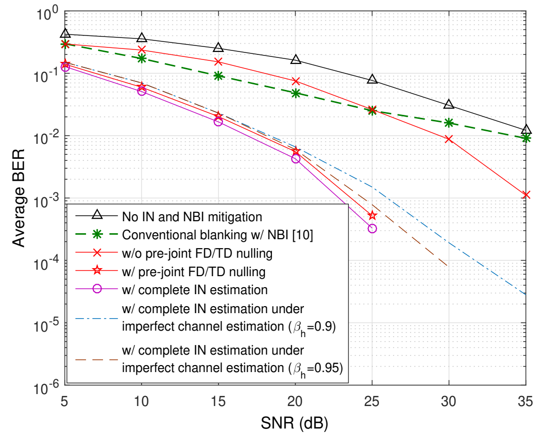

Fig. 8. BER performance comparison under the proposed scheme with the initial IN estimation intensively disturbed by NBI to show the benefit of adopting the pre-joint FD/TD nulling ($\beta = 1$).

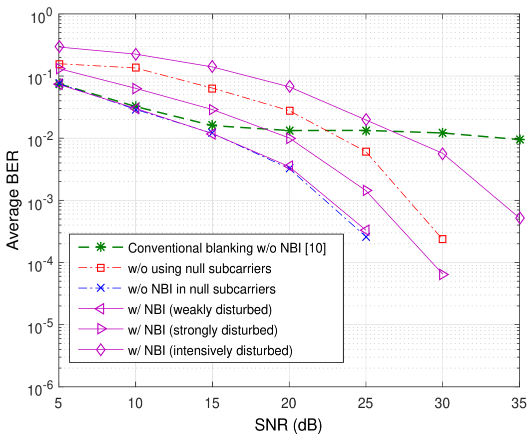

Fig. 7. BER performance comparison under the proposed scheme with one update of the IN estimation to see different impacts of NBI on the IN estimation ($\beta = 1$).

IN is required to lead to a BER performance approaching that from the complete IN estimation.

In Fig. 6, a pre-processing block is adopted to extend the use of null subcarriers, where the performance of the proposed receiver is further enhanced by the feedback of an improved initial IN estimation. It can be seen that the proposed scheme with pre-TD processing achieves 5 dB SNR gain over that without pre-TD processing. Under the pre-TD processing aided initial IN estimation, a fairly good BER performance can be obtained without iteratively updating the estimated IN vector.

In the presence of NBI ($\beta = 1$), the performance of detecting the nonzero entries in the IN vector is affected by the added σ_v^2 in (31) and (32), which may result in an incomplete IN mitigation. The impacts of different NBI environments are depicted in Fig. 7 in terms of BER performance. It can be observed that the proposed receiver works well under the weak disturbance of NBI, which achieves BER values close to that with no NBI. In the case of strong disturbance which has a high value of NBI disturbance ratio $\mu = 0.9$, the null subcarriers assisted method requires a 2.5 dB SNR gain to achieve the same BER as no NBI, which still outperforms that without using null subcarriers by approximately 2.5 dB. When the system is intensively disturbed where the NBI to background noise power ratio at the NBI contaminated subcarriers is considered to be 40 dB, the corresponding BER curve reveals a harmful impact of the ingress of the intensive NBI, which should be eliminated properly before the IN reconstruction.

In Fig. 8, the benefit of adopting the pre-joint FD/TD nulling is evaluated under the impact of intensive NBI disturbance. To achieve a sufficiently low false alarm rate $\mathcal{P}_f = 10^{-4}$, the threshold for pre-FD nulling in (34) normalised to σ_{b} is set as 39.10, while the pre-TD nulling threshold in (37) normalised to $\sigma_{\hat{\mathbf{r}}}$ has its value of 3.89. It can be seen that the deployment of the pre-joint FD/TD nulling at the proposed receiver, results in a near-optimal BER performance with the initial IN estimation only. The IN vector is accurately reconstructed by the initial estimation in the proposed scheme with the aid of pre-joint FD/TD nulling. The IN reconstruction algorithm is robust against intensive NBI, and results in approximately 12 dB gain at BER of 0.01. The effectiveness of the proposed IN mitigation scheme is validated, even under the environment of intensive NBI. The impact of imperfect channel estimation is also shown in Fig. 8. The channel frequency response matrix $\boldsymbol{H}_{\mathrm{s}}$ in (14) and (38) can be replaced by its estimate $\hat{\boldsymbol{H}}_{\mathrm{s}}$, following $\boldsymbol{H}_{\mathrm{s}} = \beta_h \hat{\boldsymbol{H}}_{\mathrm{s}} + \boldsymbol{E}$ [39], where $\boldsymbol{E}$ is an error matrix whose elements are independent identically distributed zero mean Gaussian random variables and β_h denotes the normalized correlation coefficient between $\boldsymbol{H}_{\mathrm{s}}$ and $\hat{\boldsymbol{H}}_{\mathrm{s}}$. As can be seen from Fig. 8, the proposed mitigation scheme demonstrates robustness against imperfect channel estimation with $\beta_h = 0.9$ and 0.95.

V. Conclusion

In this paper, the IN mitigation for OFDM-based high speed in-vehicle PLC systems have been studied. A null subcarriers assisted iterative receiver has been proposed to reconstruct the IN, considering the potential NBI contaminated null subcarriers. The ROC expressions of detecting nonzero entries in the IN vector have been given, which are conditioned by the presence of NBI. Moreover, a pre-FD/TD nulling block has been adopted as an extended use of null subcarriers in the proposed receiver, in order to improve the initial IN estimation by joint mitigating the high-amplitude NBI and IN. Simulation results have demonstrated a much better BER performance of the proposed receiver than that of the blanking scheme especially in the high SNR region, meanwhile, a reduced number of iterations is required with the aid of null subcarriers in the proposed scheme. In the presence of intensive NBI that the power of the NBI contaminated subcarriers is extremely high, the IN vector cannot be reconstructed accurately. Hence, the implementation of pre-mitigation makes it possible to achieve a BER performance with initial IN estimation only close to that with complete IN estimation. The proposed IN mitigation scheme is particularly useful to solve the problem of IN mitigation when NBI is present, and can be applied to future vehicular standards and other communication systems disturbed by both IN and NBI.

References

[1] A. M. Tonello and F. Versolatto, “Bottom-up statistical PLC channel modeling-Part II: Inferring the statistics,” *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2356-2363, Oct. 2010.

[2] N. Navet, Y. Song, F. Simonot-Lion and C. Wilwert, “Trends in automotive communication systems,” *Proc. IEEE*, vol. 93, no. 6, pp. 1204-1223, Jun. 2005.

[3] L. Zhang, H. Ma, D. Shi, P. Wang, G. Cai and X. Liu, “Reliability oriented modeling and analysis of vehicular power line communication for vehicle to grid (V2G) information exchange system,” *IEEE Access*, vol. 5, pp. 12449 - 12457, Jun. 2017.

[4] L. Di Bert, P. Caldera, D. Schwingshackl and A. M. Tonello, “On noise modeling for power line communications,” in *Proc. ISPLC 2011*, pp. 283-288, Apr. 2011, Udine, Italy.

[5] J. A. Cortes, L. Dez, F. J. Canete and J. J. Sanchez-Martnez, “Analysis of the indoor broadband power-line noise scenario,” *IEEE Trans. Electromagnetic Compatibility*, vol. 52, no. 4, pp. 849-858, Nov. 2010.

[6] M. Zimmermann and K. Dostert, “Analysis and modeling of impulsive noise in broad-band powerline communications,” *IEEE Trans. Electromagnetic Compatibility*, vol. 44, no. 1, pp. 249-258, Feb. 2002.

[7] J. Yin, X. Zhu and Y. Huang, “Modeling of amplitude-correlated and occurrence-dependent impulsive noise for power line communication,” in *Proc. IEEE ICC 2014*, Jun. 2014, Sydney, Australia.

[8] S. V. Zhidkov, “Performance analysis and optimization of OFDM receiver with blanking nonlinearity in impulsive noise environment,” *IEEE Trans. Veh. Technol.*, vol. 55, no. 1, pp. 234-242, Jan. 2006.

[9] F. Juwono, Q. Guo, D. Huang and K. P. Wong, “Deep clipping for impulsive noise mitigation in OFDM-based power-line communications,” *IEEE Trans. Power Del.*, vol. 29, no. 3, pp. 1335-1343, Jun. 2014.

[10] S. V. Zhidkov, “Analysis and comparison of several simple impulsive noise mitigation schemes for OFDM receivers,” *IEEE Trans. Commun.*, vol. 56, no. 1, pp. 5-9, Jan. 2008.

[11] V. N. Papilaya and A. J. H. Vinck, “Investigation on a new combined impulsive noise mitigation scheme for OFDM transmission,” in *Proc. ISPLC 2013*, pp. 86-91, Mar. 2013, Johannesburg, South Africa.

[12] D. Umehara, H. Yamaguchi and Y. Morihiro, “Turbo decoding in impulsive noise environment,” in *Proc. IEEE Globecom 2004*, Dec. 2004, Dallas, USA.

[13] H. Nakagawa, D. Umehara, S. Denno and Y. Morihiro, “A decoding for low density parity check codes over impulsive noise channels,” in *Proc. ISPLC 2005*, pp. 85-89, Apr. 2005, Vancouver, BC, Canada.

[14] F. Abdelkefi, P. Duhamel and F. Alberge, “Impulsive noise cancellation in multicarrier transmission,” *IEEE Trans. Commun.*, vol. 53, no. 1, pp. 94-106, Jan. 2005.

[15] G. Ndo, P. Siohan and M. Hamon, “Adaptive noise mitigation in impulsive environment: application to power-line communications,” *IEEE Trans. Power Del.*, vol. 25, no. 2, pp. 647-656, Apr. 2010.

[16] S. Liu, F. Yang, W. Ding and J. Song, “Double kill: Compressive sensing based narrowband interference and impulsive noise mitigation for vehicular communications,” *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5099-5109, Jul. 2016.

[17] S. Liu, F. Yang, X. Wang, J. Song and Z. Han, “Structured-compressed-sensing-based impulsive noise cancelation for MIMO systems,” *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 6921-6931, Aug. 2017.

[18] J. Lin, M. Nassar and B. Evans, “Impulsive noise mitigation in powerline communications using sparse Bayesian learning,” *IEEE J. Sel. Areas. Commun.*, vol. 31, no. 7, pp. 1172-1183, Jul. 2013.

[19] D. Donoho, “Compressed sensing,” *IEEE Trans. Inf. Theory*, vol. 52, no. 4, pp. 1289-1306, Apr. 2006.

[20] L. Lampe, “Bursty impulse noise detection by compressed sensing,” in *Proc. ISPLC 2011*, pp. 29-34, Apr. 2011, Udine, Italy.

[21] D. Wipf and B. Rao, “Sparse Bayesian learning for basis selection,” *IEEE Trans. Signal Process.*, vol. 52, no. 8, pp. 2153-2164, 2004.

[22] Y.-R. Chien, “Iterative channel estimation and impulsive noise mitigation algorithm for OFDM-based receivers with application to power-line communications,” *IEEE Trans. Power Del.*, vol. 30, no. 6, pp. 2435-2442, Dec. 2015.

[23] S. V. Zhidkov, “Impulsive noise suppression in OFDM based communication systems,” *IEEE Trans. Consum. Electron.*, vol. 4, no. 9, pp. 944-948, Nov. 2003.

[24] Y.-R. Chien, J. W. Chen and S. D. Xu, “A multilayer perceptron-based impulsive noise detector with application to power-line-based sensor networks,” *IEEE Access*, vol. 6, May. 2018.

[25] B. Praho, M. Tlich, P. Pagani, A. Zeddam and F. Nouvel, “Cognitive detection method of radio frequencies on power line networks,” in *Proc. ISPLC 2010*, pp. 225-230, Mar. 2010, Rio de Janeiro, Brazil.

[26] S. Liu, F. Yang, J. Song and Z. Han “Block sparse Bayesian learning-based NB-IoT interference elimination in LTE-advanced systems,” *IEEE Trans. Commun.*, vol. 65, no. 10, pp. 4559-4571, Oct. 2017.

[27] S. Liu, F. Yang, W. Ding, X. Wang and J. Song, “Two-Dimensional Structured-Compressed-Sensing-Based NBI Cancelation Exploiting Spatial and Temporal Correlations in MIMO Systems,” *IEEE Trans. Veh. Technol.*, vol. 65, no. 11, pp. 9020-9028, Nov. 2016.

[28] S. Liu, F. Yang, W. Ding, J. Song and A. M. Tonello, “Structured compressed sensing based narrowband interference elimination for in-home power line communications,” *IEEE Trans. Consum. Electron.*, vol. 63, no. 1, pp. 10-18, Feb. 2017.

[29] M. Tlich, A. Zeddam, F. Moulin and F. Gauthier, “Indoor powerline communications channel characterization up to 100 MHz-Part II: Time-frequency analysis,” *IEEE Trans. Power Delivery*, vol. 23, no. 3, pp. 1402-1409, Jul. 2008.

[30] M. Antoniali, F. Versolato and A. M. Tonello, “An experimental characterization of the PLC noise at the source,” *IEEE Trans. Power Del.*, vol. 31, no. 3, pp. 1068-1075, Jun. 2016.

[31] E. N. Gilbert, “Capacity of burst-noise channels,” *Bell Syst. Tech. J.*, vol. 39, pp. 1253-1266, 1960.

[32] J. Yin, X. Zhu and Y. Huang, “3D Markov chain based narrowband interference model for in-home broadband power line communication,” in *Proc. IEEE Globecom 2016*, Dec. 2016, Washington DC, USA.

[33] HomePlug Powerline Alliance, “HomePlug AV white paper,” 2015. [Online]. Available: http://www.homeplug.org/tech-resources/resources/

[34] A. Tonello and F. Pecile, “Efficient architectures for multiuser FMT systems and application to power line communications,” *IEEE Trans. Commun.*, vol. 57, no. 5, pp. 1275-1279, May 2009.

[35] K. Rabie and E. Alsusa, “Preprocessing-based impulsive noise reduction for power-line communications,” *IEEE Trans. Power Del.*, vol. 29, no. 4, pp. 1648-1658, Aug. 2014.

[36] P. Khurd, B. Liu and G. Gindi, “Ideal AFROC and FROC observers,” *IEEE Trans. Med. Imag.*, vol. 29, no. 2, pp. 375-385, Feb. 2010.

[37] I. S. Gradshteyn, I. M. Ryzhik, J. Alan and D. Zwillinger (2007). *Table of Integrals, Series, and Products*, Seventh (7th) edition. Academic Press.

[38] G. Avril, F. Moulin, A. Zeddam, M. Tlich and F. Nouvel, “Impulsive noise detection on masked carriers,” in *Proc. ISPLC 2008*, pp. 369-373, Apr. 2008, Jeju City, South Korea.

[39] X. Zhu and R. D. Murch, “Performance analysis of maximum likelihood detection in a MIMO antenna system,” *IEEE Trans. Commun.*, vol. 50, no. 2, pp. 187-191, Feb. 2002.

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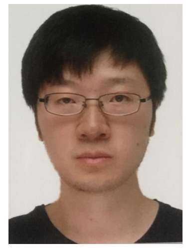

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