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OFDM Preamble Design for Synchronization Under Narrowband Interference

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***Abstract*—In this paper, an OFDM-based preamble is proposed for improving timing and frequency synchronization in the power line channel with narrowband interference (NBI) as well as transmitting several bits of transmission parameter signaling (TPS). In the time domain, an additional scrambling operation is applied to the cyclic extension of an OFDM training symbol to reduce the impact of NBI. Compared to the conventional Schmidl's and Minn's methods, the proposed preamble could provide even sharper correlation peak and achieve better timing detection in both AWGN and power line multipath channels under NBI, with a moderate complexity increase because more correlation and multiplication operations are required. Furthermore, the proposed preamble could also convey several bits of TPS via the variable distance of two training sequences allocated in the frequency domain. Better synchronization results can be achieved through analyses and simulations with the proposed method.**

***Index Terms*—Narrowband interference (NBI), power line communications (PLC), OFDM preamble design, synchronization.**

I. INTRODUCTION

Recently, there have been more and more researches on digital communications in power line channels, in which there is more convenience and more communication resources for transmission. Power line communication (PLC) has many advantages over other transmission approaches, such as the prevailing electrical wiring networks, relatively low costs, the convenience to plug in and etc. However, power line channels suffer a poor channel circumstance and can encounter severe noise, high attenuation and various interferences, such as impulse noise, multipath fading, frequency selectivity and narrowband interference (NBI) [1]–[3].

In order to combat the severe channel conditions in power line communications, orthogonal frequency division multiplexing (OFDM) has been chosen as an effective physical layer modulation technique in power line channels [4], [5]. Due to its high transmission efficiency, simple implementation and especially the good performance to overcome frequency selectivity, OFDM has been adopted by many different communication systems, including the power line communication system of ITU G.9960 standard [4], wireless local area network (WLAN) [6], [8], digital video broadcasting (DVB) [7], [9],and etc.

In OFDM systems, a reliable and efficient communication relies on good synchronization performance, which has been investigated for long [10]- [16]. Several methods have been proposed for preamble design and synchronization for OFDM systems. In literature [10], the classical sliding auto-correlation (SAC) method was proposed based on the cyclic prefix (CP). In [11], Schmidl proposed a preamble structure having two identical parts by using only even carriers in the frequency domain, which has been adopted into WLAN-based standards IEEE 802.11g [8] and WMAN-based standards IEEE 802.16e [17]. However, the SAC of this preamble produces a broad plateau around the correct timing position, which would cause ambiguity when determining the best start sample point, especially when the timing offset is beyond the scope of the length of CP so that the following operation cannot recover the right timing position. To solve this problem, Minn proposed a time-domain structure like $[\mathbf{A}\ \mathbf{A} - \mathbf{A} - \mathbf{A}]$ to reduce the plateau and sharpen the correlation peak [12]. However, the correlation result in Minn's method also introduces several sub-peaks, which might cause high false detection probability when the signal-to-noise ratio (SNR) of the channel is relatively low. Synchronization performances of the above three methods under realistic indoor PLC channel models are presented in [15]. A practical approach of preamble design in fast burst synchronization for the PLC system under some specified constraints is proposed in literature [16].

Furthermore, there is usually severe NBI in power line channels, which has a serious impact on communication reliability and synchronization. However, the above three synchronization methods could be severely deteriorated by NBI environments [18], [19]. Current methods for synchronization under NBI are not applicable and not effective. In this paper, an effective synchronization method is proposed to well solve the problem for OFDM systems under NBI.

OFDM systems usually support different symbol constellation types and channel coding rates in order to meet different quality-of-service (QoS) requirements. Therefore, the transmission parameter signaling (TPS) can facilitate the succeeding channel estimation [20]–[22], and is critical for the receiver to demodulate the received data correctly. In the existing commercialized systems such as IEEE 802.11g and IEEE 802.16e, the TPS is transmitted separately following the preamble. After the timing and frequency synchronization have been accomplished, the receiver could then move to decode the signaling part. Recently, a novel method has been proposed to integrate the basic TPS into the preamble, which could significantly facilitate the demodulation steps [23], [24].

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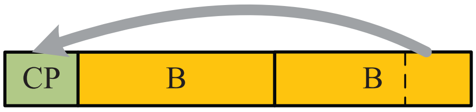
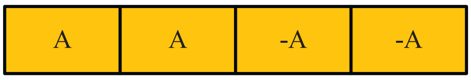


(a) Schmidl's method



(b) Minn's method

Fig. 1. Conventional OFDM preamble designs.

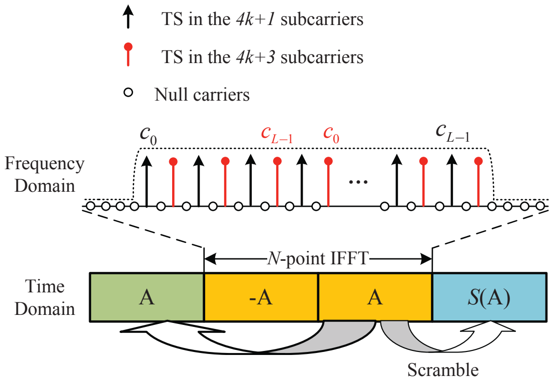


Fig. 2. Proposed OFDM preamble design.

In this paper, an OFDM-based preamble with improved time-domain structure is proposed, which inherits the merits of both Schmidl's and Minn's methods. Additionally, a novel scrambling operation is applied to the cyclic extension of the OFDM symbol in order to reduce the impact of NBI, which is usually encountered in power line channels. Furthermore, in the frequency domain, unlike the signaling method in [23] which adopts two consecutive blocks of training sequences (TSs), the two identical TSs are distributed alternately in the active sub-carriers to achieve diversity gain under the frequency-selective fading channels. The relative distance between the two TSs could be varied in order to indicate several bits of signaling information for the receiver to acquire the basic transmission parameters quickly.

The rest of this paper is organized as follows. Section II briefly introduces the OFDM signal model and reviews the two most popular conventional preamble designs. Section III and Section IV presents the proposed preamble design and the corresponding detection algorithm, respectively. The performance of the proposed preamble is evaluated by computer simulation in Section V. Finally, Section VI concludes the whole paper.

II. SIGNAL MODEL

The OFDM symbol is generated by an N-point inverse fast Fourier transform (IFFT) of the modulated data symbols $\{X_k\}$,

$$x_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k \cdot e^{j\frac{2}{\ }nk}. \tag{1}$$

Considering the channel delay spread, additive white Gaussian noise (AWGN), carrier frequency offset (CFO) and NBI, the received signal is modeled as [18],

$$r_n = \sum_{l=0}^{L\ \ -1} h_l \cdot x_{n-n_0-l} \cdot e^{j2\pi nf\ } + I_0 \cdot e^{j2\pi nf_{\mathrm{CW}}} + \nu_n, \tag{2}$$

where n_0, f_c and ν_n are the unknown symbol arrival time, CFO and AWGN, respectively. $\{h_l\}$ is the channel impulse response (CIR), which is modeled by L_h discrete weighted impulses. I_0 is the amplitude of the NBI at the frequency point f_{CW}. The CFO is usually normalized by the sub-carrier spacing $1/N$, i.e., $f_c = k_0/N + f_{\mathrm{frc}}$, where k_0 is an integer and f_{frc} is the residual fractional part of CFO.

The task of the synchronization process is to determine the timing position and estimate CFO without any knowledge of prior channel state information. To achieve this goal, Schmidl proposed a preamble structure having two identical parts as illustrated in Fig. 1(a) by using only even carriers in the frequency domain [11]. The SAC operation for timing and frequency synchronization is based on the two cyclic parts '**B**', which could provide higher robustness than common CP-OFDM symbols. However, the SAC of such preamble will produce a broad plateau around the correct timing position due to the insertion of CP. The plateau would cause ambiguity when determining the best timing sample point.

To reduce the plateau, Minn proposed a novel time-domain structure like $[\mathbf{A}\ \mathbf{A} - \mathbf{A} - \mathbf{A}]$, as illustrated in Fig. 1(b) [12]. With the deliberate design of two opposite parts, Minn's method could sharpen the correlation peak compared to Schmidl's method. However, the correlation in Minn's method introduces several sub-peaks, which might cause high false detection probability when the SNR is low.

Considering an NBI at the frequency point f_{CW}, the conventional SAC based on two identical parts is given as (ignore the noise and channel terms for simplicity),

$$\begin{aligned} R_c &= \sum_{l=0}^{L\ \ -1} r_l \cdot r_{l+N}^{*} \\ &= \sum_{l=0}^{L\ \ -1} \left(x_l + I_0 e^{j2\pi f_{\mathrm{CW}} l}\right) \cdot \left(x_l + I_0 e^{j2\pi f_{\mathrm{CW}}(l+N\ )}\right)^{*} \\ &= \sum_{l=0}^{L\ \ -1} \Big(|x_l|^2 + I_0 x_l e^{-j2\pi f_{\mathrm{CW}}(l+N\ )} \\ &\qquad + I_0 x_l^{*} e^{j2\pi f_{\mathrm{CW}} l} + I_0^2 e^{-j2\pi f_{\mathrm{CW}} N\ }\Big) \\ &\approx \sum_{l=0}^{L\ \ -1} |x_l|^2 + L_c \cdot I_0^2 e^{-j2\pi f_{\mathrm{CW}} N} \end{aligned}, \tag{3}$$

where L_c and N_c denote the length of the identical parts and the correlation lag, $(\cdot)^*$ denotes the complex conjugation. Since $\{x_l\}$ and $\{e^{j2\pi f_{\mathrm{CW}} l}\}$ are non-coherent, the rest terms in (3) are eliminated after sum averaging. It is observed from (3) that the unpredictable NBI might deteriorate the correlation peak and thus degrade the detection performance.

III. PROPOSED PREAMBLE DESIGN

The proposed preamble is composed of a length-N OFDM symbol with its two cyclic extensions, as illustrated in Fig. 2. In the frequency domain, a pair of TSs are alternatively inserted in the $\{4k+1\}$ and $\{4k+3\}$ indexed sub-carriers. The TS in the $\{4k+1\}$ sub-carriers is located at the fixed position, while the TS in the $\{4k+3\}$ sub-carriers is cyclically right shifted by ΔL, i.e.,

$$\begin{cases} Y_{4k+1} = c_k, & k = 0, 1, \cdots, L-1 \\ Y_{4k+3} = c_{(k-\Delta L) \bmod L}, & k = 0, 1, \cdots, L-1 \\ Y_k \quad = 0, & others \end{cases}, \tag{4}$$

where c_k is the length-L ($L<N/4$) pseudo-random TS with good auto-correlation property. mod denotes the modular operation. The cyclical shift length ΔL could be varied in order to indicate different signaling information. There are L choices in total for the shift length corresponding to $\log_2 L$ bits of signaling.

The active sub-carriers in (4) are then differentially encoded and transformed to the time domain by N-point IFFT operation defined in (1). Since only odd sub-carriers are used, the time-domain OFDM symbol is divided into two opposite parts, denoted as '-**A**' and '**A**' in Fig. 2. The last half part '**A**' is copied to the front as CP and also copied to the rear multiplying with a scrambling sequence $(-1)^n$. The transmitted time-domain signal is thus represented as

$$p_n = \begin{cases} x_{n+N/2}, & 0 \le n < N/2 \\ x_{n-N/2}, & N/2 \le n < 3N/2 \\ (-1)^n \cdot x_{n-N}, & 3N/2 \le n < 2N \end{cases}. \tag{5}$$

The scrambling operation could effectively reduce the impact of the NBI, which will be further discussed in the following section.

IV. PREAMBLE DETECTION ALGORITHM

In this section, both timing and frequency synchronization as well as signaling detection algorithms are detailed to illustrate the advantages of our proposed design over the conventional Schmidl's and Minn's methods.

A. Timing and fractional CFO estimation

The timing algorithm adopts the cyclic properties of the proposed preamble, where three cyclic parts are observed and used for SACs,

$$R_{1,n} = \sum_{l=0}^{N/2-1} (-1)^{(n+l)} r_{n+l}^* \cdot r_{n+l-N/2}, \tag{6}$$

$$R_{2,n} = \sum_{l=0}^{N/2-1} (-1)^{(n+l)} r_{n+l}^* \cdot r_{n+l-N}, \tag{7}$$

$$R_{3,n} = \sum_{l=0}^{N/2-1} (-1)^{(n+l)} r_{n+l}^* \cdot r_{n+l-3N/2}. \tag{8}$$

The multiplication with $(-1)^n$ in the summation of (6)-(8) is the de-scrambling operation between the three front parts and the last part '**S(A)**' of the preamble in Fig. 2. Finally, the above three correlation results are multiplied together to strengthen the correlation peak,

$$R_{c,n} = -R_{1,n}^* \cdot R_{2,n} \cdot R_{3,n}. \tag{9}$$

Unlike the conventional SAC methods, a de-scrambling operation $(-1)^n$ is firstly applied to the received signal. Since the summations in (6)-(8) could be implemented with recursive method [11], the complexity of the proposed algorithm is low. Moreover, the correlation operations here are approximately 50% more than those in Minn's method with the same preamble length, since three pairs of correlation are calculated in the proposed method while only two pairs are needed in Minn's method.

The correlation peak of $R_{c,n}$ indicates the start of the preamble and the fractional CFO is also obtained through the phase of the peak,

$$\hat{n}_0 = \arg\max_n \left\{ |R_{c,n}| \right\}, \tag{10}$$

$$\hat{f}_{frc} = \left. \frac{\arg\left(R_{c,n}\right)}{2\pi N} \right|_{n=\hat{n}_0}, \tag{11}$$

where $\arg\max\{\cdot\}$ denotes the set of variables that maximize the objective function, and $\arg(\cdot)$ denotes the phase of a complex number.

Simulation examples of the SAC for Schmidl's, Minn's and the proposed methods without channel noise are illustrated in Fig. 3. A broad plateau with the duration of CP is observed in Schmidl's method, while four sub-peaks about one-fourth height of the main peak are introduced in Minn's method. It is noted that the proposed method could avoid either plateau or sub-peaks and obtain even sharper peak than Minn's method.

Considering an NBI at the frequency point f_{CW}, the auto-correlation branch R_1 in (6) with de-scrambling operation is given as,

$$\begin{aligned} R_{1,\hat{n}_0} &= \sum_{l=0}^{N/2-1} (-1)^l \left((-1)^l x_l + I_0 e^{j2\pi f_{\mathrm{CW}} l} \right)^* \\ &\quad \cdot \left(x_l + I_0 e^{j2\pi f_{\mathrm{CW}}(l-N/2)} \right) \\ &= \sum_{l=0}^{N/2-1} \Big(|x_l|^2 + (-1)^l I_0 x_l^* e^{j2\pi f_{\mathrm{CW}}(l-N/2)} \\ &\quad + (-1)^l I_0 x_l e^{-j2\pi f_{\mathrm{CW}} l} + (-1)^l I_0^2 e^{-j2\pi f_{\mathrm{CW}} N/2} \Big) \\ &\approx \sum_{l=0}^{N/2-1} |x_l|^2 \end{aligned}. \tag{12}$$

Similarly, the correlation branches R_2 and R_3 in (7)-(8) are respectively given as

$$R_{2,\hat{n}_0} \approx -\sum_{l=0}^{N/2-1} |x_l|^2, \tag{13}$$

$$R_{3,\hat{n}_0} \approx \sum_{l=0}^{N/2-1} |x_l|^2. \tag{14}$$

From (12)-(14), it is observed that the NBI would be eliminated after sum averaging due to the scrambling operation. Therefore, the proposed timing method is robust to NBI.

B. Integer CFO estimation and signaling detection

After the timing synchronization is accomplished, the received OFDM symbol is compensated with the estimated fractional CFO and then transformed into frequency domain

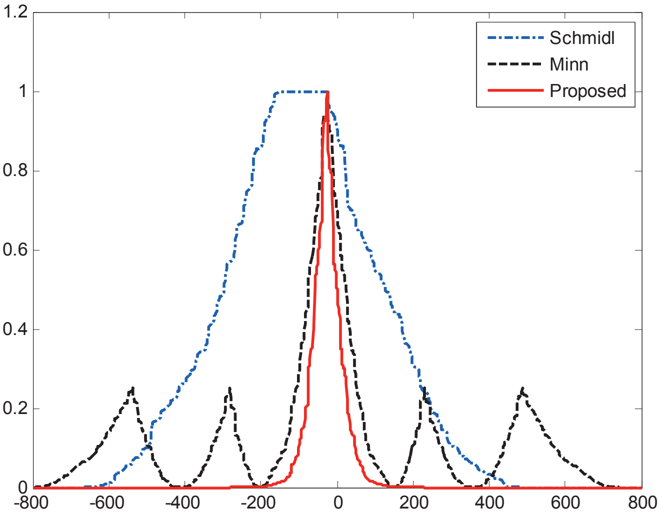


Fig. 3. Comparison for timing peaks of three methods.

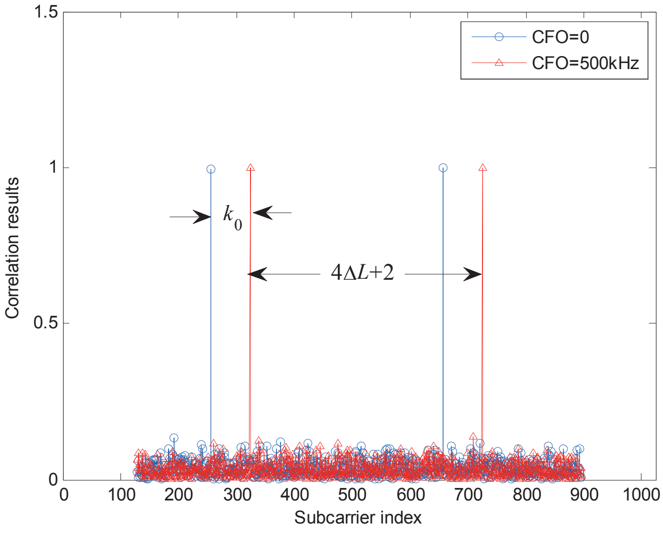


Fig. 4. Frequency-domain correlation results with different CFOs.

by N-point FFT operation. The received active carriers are denoted as

$$\hat{Y}_k^{(d)} = Y_{k-k_0}^{(d)} H_{k-k_0} e^{-j\frac{2}{\ }\Delta n\cdot k} + N\cdot I_0\cdot\delta_{k-k_{\mathrm{CW}}} + V_k, \quad (15)$$

where $Y_k^{(d)}$ is the transmitted active carrier after differential encoding operation, while H_k and V_k are the channel frequency response and the frequency domain noise term. δ_k is the Kronecker-delta function. k_{CW} is the sub-carrier index at the frequency point f_{CW}. Δn is the timing error which causes a phase rotation of the active carriers. It is noted that the integer part of CFO k_0 leads to a shift of all carriers.

The NBI could be easily removed in the frequency domain by setting the carriers with excessively large power to zero. After that, a differential decoding operation is applied to the received active carries and yields

$$\begin{aligned} Z_k &= \hat{Y}_k^{(d)}\cdot\hat{Y}_{k-2}^{(d)*} \\ &= H_{k-k_0}H_{k-k_0-2}^{*}\cdot Y_{k-k_0}e^{j\frac{2}{\ }2\Delta n} + \tilde{V}_k \ , \\ &\approx |H_{k-k_0}|^2 Y_{k-k_0}e^{j\frac{2}{\ }2\Delta n} + \tilde{V}_k \end{aligned} \quad (16)$$

where $\tilde{V}_k$ is the sum of residual noise terms. The approximation in (16) holds when the adjacent sub-carriers are closely similar in the frequency-selective fading channels.

Due to the differential decoding operation, the phase rotation caused by the timing error is canceled, leaving only a fixed phase offset. Therefore, the proposed method is also robust to timing errors.

The integer CFO and the signaling information could be simultaneously detected by the cross correlation between the received differentially decoded sub-carriers and the local TS, i.e.,

$$R_{d,k} = \frac{\sum_{l=0}^{L-1} Z_{(k+4l) \bmod 4L}\cdot c_l^*}{\sum_{l=0}^{L-1}\left|\hat{Y}_{(k+4l) \bmod 4L}\right|^2}, \quad 0\le k<N. \quad (17)$$

The correlation in (17) is expected to generate two peaks, as illustrated in Fig. 4. The integer CFO could be estimated through the shift of the first peak from its reference position when CFO=0, while the signaling is inferred from the distance between those two peaks.

V. PERFORMANCE EVALUATION

In this section, computer simulations are implemented to evaluate the performance of the proposed preamble. The simulation parameters are given in Table I. The length of TS is chosen to be 192, and could be used to indicate at least 7-bit of signaling information. A multipath PLC channel model [25] with NBI is adopted to evaluate the detection algorithm in power line transmission and reception scenarios. The parameter profile of the PLC channel is listed in Table II. An NBI with the power of -12 dB compared to the signal average power is also introduced in the simulations.

TABLE I
SIMULATION PARAMETER.

Parameter	**Value**
Carrier Frequency	6 MHz
Bandwidth	8 MHz
Symbol Rate	7.56 MSymbol/s
FFT Size	1024
Length of TS	192
Symbol Duration	270.9 us
CFO	30 kHz
NBI power	-12 dB

TABLE II
PLC CHANNEL PARAMETER PROFILE.

Path Index	$d_i(m)$	g_i		
1	200	0.64	k	1.0
2	222.4	0.38	$a_0(s/m)$	0
3	244.8	-0.15	$a_1(s/m)$	7.8×10^{-10}
4	267.5	0.05		

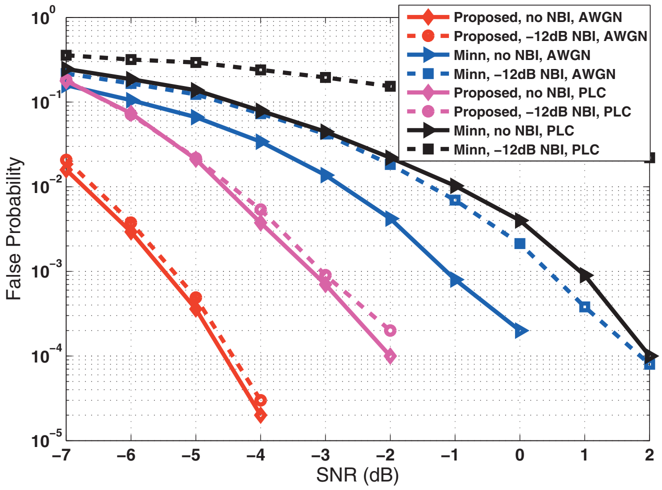


Fig. 5. False probability of preamble detection in AWGN and PLC channels when the missed probability is around 10^{-3}.

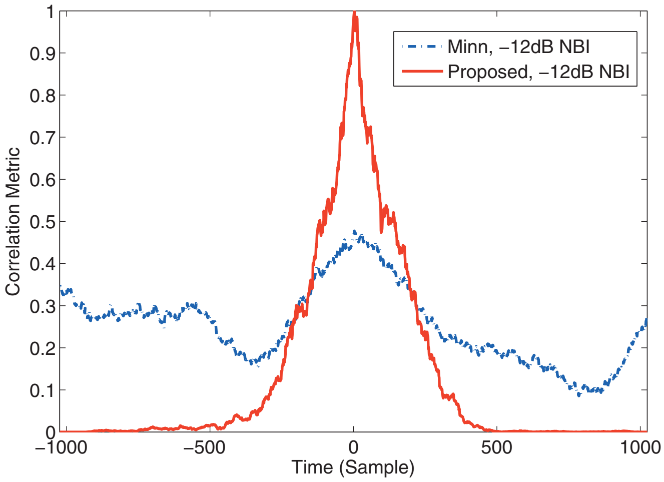


Fig. 6. Timing correlation peaks for two methods under NBI.

Firstly, the detection performance of the preamble is evaluated by the false probability and the missed probability of the SAC peak detection. The false probabilities of Minn's method and the proposed method are compared in Fig. 5 when the missed probability is required at a level of 10^{-3}.The false detection probability of the proposed preamble is improved by about 4dB compared to Minn's method in both AWGN and PLC channels when there is no NBI, with the cost of more correlation and multiplication operations than Minn's method. When the -12dB NBI is considered (marked with dashed lines in Fig. 5), it is noted that Minn's method degrades more than 1 dB in AWGN channel and more than 4 dB in the PLC channel, while the proposed method is hardly affected.

Concerning the impact of the introduction of NBI on timing detection performance, simulation results of the SAC for Minn's and the proposed methods under the -12dB NBI in the power line channel are illustrated in Fig. 6 in comparison with those in Fig. 3. The timing correlation peak in Minn's method under the -12dB NBI is much smaller than that without NBI, as is illustrated in Fig. 3. Furthermore, the sub-peaks in Minn's method are higher and the central peak is not as sharp as that without NBI, which is much likely to cause timing detection errors. However, the peak is hardly affected by the -12dB NBI in the proposed method, thus achieving as good performance of timing detection as that without NBI.

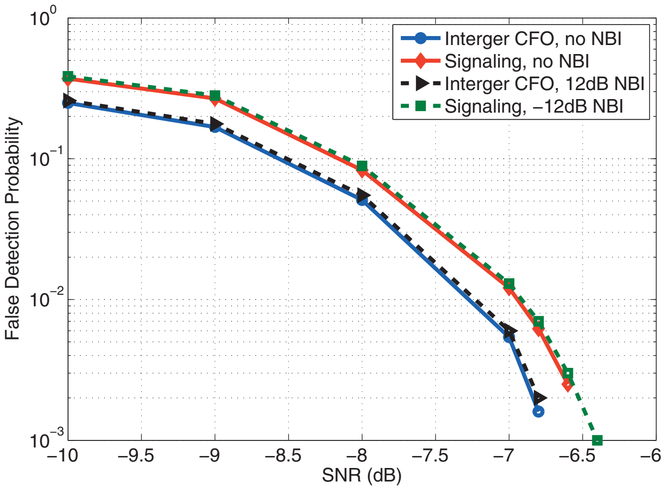


Fig. 7. False probability of integer CFO estimation and signaling detection.

The false probabilities of the integer CFO estimation and signaling detection are depicted in Fig. 7. From Fig. 4 and Fig. 7, it's observed that both integer CFO and signaling could be well estimated if the preamble is detected. It should be pointed out that, only if both peaks are detected then the signaling could be decoded correctly. Therefore, the false probability of signaling detection $P_{f,\text{Sig}}$ and the false probability of integer CFO estimation $P_{f,\text{IntCFO}}$ approximate the following equation,

$$P_{f,\text{Sig}} = 1 - (1 - P_{f,\text{IntCFO}})^2. \qquad (18)$$

The simulation results in Fig. 7 are aligned with the above analysis.

VI. CONCLUSION

An OFDM-based preamble has been designed for improving timing and frequency synchronization as well as robust signaling information transmission in the power line channels with NBI. Compared to conventional Schmidl's and Minn's methods, the proposed preamble could achieve better timing synchronization performance with a moderate cost of complexity. With a simple scrambling operation, the proposed preamble could effectively combat the narrowband interference in power line channels. Furthermore, by using special designed sub-carrier pattern, the preamble could also convey several bits of signaling for the receiver to acquire the basic transmission parameters quickly. Simulation results verify that the proposed preamble design is applicable in power line communication channels.

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