This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2365579, IEEE Transactions on Power Delivery

An Optimal Interleaving Scheme with Maximum Time-Frequency Diversity for PLC Systems

Sicong Liu, Fang Yang, *Senior Member, IEEE*, and Jian Song, *Senior Member, IEEE*

***Abstract*—In this paper, an optimal interleaving scheme with maximum time-frequency diversity is proposed to combat against the narrowband interference (NBI) and time-domain impulsive noise (TIN) for orthogonal frequency division multiplexing (OFDM) systems in power line communications (PLC). To improve both the anti-NBI and anti-TIN performance, we propose two criteria based on which the optimized interleaving scheme is designed: (i) to increase the number of different OFDM blocks for one forward error correction (FEC) codeword, which is aimed at TIN mitigation; and (ii) to increase the number of different sub-carriers mapped to the data symbols in one FEC codeword, which is aimed at NBI mitigation. Simulations show that the proposed interleaving scheme can effectively reduce the impairments caused by NBI and/or TIN in OFDM systems under PLC environments, and hence achieve better performance than the conventional block interleaving scheme.**

***Keywords*—time-frequency interleaving, PLC, OFDM, narrowband interference, impulsive noise.**

I. Introduction

Power line communications (PLC) have many advantages over other transmission approaches, such as the prevailing electrical wiring networks, the ubiquitous interfaces to plug in and relatively lower costs, the convenience and efficiency to build up the PLC systems, etc. An increasing number of researches on digital communications in power line channels and its applications for smart grid have arisen recently [1]- [4]. Orthogonal frequency division multiplexing (OFDM) technique is widely adopted in various communication systems, including PLC systems, the digital television terrestrial broadcasting (DTTB) systems [5] [6], etc. The OFDM technique divides the entire bandwidth into many parallel narrow bands which can provide the higher-spectrum efficiency as well as better capability to handle the multi-path effect. There have been many researches on the OFDM technique, such as channel estimation [7], peak-to-average-ratio (PAPR) reduction [8] and synchronization [9]. Specially, a broadband power line communication system using OFDM technique with LDPC code is specified in the power line communication system of ITU G.9960 standard, i.e. the G.hn standard, which has been adopted in many communication systems such as in-home networks and smart grid applications [10].

This work was supported by NSFC (Grant No. 61401248, 61471219), the Science Fund for Creative Research Groups of NSFC (61321061), and China Electric Power Research Institute (CEPRI) (Grand No.20142000191).

The authors are with the Department of Electronic Engineering & Research Institute of Information Technology, Tsinghua University and Tsinghua National Laboratory for Information Science and Technology (TNlist), Beijing 100084, P. R. China. Jian Song is also with National Engineering Lab. for DTV (Beijing), Beijing 100191, P.R China (E-mail: liusc12@mails.tsinghua.edu.cn, {fangyang, jsong}@tsinghua.edu.cn).

Although there are advantages for using PLC systems, the channel environment is quite poor. The PLC channel can be modeled by a multi-path channel with frequency-selectivity [11]. There also exist different kinds of attenuation and interferences, such as the narrowband interference (NBI) and the time-domain impulse noise (TIN) in the power line channel. Frequency-selectivity can be well mitigated using the OFDM technique, nevertheless the NBI and TIN in the PLC channel should be specially taken into consideration since they can both cause severe degradation on the system performance, which has drawn much research attention [12] [13].

Interleaving is aimed at providing diversity in time, frequency and/or spatial domain, and has been adopted in the PLC system since the channel conditions of PLC are so poor that more diversity is beneficial to the system performance. Several interleaving schemes to improve the performance of different communication systems have been investigated [14]- [16]. Wang and Kobayashi proposed a method to design an interleaver with practical size for turbo codes [14]. Literature [15] investigated an adaptive interleaved beamforming approach for broadband MIMO/OFDM systems in which beamforming is adaptively interleaved in the spatial domain to achieve performance improvements over conventional adaptive antenna array based OFDM systems in wireless channels. In broadcasting systems, such as the prevailing second generation terrestrial digital video broadcasting standard (DVB-T2), interleaving is adopted to ensure better performance under the severe propagation environment [16]. However, these interleaving methods are not optimized for mitigating the performance degradation due to special impairments, such as TIN and NBI.

For the purpose of reducing the impact of impulse noise in OFDM systems, several methods have been proposed [17] [18]. An interleaving scheme performed post the inverse discrete Fourier transform (IDFT) can achieve better performance under TIN [17]. However, the method is very sensitive to the QAM order and will suffer from remarkable degradation in 64-QAM or higher-order QAM constellations. The performance of the coded OFDM system and the impact of the length of the adopted bit interleaver on coding performance are analyzed in [18]. The aforementioned methods are not specifically designed or optimized for mitigating NBI impairments.

In order to deal with the impairments due to NBI, an OFDM system using convolutional coding with an interleaver designed for channels under narrowband and impulsive noise is described in [19] with bit interleaving rather than symbol interleaving proposed, and the interleaver is specially designed

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2365579, IEEE Transactions on Power Delivery

for systems using convolutional coding and BPSK modulation only. This constrains its application and performance in other systems, and there is no experimental or simulation results provided in the paper to show the performance.

In this paper, we propose an optimized time-frequency interleaving scheme, which is designed according to two criteria, to combat against NBI and TIN in the PLC system. The two proposed criteria based on which the optimized interleaver is designed can remarkably improve time and frequency diversity. The first criterion is met by optimizing the distribution of OFDM blocks in the FEC codewords, while the second criterion is satisfied with the optimized distribution of sub-carriers in the FEC codewords. Hence, block interleaving with optimized block size is utilized as time interleaving, while the novel frequency interleaving method realized by the proposed row shifting in sub-matrix operation is performed. Furthermore, the proposed interleaving process is at the symbol level (i.e. data symbol level) rather than the bit level, which leads to more effectiveness and low implementation complexity.

The rest of this paper is organized as follows: The characteristics of the system model for which the interleaver is designed are described in Section II. The statistical models of the NBI and TIN in the PLC channel are given in Section III. The optimized interleaving scheme along with the two criteria for designing the optimized interleaver for PLC systems is derived in Section IV. The paper concludes with a quantitative analysis for the interleaving schemes and simulation results in Section V, and a summary.

II. System Model with Time-Frequency Interleaving

The OFDM system model used for our analysis is depicted in Fig. 1. The source bit stream $\{b_k\}$ is passing through the encoder and generates forward error correction (FEC) codewords $\{\mathbf{e}_l\}$ with the length of L_b . Bit-to-symbol mapping is performed by M-QAM constellation, which produces complex data symbols $\{c_t\}$. The data symbols are then interleaved in the block interleaver, which is adopted as a time and/or frequency interleaver, with I_R rows and I_C columns. Afterwards, the pilots are inserted, and combined with the interleaved data symbols to form the OFDM block in the frequency domain. The number of data sub-carriers in an OFDM block is N. The frequency interleaving is performed before the OFDM block data is processed by the IDFT module to obtain the time-domain OFDM symbol $\boldsymbol{x}_m$. The OFDM symbols are then transmitted over the PLC channel deteriorated by NBI and TIN. The received signal $\hat{\boldsymbol{x}}_m$ can be expressed as

$$\hat{\boldsymbol{x}}_m = \boldsymbol{x}_m + \boldsymbol{w} + \boldsymbol{n}_{NBI} + \boldsymbol{i}_{TIN} \tag{1}$$

where $\mathbf{w}$ is the background noise in the PLC channel modeled as additive white Gaussian noise (AWGN) with zero mean and variance of σ_w^2 , and $\boldsymbol{n}_{NBI}$ and $\boldsymbol{i}_{TIN}$ denote NBI and TIN, respectively.

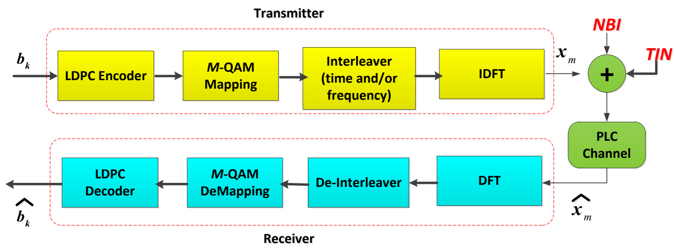

Fig. 1. OFDM system with interleaver.

Finally, the receiver performs the inverse operations of the transmitter in a reversed order, and obtains the transmitted bits $\{b_k\}$.

III. Statistical Models of the NBI and the TIN

We discuss the state-of-the-art statistical models for the NBI and TIN in PLC systems in this section. The proposed time-frequency interleaving approach is non-parametric, but the PLC transmission environments with the NBI and the TIN can be simulated and the effectiveness of the proposed approach can be verified through these statistical models.

A. Statistical NBI Model in PLC

The statistical NBI signal model in the frequency-domain can be denoted as the vector of $\tilde{\mathbf{e}} = \left[e_0, e_1, \cdots, e_{N-1}\right]^T$ of length N with only few nonzero entries. The support of the NBI Γ is defined as the set of the positions of the nonzero entries, and is given by $\Gamma = \{k\,|e_k \neq 0\,,\ k = 0, 1, \cdots, N-1\}$. For the NBI signal model adopted in this paper, the positions of the nonzero entries are randomly distributed in all the data sub-carriers. The distribution of the support of the NBI is stochastic, which is also adopted and verified by existing NBI models [20] [21]. Without loss of generality, this NBI model is a general case for many situations, including the practical situation in which multiple NBI nonzero entries are clustered in some interferer groups. The sparsity level K of the NBI is defined as the cardinality of the support, i.e. $K = |\Gamma|$. The interference-to-noise ratio (INR) is defined as P_e / σ_w^2, where $P_e = \sum_{k\in\Gamma} |e_k|^2/K$ denotes the average power of the NBI. INR is an indicator of the NBI intensity compared with the background noise. The intensity of NBI is also described by the signal-to-interference ratio (SIR), which is given by

$$\text{SIR} = \frac{E\{|\boldsymbol{x}_m|^2\}}{P_e} \tag{2}$$

Since the sparsity level of the NBI signal model is variable and the distribution of the support of the NBI is random, the NBI model in this paper is more general and more practical for PLC systems compared with the NBI models in [20] and [21] where only one nonzero entry, i.e. only one sinusoidal component, is considered.

B. Statistical TIN Model in PLC

The statistical properties of the instantaneous amplitude and the random emissions of the TIN in the PLC systems have been modeled in literature empirically, mainly including the burst block-sparse model [22], the Gaussian mixture model [23] and the Middleton's Class A model [24].

1) Burst Block-Sparse Model: In practical PLC systems, TIN occurs in bursts and corrupt blocks of received OFDM signal samples [22]. The burst block-sparse model in [22] assumes that only a small portion of the received samples are corrupted by TIN, and the corrupted samples are grouped in burst blocks. Hence, the occurrence of TIN bursts is in-between the extreme cases of i.i.d. TIN and long TIN bursts that destroy entire OFDM symbol [22][31]. The burst block-sparse model is given by

$$\boldsymbol{i}_{TIN} = [\overbrace{i_1, \cdots, i_D}^{\boldsymbol{i}^T[1]}, \cdots, \overbrace{i_{N-D+1}, \cdots, i_N}^{\boldsymbol{i}^T[p]}]^T \tag{3}$$

where the block-size of bursts is D and only $q \ll p$ vectors $\boldsymbol{i}[j]$ have non-zero Euclidean norm [22].

The probability of Λ which is the number of TIN bursts per second follows Poisson process [25], and is given by $P(\Lambda) = \lambda^{\Lambda} e^{-\lambda}/\Lambda!$, where λ denotes the rate of TIN arrivals.

2) Gaussian Mixture Model: The instantaneous amplitude of the time-domain asynchronous impulsive noise in the PLC network can be modeled by the Gaussian mixture distribution [23], with the probability density distribution (pdf) given by $p_Z(z) = \sum_{j=0}^{J_m} \beta_j \cdot g_j(z)$, where $g_j(z)$ is a Gaussian pdf with zero mean and variance of σ_j^2, and β_j is the mixture coefficient of the corresponding Gaussian pdf.

3) Middleton's Class A Model: A common statistical model of the TIN instantaneous amplitude is the Middleton's Class A model with the parameters of the overlapping factor A and the background-to-impulsive-noise power ratio Ω [24]. Gaussian mixture distribution can generate the special case of Middleton's Class A distribution when the parameters $\beta_j = e^{-A}\frac{A^j}{j!}$ and $\sigma_j^2 = \frac{j/A+\Omega}{1+\Omega}$ as $J_m \to \infty$. The Middleton's Class A model is widely adopted in analytical research and simulations for PLC systems [26] [27].

IV. Time-Frequency Interleaving Method

A. Conventional Interleaving Methods

As for the conventional block interleaving scheme, data symbols are written row-wise into the block interleaver with I_R rows and I_C columns, and then read column-wise out to form the OFDM blocks. The conventional block interleaving is time interleaving, aiming at mitigation of TIN. Time-domain burst errors could be dispersed into several FEC codewords to reduce the probability of decoding errors by block interleaving.

It is crucial to choose an appropriate block size for a block interleaver to achieve better anti-TIN capability for a certain system. The row number I_R is usually referred to as the interleaving depth, while the column number I_C is the interleaving width. If the block size is not specially designed for OFDM systems in the presence of TIN, the performance will degrade greatly. Meanwhile, in the presence of NBI, the conventional block interleaving scheme may have a serious drawback in sub-carrier allocation of LDPC codewords.

Another conventional interleaver, the random bit interleaver, distributes the bits among several codewords into different time slots and sub-carriers. The design of a bit interleaver is also aimed at providing larger time/frequency diversity, which is a fundamental idea of the proposed scheme in this paper. However, in the presence of TIN and NBI, a good random bit interleaver is very difficult to design in practice, and one bit interleaver is not robust and is likely to degrade in different constellations, interleaving depths or transmission modes.

B. Proposed Interleaving Method

In this work, we propose two criteria for improving and maximizing the time diversity and frequency diversity, respectively, and the optimized interleaver is designed to combat against both TIN and NBI according to the two criteria.

Firstly, for better anti-TIN capability, we propose ***Criterion 1*** as the criterion for choosing the optimized block size for the block interleaver as time interleaving. Under this criterion, the time diversity of the PLC system is maximized.

***Criterion 1**. The Maximum Independent OFDM Block (MIOB) Criterion*: to increase the number of different independent OFDM blocks for one FEC codeword.

Since the TIN bursts occur in groups and will ruin the data symbols of the OFDM block when they occur, the OFDM blocks should be average distributed in the codewords. If the allocation of OFDM blocks for one codeword is not average, e.g. the number of different OFDM blocks for a specific codeword is smaller and the number of data symbols of the TIN deteriorated OFDM block is larger on average, the impairments caused by TIN are more concentrated in this codeword, resulting in higher probability of decoding errors.

Therefore, the number of different OFDM blocks for one FEC codeword, i.e. the parameter of independent OFDM block (IOB) number N_{IOB}, should be increased to improve the anti-TIN capability. With the increase of IOBs mapped to each codeword, the possibility of unsuccessful decoding due to the concentration of TIN bursts is decreased. Moreover, we propose a time-domain merit factor ξ_T as a general indicator of N_{IOB} in one codeword to measure the anti-TIN capability quantitatively as

$$\xi_T = \frac{1}{L_C} \sum_{n=0}^{L_C-1} \frac{N_{IOB}(n)}{\min\left\{\dfrac{I_R \cdot I_C}{N}, L_{sym}\right\}} \tag{4}$$

where L_{sym}, L_C and $N_{IOB}(n)$ denote the number of data symbols in each LDPC codeword, the number of LDPC codewords in the interleaver, and the number of IOBs in the nth LDPC codeword respectively. Hence ξ_T is the average of the ratio of $N_{IOB}(n)$ to its maximum value $\min\{I_R \cdot I_C/N, L_{sym}\}$.

To satisfy ***Criterion 1***, the design of the block size can be concluded as an optimization problem as

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2365579, IEEE Transactions on Power Delivery

$$opt : \max_{I_R, I_C} \{\xi_T\} \tag{5}$$

To optimize (5), intuitively we should make sure that each LDPC codeword occupies as many IOBs as possible. After the optimization of (5), we can obtain the optimized interleaving block size design as given by,

$$I_C = \frac{L_b}{p \cdot \log_2(M)} = L_{sym}/p \tag{6}$$

$$I_R = \delta \cdot \mathscr{L}\{N, L_{sym}\}/I_C \tag{7}$$

where $\mathscr{L}\{\cdot,\cdot\}$ is the least common multiple operator, and L_b denotes the number of bits in a codeword. The parameter p is optional and is usually set to a small prime number, such as 2, 3, 5, etc. Eq. (7) ensures that the proposed interleaver contains integer number of OFDM blocks and LDPC codes. The total interleaving delay is measured by the number of data symbols in the interleaver given by $I_R \cdot I_C = \delta \cdot \mathscr{L}\{N, L_{sym}\}$, where δ is an integer that can be adjusted according to the acceptable transmission delay.

With the proposed block size in (6) and (7), the parameter of N_{IOB} and the anti-TIN capability of the block interleaver will be optimized. Equation (6) assures that each LDPC codeword occupies exactly p rows in the interleaver, which makes it possible for each codeword to be mapped to all the OFDM blocks without loss. Meanwhile, from (7) it can be deduced that each OFDM block occupies one column or more if $N \geq I_R$, which is equivalent to

$$\mathcal{G}\{L_{sym}, N\} \geq p \tag{8}$$

where $\mathcal{G}\{\cdot,\cdot\}$ is the greatest common divisor operator. Recall that we have set p as a small prime number. The reason is that when p is set as a small prime number, the parameter L_{sym} and N specified in G.hn or other OFDM systems are large enough to contain p as a common divisor. In this condition, it is easy to meet (8).

Hence each LDPC codeword will contain all the OFDM blocks in the interleaver, which is the optimized case against TIN and is reached based on ***Criterion 1***. However, with conventional block size, each LDPC codeword is much likely to occupy less than one row, or each OFDM block is much likely to occupy less than one column. This means N_{IOB} of the LDPC codewords are smaller, leading to poorer performance under TIN.

Afterwards, ***Criterion 2*** is proposed as the criterion to design the optimized frequency interleaving scheme for better anti-NBI capability, with the constraint of ***Criterion 1*** to ensure anti-TIN capability. Hence under both the two criteria, both the time and frequency diversity of the PLC system can be maximized.

Criterion 2*. The Maximum Independent Sub-Carrier (MISC) Criterion*: to increase the number of different independent OFDM sub-carriers mapped to the data symbols in one FEC codeword.

The reason to set up ***Criterion 2*** is similar to that of ***Criterion 1***. If the allocation of sub-carriers of one codeword is uneven, e.g. the number of different sub-carriers for a specific codeword is smaller and the number of data symbols mapped to the NBI impacted sub-carrier is larger on average, the impairments caused by NBI are more concentrated in this codeword, leading to the decoding errors even though the average signal-to-noise ratio is high enough to decode other codewords correctly.

Hence the number of different sub-carriers mapped to the data symbols of each codeword, i.e., the parameter of independent sub-carrier (ISC) number N_{ISC}, should be increased in order to distribute the NBI-contaminated sub-carriers in more codewords. Allocation of sub-carriers of the data symbols in one FEC codeword is better scattered and more average when N_{ISC} is larger, which would lead to more robust anti-NBI performance. To quantitatively evaluate the anti-NBI capability of different interleaving schemes and facilitate the frequency interleaving design based on ***Criterion 2***, we propose another frequency-domain merit factor ξ_F as a general indicator of N_{ISC} in one codeword, which is given by

$$\xi_F = \frac{1}{L_C} \sum_{n=0}^{L_C - 1} \frac{N_{ISC}(n)}{\min\{N, L_{sym}\}} \tag{9}$$

where $N_{ISC}(n)$ is the number of ISCs of the nth LDPC codeword. ξ_F is the average of the ratio of $N_{ISC}(n)$ to its maximum value $\min\{N, L_{sym}\}$, which can be achieved under ideally average sub-carrier distribution.

The design of the frequency interleaving scheme to meet ***Criterion 2*** can be also concluded as an optimization problem described by,

$$opt : \max \left\{ \xi_F \,\middle|\, I_C = \frac{L_{sym}}{p}, I_R = \frac{\delta \cdot \mathscr{L}\{N, L_{sym}\}}{I_C} \right\} \tag{10}$$

The constraints in (10) are set by (6) and (7) to ensure that the anti-TIN capability is not affected during the optimization process of ξ_F. To solve the problem described in (10), from an intuitive perspective of view, we need to make sure that the data symbols of each LDPC codeword are mapped to as many ISCs as possible. Hence, we propose a novel frequency interleaving scheme using block interleaver as shown in Fig. 2. Firstly, data symbols are written row-wise into the block interleaver. The interleaving matrix is divided into several sub-matrices by column, each having the same number of columns. The number of sub-matrices S is optional and can be any divisor of I_C . The basic concept of the proposed interleaving scheme is to perform a novel row shifting in sub-matrix operation in the block interleaver. Assuming that $\boldsymbol{C}^{(r)}$ denotes the rth sub-matrix and $\boldsymbol{C} = [\boldsymbol{C}^{(0)}, \boldsymbol{C}^{(1)}, \cdots, \boldsymbol{C}^{(S-1)}]$ represents the block matrix, the row shifting in sub-matrix operation is to shift the rows of sub-matrix $\boldsymbol{C}^{(r)} (r = 0, 1, \cdots, S-1)$ cyclically down by f_r rows to produce the shifted sub-matrix $\widetilde{\boldsymbol{C}}^{(r)}$, which is expressed by

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2365579, IEEE Transactions on Power Delivery

$$\widetilde{\mathbf{c}}_i^{(r)} = \mathbf{c}_j^{(r)}, j = (i + I_R - f_r) \bmod I_R, 0 \le i, j < I_R \tag{11}$$

where $\mathbf{c}_j^{(r)}$ and $\widetilde{\mathbf{c}}_i^{(r)}$ denote the jth and ith rows of $\boldsymbol{C}^{(r)}$ and $\widetilde{\boldsymbol{C}}^{(r)}$, respectively. The numbers of rows to be shifted for each sub-matrix can be any integer. To simplify the calculation, f_r can be given by

$$f_r = p \cdot r, 0 \le r < S \tag{12}$$

where p is decided by (6). After the row shifting in sub-matrix operation, the derived block matrix $\widetilde{\boldsymbol{C}}$ is read column-wise out to form OFDM blocks.

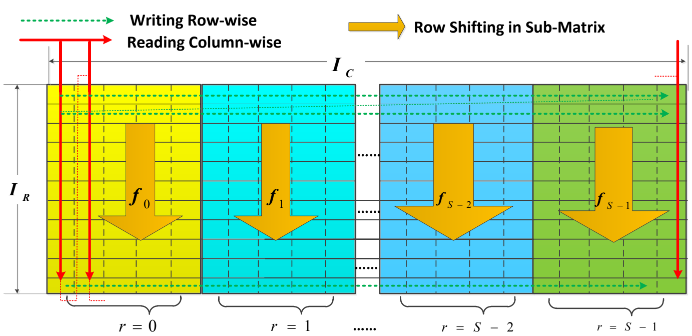

Fig. 2. Proposed Time-Frequency Interleaving Scheme.

Let us compare the anti-NBI capabilities between the conventional block interleaving scheme and the proposed frequency interleaving scheme. For the conventional scheme, we define every $\mathscr{L}\{I_R, N\}$ data symbols in the block interleaver as a "cyclic unit", which contains integer number of columns and OFDM blocks. Data symbols of each cyclic unit would be mapped to the sub-carriers with the same pattern repeatedly, since the mapping patterns of all cyclic units are the same. Hence the allocation of sub-carriers to a specific codeword in the other cyclic units is the same as in the first one, which provides no contribution to N_{ISC}.

However, in the proposed scheme, since each cyclic unit can be treated as a sub-matrix and is shifted down by different number of rows defined by (12) before forming OFDM blocks, patterns of sub-carriers mapped to the data symbols in a specific codeword within different sub-matrices are different and not repeated. From these analyses and (12), the proposed scheme can achieve the optimized ξ_F for (10) obviously. Therefore, N_{ISC} of a codeword in the proposed scheme is much larger than that in the conventional scheme, leading to a better anti-NBI capability. Since the row shifting in sub-matrix operation has the effect of scattering the patterns of data symbols mapping to sub-carriers, the operation can be regarded as frequency interleaving. Consequently the proposed scheme is a time-frequency interleaving.

According to the two proposed criteria, the optimal time-frequency interleaver is designed with largest time and frequency diversity. This goal is achieved through the two optimization problems aiming at combat against TIN and NBI, respectively. By utilizing both the time and frequency interleaving, we can improve the anti-NBI and anti-TIN capabilities of OFDM systems, such as G.hn system using LDPC coding studied in this paper. Experimental simulations are carried out in different channel interference environments with the parameters specified in G.hn standard to show the performance improvements of the proposed scheme in the next section.

V. Evaluation and Simulation Results

A. *Interleaving Performance Evaluation*

The computation of the merit factors of the proposed ***Criterion 1***, the proposed ***Criterion 1&2***, the conventional block interleaving and random bit interleaving schemes are listed in Table I with LDPC length $L_b = 8640$ and data sub-carrier number $N = 256$, which is specified in the PLC G.hn system [10]. The column and row numbers of the interleaver are also given in Table I, which shows that the conventional block interleaving and random interleaving schemes have the same interleaving delay with that of the proposed scheme in both 16QAM and 64QAM modulations. The interleaving delay for the proposed scheme and the benchmarks are fixed for effective comparison. It is noticed that ξ_T of the proposed ***Criterion 1*** scheme is much larger than that of the conventional block and random interleaving schemes, and ξ_F of the proposed ***Criterion 1&2*** scheme is also significantly larger than those of the conventional block and random interleaving schemes in both QAM modes. It is quantitatively indicated that the anti-TIN and anti-NBI capabilities of the proposed schemes meeting ***Criterion 1*** and ***Criterion 2*** are remarkably better than those of its counterparts. According to the merit factors ξ_T and ξ_F, both the maximum time and frequency diversities are achieved using the proposed ***Criterion 1&2*** interleaving scheme since both ξ_T and ξ_F reach their maximum theoretical value of one. Due to these analyses, it is verified that the maximum time-frequency diversity can be achieved.

TABLE I
Evaluation with Merit Factors

Schemes	QAM Order	ξ_T	ξ_F	I_R	I_C	ITLV Delay
S1. Criterion 1&2	16	1	1	240	432	103680
S2. Criterion 1	16	1	0.3125	240	432	103680
S3. Block ITLV	16	0.5500	0.3125	480	216	103680
S4. Random ITLV	16	0.7134	0.8269	-	-	103680
S1. Criterion 1&2	64	1	1	120	288	34560
S2. Criterion 1	64	1	0.6250	120	288	34560
S3. Block ITLV	64	0.5667	0.6250	480	72	34560
S4. Random ITLV	64	0.7268	0.8640	-	-	34560

Furthermore, it can be verified the performance is guaranteed or improved under multi-path fading channels. The performance against multi-path fading can be quantitatively measured by the "duo-distance", which is commonly used in literature [14]. The duo-distance can be defined as the interleaving duo-distance d_1 and the de-interleaving duo-distance d_2. The interleaving duo-distance d_1 of a pair of

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2365579, IEEE Transactions on Power Delivery

adjacent data symbols at the input of the interleaver is defined as the distance of these two data symbols at the output of the interleaver. Similarly, the de-interleaving duo-distance d_2 of a pair of adjacent data symbols at the output of the interleaver is defined as the distance of these two data symbols at the input of the interleaver. The duo-distances d_1 and d_2 should be made as large as possible in order to lower the correlation between the interleaver input sequence and the output sequence, and this will disperse the data symbols of one codeword into scattered frequencies and scattered time slots, leading to better performance under time-selective and frequency-selective fading channels.

TABLE II
DUO-DISTANCES OF THE INTERLEAVING SCHEMES

I_R	I_C	QAM Order	Proposed ITLV	Block ITLV
240	432	16	$\bar{d}_1 = 477.89$ $d_{1,min} = 240$ $\bar{d}_2 = 859.74$ $d_{2,min} = 432$	$\bar{d}_1 = 289.76$ $d_{1,min} = 240$ $\bar{d}_2 = 578.31$ $d_{2,min} = 432$
120	288	64	$\bar{d}_1 = 238.18$ $d_{1,min} = 120$ $\bar{d}_2 = 570.43$ $d_{1,min} = 288$	$\bar{d}_1 = 127.92$ $d_{1,min} = 120$ $\bar{d}_2 = 351.66$ $d_{1,min} = 288$

The duo-distances d_1 and d_2 of the proposed ***Criterion 1&2*** interleaving scheme and the conventional block interleaving scheme are given in Table II. It is noted that the average duo-distances $\bar{d}_1$ and $\bar{d}_2$ of the proposed interleaving scheme are both significantly larger than those of the conventional block interleaving scheme, and the minimum duo-distances $d_{1,min}$ and $d_{2,min}$ are the same, which explicitly indicates that the data symbols of the proposed interleaving scheme are thoroughly dispersed in both time and frequency dimensions. Hence the performance of the proposed interleaving scheme can be guaranteed and even better than the conventional block interleaving under multi-path fading channels.

Based on the fact that the merit factors ξ_T and ξ_F are optimized and the large duo-distances d_1 and d_2 are guaranteed at the same time, it can be concluded theoretically that the proposed ***Criterion 1&2*** interleaving scheme achieves the optimal anti-NBI and anti-TIN capabilities and the maximum time-frequency diversity under both AWGN and multi-path fading channels, with guaranteed interleaving performance under frequency-selective channels.

B. Simulation Results of BER Performance

Simulations of the proposed ***Criterion 1***, ***Criterion 1&2*** schemes and the conventional block interleaving and random bit interleaving schemes with the same interleaving delay are performed in the G.hn system, and relevant simulation parameters are listed in Table III. $\delta = 3$ is used to fix the interleaving delay for the proposed scheme and the benchmarks. The AWGN channel and a multi-path PLC channel model [11] with NBI and TIN are adopted to evaluate the effectiveness of the schemes. The detailed parameters of the PLC multi-path channel are given in [11]. Non-ideal channel estimation is used at the receiver in the simulations. The SIR and sparsity level K of the NBI for different different QAM orders are given in Table III. All the N data sub-carriers are used to transmit data in simulations. As is described in Section III, the TIN occurrence has the burst block-sparse property [22], and the arrival rate of the TIN bursts is described by a Poisson point process with a medium value of $\lambda = 50/\text{sec}$ [28]. The instantaneous amplitude of the TIN is modeled by the Middleton's Class A distribution with the parameters of A and Ω that are also given in Table III.

TABLE III
SIMULATION PARAMETERS

Schemes	I_R	I_C	QAM Order	NBI Parameters	TIN Parameters
Proposed	240	432	16	$K = 5$	$A = 0.15$
Block ITLV	480	216		SIR= -2.9 dB	$\Omega = 0.02$
Random ITLV	-	-			
Proposed	120	288	64	$K = 4$	$A = 0.1$
Block ITLV	480	72		SIR= -2.7 dB	$\Omega = 0.01$
Random ITLV	-	-			

BER performances of different interleaving schemes under the AWGN channel with different interferences are depicted in Figs. 3, 4 and 5, respectively. It can be noted from Fig. 3 that with both NBI and TIN, the proposed two schemes can achieve more than 2 dB and 1 dB gain compared to those of block interleaving and random interleaving, respectively, under the AWGN channel in both 16QAM and 64QAM. Results in Fig. 3 indicate that the proposed two criteria and the optimized interleaver designed according to them have remarkable advantages over the counterparts.

In Fig. 4, it is shown that under AWGN channel with only NBI, the proposed ***Criterion 1&2*** scheme is the best among the three schemes, with more than 1dB gain in 16QAM and 0.7dB gain in 64QAM. This verifies the effectiveness of ***Criterion 2*** and the row shifting in sub-matrix operation in improving the anti-NBI capabililty, since the other two schemes are not designed by ***Criterion 2***. From the theoretical analysis in Section IV and the quantitative analysis in Table I, ξ_F of the proposed ***Criterion 1&2*** scheme is the best among all the three schemes indicating the best anti-NBI capability, which is verified by the results in Fig. 4.

The anti-TIN capability is also verified from Fig. 5, where both the proposed ***Criterion 1*** and the proposed ***Criterion 1&2*** schemes achieve more than 1dB gain at the BER of 10^{-5} in 64QAM, and 0.3dB gain in 16QAM compared with that of conventional block interleaving. Since ξ_T of conventional block interleaving is the poorest in Table I, it is proved that the anti-TIN capability is greatly improved by designing the interleaver block size according to ***Criterion 1***.

The BER performances under the PLC multi-path channel are also depicted in Fig. 6, 7 and 8. Similarly, it is observed from Fig. 6 that considering non-ideal practical channel estimation with both NBI and TIN, the proposed two schemes

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2365579, IEEE Transactions on Power Delivery

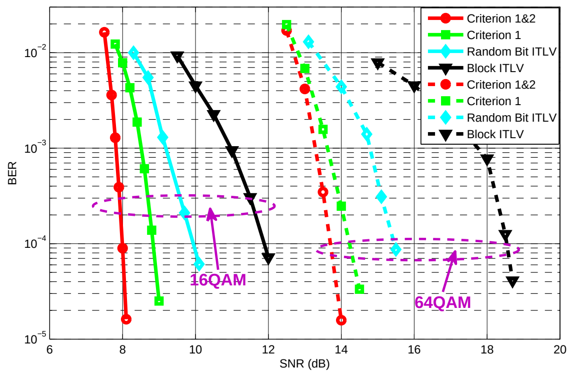

Fig. 3. BER performance under AWGN with NBI and TIN.

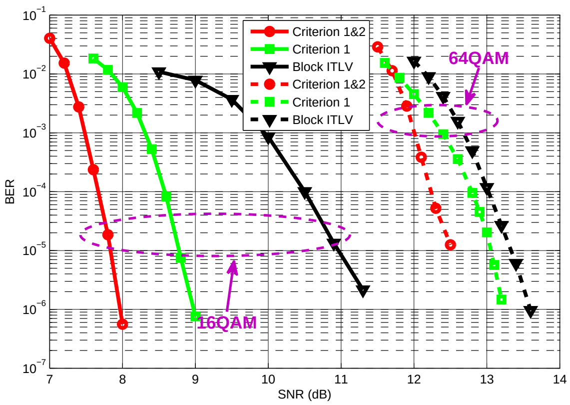

Fig. 4. BER performance under AWGN with only NBI.

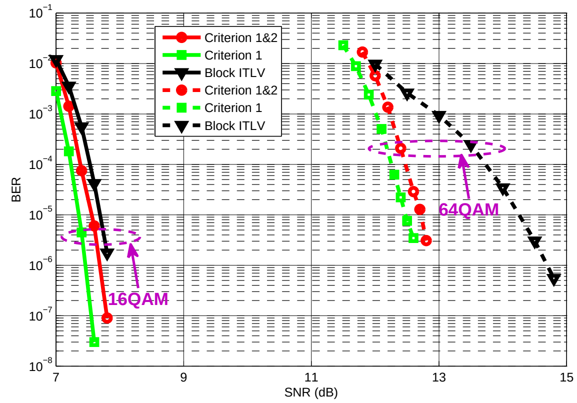

Fig. 5. BER performance under AWGN with only TIN.

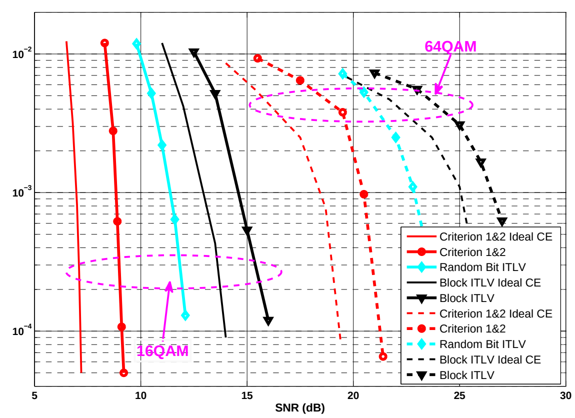

Fig. 6. BER performance under PLC channel with NBI and TIN.

can achieve more than 4 dB and 2 dB gain over the block and random interleaving schemes, respectively, at the BER of 10^{-4} under the PLC multi-path fading channel in 16QAM and 64QAM. It is also noted that with ideal channel knowledge, the proposed interleaving scheme has a slightly larger gain over its counterparts compared to the case with non-ideal practical channel estimation at the receiver. However, with non-ideal channel estimation, the proposed optimization criteria still work well and significantly outperforms its counterparts. It can also be noted from Fig. 7 that the proposed scheme outperforms block interleaving by more than 3dB and 4dB in 16QAM and 64QAM at the target BER of 10^{-4}, which indicates that the proposed scheme is capable of mitigating NBI impacts under frequency-selective fading channels. The anti-TIN capability can be also verified through Fig. 8, where the BER performance of the proposed scheme outperforms block interleaving by more than 2.4dB and 3.7dB in 16QAM and 64QAM at the BER of 10^{-4}.

The simulation results are all consistent with the previous theoretical analysis and the quantitative analysis of the merit factors ξ_T and ξ_F in Table I and the duo-distances d_1 and d_2 in Table II, which proves the validity of the proposed two criteria and the effectiveness and robustness of the optimal interleaving scheme designed based on them.

VI. Conclusion

In this paper, an optimized time-frequency interleaving scheme is proposed, which employs the block size optimization to improve the anti-TIN capability, and a simple row shifting in sub-matrix operation to optimize the performance in the presence of NBI. Two criteria to maximize the time and frequency diversity are set up in the optimization process. Through both quantitative analysis and simulation results, it is derived that the proposed schemes can achieve better anti-NBI and anti-TIN capabilities than the conventional scheme with shorter interleaving delay and less complexity. The proposed scheme is expected to provide a simple and efficient interleaving method for OFDM-based PLC systems to combat against NBI and TIN in practice, and is theoretically applicable to other channel environments with NBI and/or TIN.

References

[1] A. Sarafi, A. Drougas, and P. Cottis, "Cross-layer resource allocation in medium-voltage broadband over power-line networks," *IEEE Trans. Power Del.*, vol. 27, no. 4, pp. 2247–2254, Oct. 2012.

[2] P. Lopes, J. Pinto, and J. Gerald, "Dealing with unknown impedance and impulsive noise in the power-line communications channel," *IEEE Trans. Power Del.*, vol. 28, no. 1, pp. 58–66, Jan. 2013.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2365579, IEEE Transactions on Power Delivery

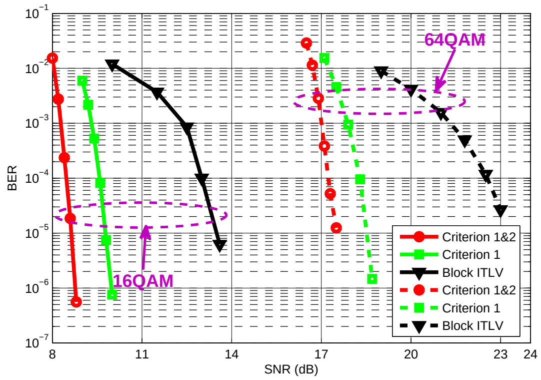

Fig. 7. BER performance under PLC channel with only NBI.

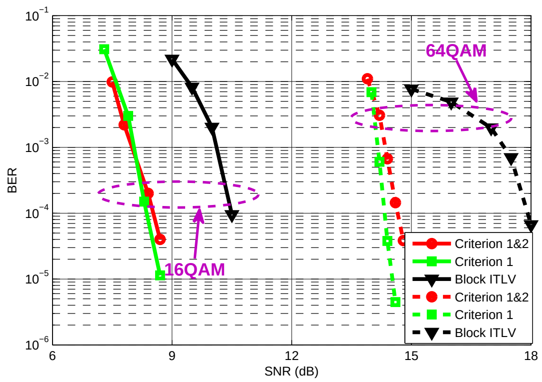

Fig. 8. BER performance under PLC channel with only TIN.

[3] T. Papadopoulos, C. Kaloudas, A. Chrysochos, and G. Papagiannis, "Application of narrowband power-line communication in medium-voltage smart distribution grids," *IEEE Trans. Power Del.*, vol. 28, no. 2, pp. 981–988, Apr. 2013.

[4] A. Sarafi, G. Tsiropoulos, and P. Cottis, "Hybrid wireless-broadband over power lines: a promising broadband solution in rural areas," *IEEE Commun. Mag.*, vol. 47, no. 11, pp. 140–147, Nov. 2009.

[5] J. Song, Z. Yang, L. Yang, K. Gong, C. Pan, J. Wang, and Y. Wu, "Technical review on Chinese digital terrestrial television broadcasting standard and measurements on some working modes," *IEEE Trans. Broadcast.*, vol. 53, no. 1, pp. 1–7, Mar. 2007.

[6] L. Dai, Z. Wang, and Z. Yang, "Next-generation digital television terrestrial broadcasting systems: Key technologies and research trends," *IEEE Commun. Mag.*, vol. 50, no. 6, pp. 150–158, Jun. 2012.

[7] X. Zhou, F. Yang, and J. Song, "Novel transmit diversity scheme for TDS-OFDM system with frequency-shift m-sequence padding," *IEEE Trans. Broadcast.*, vol. 58, no. 2, pp. 317–324, Jun. 2012.

[8] F. Yang, K. Yan, C. Pan, and J. Song, "PAPR reduction for systems using SRRC filters based on modified ACE," *IEICE Trans. Funda.*, vol. E96-A, no. 7, pp. 1675–1677, Jul. 2013.

[9] L. He, F. Yang, C. Zhang, and Z. Wang, "PAPR reduction for systems using SRRC filters based on modified ACE," *IEEE Trans. Consum. Electron.*, vol. 56, no. 4, pp. 2141–2147, Nov. 2010.

[10] *ITU G.9960, Unified High-Speed Wire-Line Based Home Networking Transceivers - System Architecture and Physical Layer Specification*, ITU-T Std., Jun. 2010.

[11] M. Zimmermann and K. Dostert, "A multipath model for the powerline channel," *IEEE Trans. Commun.*, vol. 50, no. 4, pp. 553–559, Apr. 2002.

[12] M. Marey and H. Steendam, "Analysis of the narrowband interference effect on OFDM timing synchronization," *IEEE Trans. Signal Process.*, vol. 55, no. 9, pp. 4558–4566, Sep. 2007.

[13] A. Mehboob, L. Zhang, and J. Khangosstar, "Adaptive impulsive noise mitigation using multi mode compressive sensing for powerline communications," in *IEEE ISPLC' 12*, Mar. 2012, pp. 368–373.

[14] D. Wang, "On design of interleavers with practical size for turbo codes," in *IEEE ICC' 00*, Jun. 2000, pp. 618–622.

[15] Y. Pan, K. B. Letaief, and Z. Cao, "MIMO/OFDM with adaptive interleaved beamforming and power allocation for high-capacity wireless access," in *IEEE VTC' 04*, May 2004, pp. 1906–1910.

[16] *Digital Video Broadcasting (DVB); Framing structure, channel codingand modulation for a second generation digital terrestrial television-broadcasting system (DVB-T2)*, ETSI EN 302 755 Std., Sep. 2009.

[17] A. Al-Dweik, A. Hazmi, B. Sharif, and C. Tsimenidis, "Efficient interleaving technique for OFDM system over impulsive noise channels," in *IEEE PIMRC' 10*, Sep. 2010, pp. 167–171.

[18] P. Amirshahi, S. M. Navidpour, and M. Kavehrad, "Performance analysis of OFDM broadband communications system over low voltage power-line with impulsive noise," in *IEEE ICC' 06*, Jun. 2006, pp. 367–372.

[19] S. Ramseier, "Shuffling bits in time and frequency: an optimum interleaver for OFDM," in *IEEE ICC' 03*, May 2003, pp. 3418–3422.

[20] J. Zhang and J. Meng, "Noise resistant OFDM for power-line communication systems," *IEEE Trans. Power Del.*, vol. 25, no. 2, pp. 693–701, Apr. 2010.

[21] D. Darsena, G. Gelli, L. Paura, and F. Verde, "NBI-resistant zero-forcing equalizers for OFDM systems," *IEEE Commun. Lett.*, vol. 9, no. 8, pp. 744–746, Aug. 2005.

[22] L. Lampe, "Bursty impulse noise detection by compressed sensing," in *IEEE ISPLC'11*, Apr. 2011, pp. 29–34.

[23] M. Nassar, K. Gulati, Y. Mortazavi, and B. Evans, "Statistical modeling of asynchronous impulsive noise in powerline communication networks," in *IEEE GLOBECOM' 11*, Dec. 2011, pp. 1–6.

[24] D. Middleton, "Statistical-physical models of electromagnetic interference," *IEEE Trans. Electromagn. Compat.*, vol. 19, no. 3, pp. 106–127, Aug. 1977.

[25] N. Andreadou and F. Pavlidou, "Modeling the noise on the OFDM power-line communications system," *IEEE Trans. Power Del.*, vol. 25, no. 1, pp. 150–157, Jan. 2010.

[26] D. Umehara, H. Yamaguchi, and Y. Morihiro, "Turbo decoding in impulsive noise environment," in *IEEE GLOBECOM' 04*, Nov. 2004, pp. 194–198.

[27] R. Schober and L. Lampe, "Sequence detection and adaptive channel estimation for ISI channels under class-a impulsive noise," *IEEE Trans. Commun.*, vol. 52, no. 9, pp. 1523–1531, Sep. 2004.

[28] M. Zimmermann and K. Dostert, "Analysis and modeling of impulsive noise in broad-band powerline communications," *IEEE Trans. Electromagn. Compat.*, vol. 44, no. 1, pp. 249–258, Feb. 2002.

Sicong Liu received his B.S.E. in electronic engineering from Tsinghua University, Beijing, China. Currently, he is pursuing the Ph.D. degree in electronic engineering in Tsinghua University. His research interests include power line communications and interference mitigation.

Fang Yang received his B.S.E. and Ph. D. degree in 2005 and 2009, respectively, from the Department of Electronic Engineering in Tsinghua University, Beijing China. Currently, he is working as an associate professor at the DTV Technology R&D Center, Tsinghua University. His research interests lie in the field of channel estimation and interference cancellation for digital wireless communication system, space-time coding and diversity techniques, as well as the training sequence design. He is a Senior Member of IEEE.

Jian Song received his B. Eng and Ph. D. degrees in Electrical Engineering both from Tsinghua University, Beijing China in 1990 and 1995, respectively and worked for the same university upon his graduation. He has worked at The Chinese University of Hong Kong and University of Waterloo, Canada in 1996 and 1997, respectively. He has been with Hughes Network Systems in USA for 7 years before joining the faculty team in Tsinghua in 2005 as a professor. He is now the director of Tsinghua's DTV Technology R&D center. He has been working in quite different areas of fiber-optic, satellite and wireless communications, as well as the power line communications. His current research interest is in the area of digital TV broadcasting. Dr. Song has published more than 110 peer-reviewed journal and conference papers. He holds two US and more than twenty Chinese patents. He is a Senior Member of IEEE and a Fellow of IET.