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Pseudo pilot-aided OFDM system with high spectral efficiency for high performance coaxial transmission

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Abstract High performance network over coax (HINOC) has become next-generation broadcasting network (NGB) industry standard of China, as well as International Telecommunication Union (ITU) telecommunication standard, which adopts orthogonal frequency division multiplexing (OFDM) technique and high order modulation formats. As is known, in OFDM system, phase noise destroys the orthogonality of the subcarriers and degrades the performance of the system especially when the data are transmitted in high order modulation formats. In this paper, we propose a high spectral efficiency OFDM system utilizing a novel and almost blind phase noise compensation method mainly used for high performance coaxial transmission. In our system, some subcarriers, which remain to transmit unknown useful data in lower order modulation formats, are selected as pseudo pilots instead of pilots to suppress phase noise effectively and high spectral efficiency can be achieved with the aid of puncturing mechanisms. Simulation results show that the proposed pseudo pilot-aided OFDM system can achieve the performance of the pilot-aided counterpart yet acquiring higher spectral efficiency.

Keywords orthogonal frequency division multiplexing (OFDM), high performance network over coax (HINOC), phase noise, pseudo pilots, broadcasting

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1 Introduction

Orthogonal frequency division multiplexing (OFDM) is a technology that modulates the data on the orthogonal subcarriers to send. Due to its robustness against inter-symbol interference (ISI), flexibility of band distribution and high spectral efficiency, OFDM has been widely used in broadband digital communications, such as wireless or coaxial digital television and radio systems, wireless networks and long time evolution (LTE) mobile telecommunication systems.

Among these systems, the coaxial OFDM system has the characters of short transmission distance and good channel environment. So it is possible to transmit data with high modulation formats, such as 1024 quadrature amplitude modulation (QAM) or 4096QAM, and less or no pilots are used to achieve high spectral efficiency. For example, Chinese digital television (DTV) standard digital terrestrial multimedia

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broadcast (DTMB) based on time domain synchronous OFDM (TDS-OFDM) contains no frequency-domain pilots. The designed pseudo noise (PN) sequence is used as a training sequence (TS) for synchronization and channel estimation [1, 2]. These years, our team has made many efforts to study high performance network over coax (HINOC) technique, which performs as an access system over coax and uses OFDM technology. In first generation HINOC, due to the excellent channel environment, weak channel protection and adaptive modulation with the highest modulation format of 1024QAM have been adopted while pilots are not used in order to improve transmission efficiency. Now HINOC has become NGB industry standard of China, as well as ITU telecommunication standard [3–7].

As other technologies for coax communication, HINOC aims to achieve one Gigabit transmission rate which means higher-order modulation format should be used. In this situation, the effects of phase noise will sharply worsen the system performances and have to be taken into account, since compared with single carrier (SC) communication systems, OFDM is more sensitive to phase noise induced by crystal oscillator, especially when the symbol duration is long and the modulation format is of high order [8] .

In OFDM systems, phase noise will cause common phase error (CPE) and inter carrier interference (ICI), which have different effects on different OFDM symbols and subcarriers. The ICI effect behaves like Gaussian noise while CPE rotates the phase of all constellation points in a common direction [9, 10]. So CPE is relative easy to remove, and much attention has been paid to it [11]. For ICI, more efforts are needed and some effective methods are also proposed to suppress it [12–16]. These methods commonly use pilots to suppress the phase noise, which reduces the spectral and transmission efficiency. And for coaxial transmission technique such as HINOC, less or no pilots should be used. In our previous work, we proposed a blind ICI suppression method in coherent OFDM passive optical network (OFDM-PON) [17]. However, the method in [17] is mainly applied in constant modulus or low modulation order OFDM systems. For high order modulation, its performance will degenerate obviously. Besides, it is of some high computation complexity and requires large digital signal processing (DSP) resources. So it cannot be used in coaxial transmission system.

In this paper, we propose a high spectral efficiency OFDM system utilizing a novel and almost blind phase noise compensation method mainly used for high performance coaxial transmission. In this system, almost all the pilot subcarriers are removed to increase the spectral efficiency. The so-called pseudo pilots, are generated by performing lower order modulation to some selected subcarriers. In fact, they are actually data subcarriers that carry information unknown to the receiver. Pseudo pilots are used instead of pilots for phase noise compensation. Besides, coding and puncturing techniques are also used in the proposed system to make up for the transmission efficiency loss induced by the lower order modulation of pseudo pilots.

This paper is organized as follows. In Section 2, we present the structure and theory of the proposed pseudo pilot-aided phase noise compensation method and OFDM system. Section 3 shows the simulation results and discussion. Finally we draw a conclusion in Section 4.

2 The proposed pseudo pilot-aided OFDM system

Figure 1 shows the structure of the proposed pseudo pilot-aided OFDM system. Different from traditional OFDM systems, the puncturing and mapping modules controlled by pseudo pilots configuration module as well as the pseudo pilot-aided OFDM demodulation module have been introduced to attain high spectral efficiency.

2.1 Theory of the pseudo pilot-aided OFDM system

In the following deduction, the proposed OFDM system will be divided into transmitter and receiver to analyze separately.

At the transmitter, the coding schemes such as BCH, Turbo and low density parity check (LDPC) are needed at first. Then, the jth data block $\boldsymbol{d}_j = [d_j(0)\ d_j(1)\ \cdots\ d_j(n-1)]$ will be punctured according to

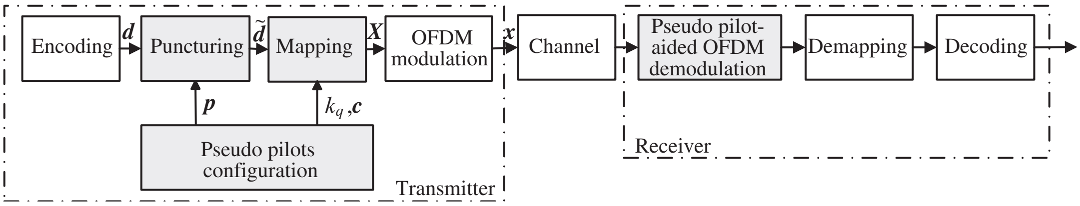

Figure 1 OFDM system with the proposed almost blind phase noise compensation method.

the puncturing vector $\boldsymbol{p} = [p(0)\ p(1)\ \cdots\ p(n-1)]$ as

$$\tilde{\boldsymbol{d}}_j = \boldsymbol{d}_j \odot \boldsymbol{p}, \tag{1}$$

where n denotes the number of bits in every OFDM symbol after encoding module, $\odot$ denotes dot multiplication and the element $p(i)$ $(i = 0, 1, \ldots, n-1)$ equals to 0 or 1. If $p(i)$ equals to 0, the corresponding ith bit will be punctured; otherwise it will be retained, so $\tilde{\boldsymbol{d}}_j$ has $\sum_{i=0}^{n-1} p(i)$ elements. Here $\boldsymbol{p}$ is determined by pseudo pilots configuration module and we can puncture uniformly or just on the head or tail of the data block. Considering the case that pseudo pilots are uniformly inserted in the subcarriers, let k_q denote the index of pseudo pilots and $k_q = k_0 + qD$ $(q = 0, 1, \ldots, M-1)$, where D is the density and M is the number of pseudo pilots. In the mapping module, the data left after puncture are mapped and modulated to different subcarriers according to the mapping vector

$$\boldsymbol{c} = [c\,(0)\ \ c\,(1)\ \cdots\ c\,(N-1)]\,, \tag{2}$$

which together with $\{k_q\}$ $(q = 0, 1, \ldots, M-1)$ are also provided by the pseudo pilots configuration module. Here N denotes the number of subcarriers in a OFDM symbol and $c(i)$ $(i = 0, 1, \ldots, N-1)$ denotes the modulation format of the ith subcarrier is $2^{c(i)}$QAM.

Pseudo pilots are inserted in the mapping module by setting $\{c(k_q)\}$ $(q = 0, 1, \ldots, M-1)$ smaller than data subcarriers, i.e., pseudo pilots are inserted by performing lower order modulation to selected subcarriers compared with the usual data subcarriers. And in order to avoid the reduction of transmission efficiency caused by inserting pseudo pilots, a number of bits should be punctured in the previous module. So $\boldsymbol{p}$, M and $\boldsymbol{c}$ have certain relationship and should be considered together in the pseudo pilots configuration module. For the convenience of analysis, suppose that

$$c(i) = \begin{cases} c(0), & \text{for } i \neq k_q, \\ c(k_0), & \text{for } i = k_q, \end{cases} \tag{3}$$

where $c(0) > c(k_0)$. Then the elements of $\boldsymbol{p}$ satisfy the equation as

$$\sum_{i=0}^{n-1} p\,(i) = n - M[c(0) - c(k_0)], \tag{4}$$

i.e., if $M[c(0) - c(k_0)]$ bits cannot be transmitted caused by inserting pseudo pilots, they should be punctured. And with the aid of decoding technology, the bits punctured will be recovered at the receiver. When adaptive modulation is utilized in the OFDM system, the modulation formats of pseudo pilots and the other subcarriers may not remain the same. According to the SNR of the subcarrier, pseudo pilots configuration can determine the update of $\boldsymbol{p}$, M and $\{c(k_q)\}$ $(q = 0, 1, \ldots, M-1)$ in the same way to achieve the best performance.

Finally, after the conventional OFDM modulation, the jth OFDM symbol $x_j = [x_j(0)\ x_j(1)\ \cdots\ x_j(N-1)]^{\mathrm{T}}$ $(j = 1, 2, \ldots)$ is obtained as

$$x_j(i) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_j(k) \exp\left(-\frac{\mathrm{j}2\pi ki}{N}\right),\ \ i = 0, 1, \ldots, N-1. \tag{5}$$

The superscript T denotes transpose.

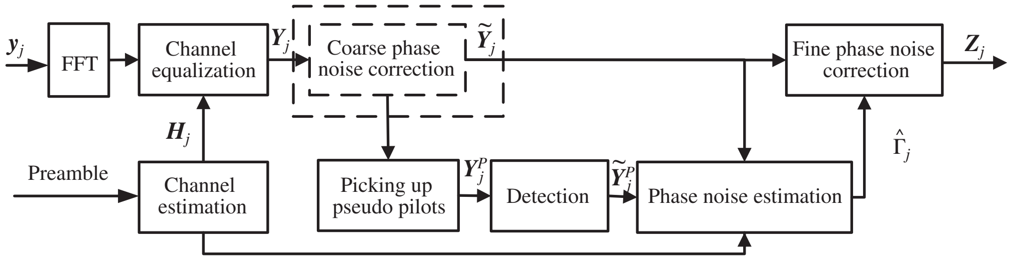

Figure 2 Block diagram of pseudo pilot-aided OFDM demodulation.

At the receiver, assuming a perfect time and frequency synchronization at the receiver and considering a typical coaxial OFDM system, we can obtain the jth received OFDM symbol as

$$\boldsymbol{y}_j = \boldsymbol{\Phi}_j \boldsymbol{T}_j \boldsymbol{x}_j + \boldsymbol{w}_j, \tag{6}$$

where

$$\boldsymbol{\Phi}_j = \mathrm{diag}([\mathrm{e}^{\mathrm{j}\phi_j(0)}\ \mathrm{e}^{\mathrm{j}\phi_j(1)}\ \cdots\ \mathrm{e}^{\mathrm{j}\phi_j(N-1)}]) \tag{7}$$

is a diagonal matrix to describe the phase noise induced by crystal oscillators at both the transmitter and receiver. $\boldsymbol{h}_j = [h_j(0)\ h_j(1)\ \cdots\ h_j(L-1)]$ is the channel impulse response (CIR) vector and $\boldsymbol{T}_j$ here is an $N \times N$ circulant matrix with the first row vector as $[h_j(0)\ 0\ \cdots\ 0\ h_j(L-1)\ h_j(L-2)\ \cdots\ h_j(1)]$. $\boldsymbol{w}_j = [w_j(0)\ w_j(1)\ \cdots\ w_j(N-1)]^{\mathrm{T}}$ denotes the additive white Gaussian noise (AWGN).

The proposed pseudo pilot-aided OFDM demodulation is shown in Figure 2. After FFT, channel equalization should be performed. The necessary estimation of frequency-domain channel transmission matrix $\boldsymbol{H}_j$ can be derived by several time-domain or frequency-domain channel estimation methods [18,19] and the received symbol $\boldsymbol{y}_j$ can be equalized as

$$\boldsymbol{Y}_j = {\boldsymbol{H}_j}^{-1} \boldsymbol{F} \boldsymbol{y}_j, \tag{8}$$

where $\boldsymbol{F} = [\boldsymbol{f}_0\ \boldsymbol{f}_1\ \ldots\ \boldsymbol{f}_{N-1}]^{\mathrm{H}}$ denotes FFT transformation and the superscript H denotes Hermitian transpose. The element $\boldsymbol{f}_m$ is described as

$$\boldsymbol{f}_m = \frac{1}{\sqrt{N}} \left[1\ \mathrm{e}^{\mathrm{j}\frac{2\pi}{N}m}\ \cdots\ \mathrm{e}^{\mathrm{j}\frac{2\pi(N-1)}{N}m}\right]^{\mathrm{T}}. \tag{9}$$

After channel equalization, pseudo pilots are picked up from $\boldsymbol{Y}_j$ to form $\boldsymbol{Y}_j^p = [Y_j(k_0)\ Y_j(k_1)\ \cdots\ Y_j(k_{M-1})]^{\mathrm{T}}$ for the estimation of phase noise. These pseudo pilots all carry useful unknown information and cannot be used to estimate phase noise directly as conventional pilots.

However, since a lower error probability compared with that of the other data symbols, it is possible to perform the detection of pseudo pilots $\tilde{\boldsymbol{Y}}_j^p$ by demapping and mapping. Then the remapping pseudo pilots can be used to estimate the phase noise instead of pilots.

The diagonal of $\boldsymbol{\Phi}_j$ denoted by $\boldsymbol{\Psi}_j$ can be expanded by orthogonal basis as

$$\boldsymbol{\Psi}_j = \boldsymbol{B} \boldsymbol{\Gamma}_j, \tag{10}$$

where $\boldsymbol{B} = [b_0\ b_1\ \cdots\ b_{\varsigma-1}]$ and $[b_0\ b_1\ \cdots\ b_{\varsigma-1}]$ are orthogonal bases of ς-dimensional space. $\boldsymbol{\Gamma}_j = [\gamma_j(0)\ \gamma_j(1)\ \cdots\ \gamma_j(\varsigma-1)]^{\mathrm{T}}$ is the coefficient vector. Following the method [16], the conjugation of phase noise expansion coefficients can be estimated as

$$\hat{\boldsymbol{\Gamma}}_j^* = \left({\boldsymbol{C}_j}^{\mathrm{H}} \boldsymbol{C}_j\right)^{-1} {\boldsymbol{C}_j}^{\mathrm{H}} \tilde{\boldsymbol{Y}}_j^p, \tag{11}$$

where

$$\boldsymbol{C}_j = \boldsymbol{S} {\boldsymbol{H}_j}^{-1} \boldsymbol{F} \mathrm{diag}(\boldsymbol{y}_j) \boldsymbol{B}^*, \tag{12}$$

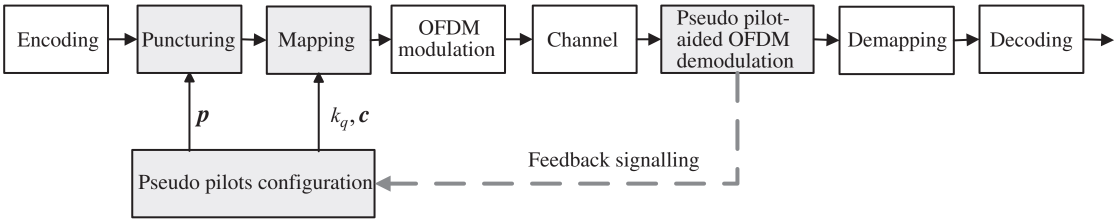

Figure 3 Schematic of the proposed system in closed-loop mode.

in which $\boldsymbol{S} = [\boldsymbol{e}_{k_0}\ \boldsymbol{e}_{k_1}\ \cdots\ \boldsymbol{e}_{k_{M-1}}]^{\mathrm{T}}$ and $\boldsymbol{e}_{k_i}$ is an $N \times 1$ vector with k_ith entry equal to 1 and the other equal to 0. The superscript * denotes conjugation. Then the final output $\boldsymbol{z}_j$ after phase noise correction can be obtained as

$$\boldsymbol{z}_j = \boldsymbol{H}_j{}^{-1}\boldsymbol{F}\mathrm{diag}(\boldsymbol{y}_j)\boldsymbol{B}^*\hat{\boldsymbol{\Gamma}}_j^*. \tag{13}$$

As shown in Figure 1, after the proposed pseudo pilot-aided OFDM demodulation, soft QAM detection is adopted to the signal $\boldsymbol{z}_j$, so that we can get soft detection information for the following soft decoding. In order to recover the bits punctured at transmitter, the soft information for the position punctured can be calculated according to their probability of occurrence, or given directly. Finally, the decoding module decodes the soft detection information and recovers the transmitted data.

2.2 Coarse phase noise correction

When phase noise is serious, there would be a phase ambiguity problem. The constellation rotation caused by CPE is beyond the detection threshold and the pseudo pilots cannot be recovered by demapping and mapping. For this case, we add only 1 pilot in each OFDM symbol, rather than 5 pilots [17] , to solve this problem. The only 1 pilot is used to operate a coarse CPE correction after channel equalization as shown in the dotted box of Figure 2. First, a coarse phase shift can be estimated as

$$\mathrm{e}^{\mathrm{j}\bar{\phi}_j} = \frac{\boldsymbol{Y}_j(k_p)}{\boldsymbol{F}\boldsymbol{x}_j(k_p)}, \tag{14}$$

where k_p denotes the index of the only pilot. Then coarse phase noise correction can be operated as

$$\tilde{\boldsymbol{Y}}_j = \boldsymbol{Y}_j\mathrm{e}^{-\mathrm{j}\bar{\phi}_j}, \tag{15}$$

and the pseudo pilots are picked up from $\tilde{\boldsymbol{Y}}_j$ instead of $\boldsymbol{Y}_j$ as $\boldsymbol{Y}_j^p = [\tilde{Y}_j(k_0)\ \tilde{Y}_j(k_1)\ \cdots\ \tilde{Y}_j(k_{M-1})]^{\mathrm{T}}$.

2.3 Closed-loop mode

Except the open-loop working mode as shown in Figure 1, the proposed OFDM system can also work in a closed-loop mode as shown in Figure 3, in which a feedback signaling can be utilized by the pseudo pilots configuration module to reconfigure $\{k_q\}$ $(q = 0, 1, \ldots, M-1)$, $\boldsymbol{c}$ and $\boldsymbol{p}$ dynamically. This mode works in an iterative way to achieve the optimal or suboptimal pseudo pilots configuration according to the real-time channel condition. The effects of the above parameters on the system performance will be discussed in detail in Section 3.

2.4 Computation complexity analysis

The main complexity of the proposed pseudo pilots method is induced by calculating $\hat{\boldsymbol{\Gamma}}_j^*$ (Eq. (11)), $\boldsymbol{C}_j$ (Eq. (12)) and $\boldsymbol{z}_j$ (Eq. (13)) which include both matrix multiplication and inversion. For diagonal matrix exists and FFT can be used, the actual multiplications needed to calculate them are respectively $O(N\varsigma\log(N))$, $O(N^2\varsigma) + O(\varsigma^3)$ and $O(N\log(N))$. Besides, the proposed pseudo pilot method also needs some additional complexity of puncture, pseudo pilot detection and configuration. In fact, puncture module is just to select some bits not to transmit at transmitter and fill zeros at the same position at receiver. Pseudo pilot detection is performed by demapping and mapping. Pseudo pilot configuration is to determine the number and modulation formats of the pseudo pilots according to the channel condition. Compared with conventional pilot aided method, the computation complexity caused by them is very limited. Moreover, the forward error correction codes, such as LDPC in this paper, are always necessary for communication systems, so the corresponding computation complexity is not brought by the proposed pseudo pilot method.

3 Simulation results and discussion

Following the standard of HINOC, we set up a coaxial OFDM system to verify the performance of the proposed method, whose number of subcarriers is 256 and bandwidth is 16 MHz. According to our previous practical measured coaxial channel, the SNR is set to be 36 dB and 1024QAM is adopted to achieve high transmission rate. LDPC code (1152, 960), which is proposed for unified high-speed wire-line based home network transceivers [20], is employed in our simulations. For decoding at the receiver, the log likelihood ratios (LLR) of the punctured bits are regarded as 0 for their recovering. In HINOC, signaling frame is sent regularly for CIR, carrier initial phase offset, carrier frequency offset and sample clock frequency offset estimation. Because of the slowly varying property of coaxial channel, the weighted inter-frame averaging-based channel estimation bring very high estimation precision [21]. The synchronization sequence of the signaling frame and data frame guarantee the frequency and timing synchronization. But in this paper, we pay main attention to the phase noise compensation, so we assume that a perfect frequency-domain channel transmission matrix $\boldsymbol{H}$ can be obtained after channel estimation.

As is analyzed, the accuracy of the detection of pseudo pilots determines the system performance. So how to select M and $\{c(k_q)\}$ $(q = 0, 1, \ldots, M-1)$ is the key point. In the following parts, we will study the influence of these parameters on the proposed OFDM system.

3.1 Modulation formats of pseudo pilots

Figure 4 shows the influence of the modulation format of pseudo pilots on the performance of the proposed OFDM system with and without coarse phase noise correction. We set the range of the variance of phase noise σ_p^2 from 0.002 to 0.04, and 5% pseudo pilots are inserted. The different modulation formats QPSK, 16QAM and 64QAM are considered.

As is shown in Figure 4, pseudo pilots modulated by 16QAM and 64QAM cannot work well even when σ_p^2 is 0.002 without coarse phase noise correction. But for QPSK, a different result can be found. Here the pseudo pilots with modulation format QPSK can tolerate more serious phase noise and get more accurate data after detection to do phase noise estimation. But when σ_p^2 becomes a little larger, its performance becomes worse greatly. At this time, the constellation rotation caused by phase noise is beyond the detection threshold and the detection of pseudo pilots is not accurate enough to estimate the phase noise. Overall, as the modulation format of pseudo pilots, QPSK can work much better than 16QAM and 64QAM.

With the aid of the extra coarse phase noise correction, the BER performance improves greatly because of a more accurate detection of the pseudo pilots. In this case, 16QAM behaves the best among the three modulation formats. Although QPSK can achieve the best pseudo pilot detection, more punctured bits for its lower modulation formats results in worse performance. For 64QAM, the modulation format is too high to perform pseudo pilot detection. So a proper choice of modulation formats has major influence on the system performance.

3.2 The number of pseudo pilots

Figure 5 shows the influence of the number of pseudo pilots on the performance of the proposed OFDM system. Here the modulation format of pseudo pilots is fixed as QPSK and 16QAM. Coarse phase noise is applied and σ_p^2 is also increased from 0.002 to 0.04. We can see from the figure that, for different modulation and variance of phase noise, the number of pseudo pilots matters differently. For QPSK, 3% and 7% pseudo pilots behave better than 12% when $\sigma_p^2 = 0.002$. When phase noise becomes a little worse,

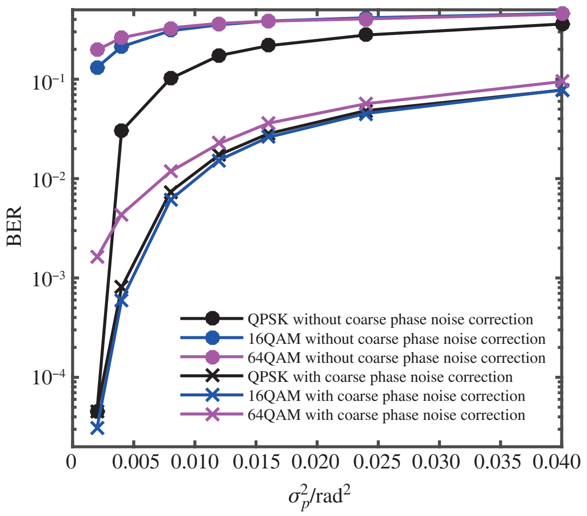

Figure 4 (Color online) BER versus the variance of the phase noise σ_p^2 considering different modulation formats of pseudo pilots with and without coarse phase noise correction.

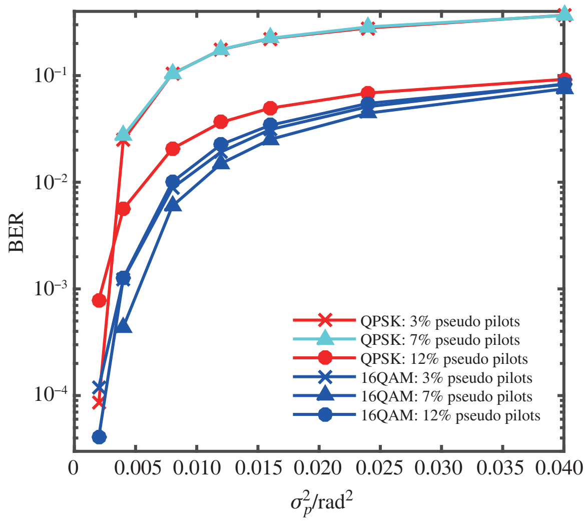

Figure 5 (Color online) BER versus the variance of the phase noise σ_p^2 considering different number of pseudo pilots when coarse phase noise correction is applied.

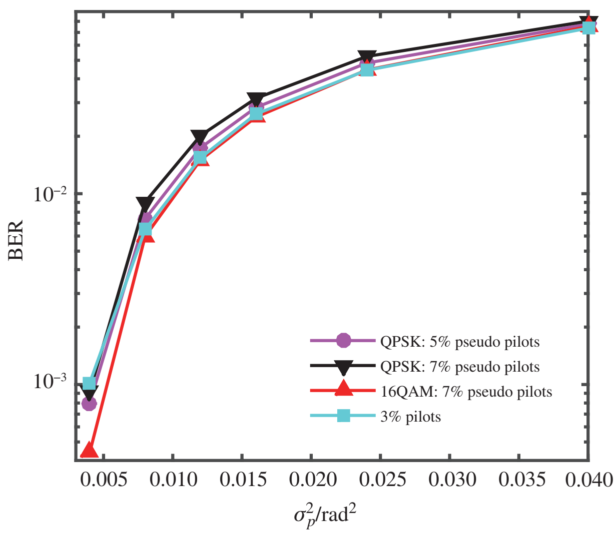

Figure 6 (Color online) BER versus the variance of the phase noise σ_p^2 when pseudo pilot-aided method and pilot-aided method are applied.

12% pseudo pilots become better. But for 16QAM, 7% pseudo pilots always has the best performance. So we may think 7% pseudo pilots of 16QAM is actually the results of closed-loop mode in this channel condition. The other curves are the results of open-loop mode. Obviously, the closed-loop mode has the better performance than open-loop mode. Overall, the lower the modulation format of pseudo pilot is, to guarantee high spectral efficiency, the more bits will be punctured and the more difficult the LDPC decoding module will be to recover the punctured bits. On the other hand, lowering the modulation format makes the phase noise estimation more accurate. Increasing the number of pseudo pilots has a similar effect. So the most important thing is to configure the modulation format and number of the pseudo pilots according to different phase noise and CIR.

3.3 The contrast between pseudo pilots and pilots

In the second generation HINOC standard, 3% pilots are inserted in each OFDM symbol, so we select it as a comparison. Figure 6 shows the contrast system performance between the proposed pseudo pilot-aided method and 3% pilot-aided method. Coarse phase noise correction is also applied in pseudo pilot-aided method. The cyan curve represents the performance of conventional 3% pilot-aided method [16]. We can find that the performance of using pseudo pilots is close to that of using pilots. On the condition of higher spectral efficiency, if we appropriately adjust the modulation format and number of the pseudo pilots, our proposed system may have better performance than the 3% pilot-aided system, as the red curve shows in Figure 6. We can see that 7% pseudo pilots with 16QAM modulation has better performance than 3% pilots when σ_p^2 is small and can approach its performance when σ_p^2 is large.

For conventional methods, more pilots will bring better BER performance, meanwhile more loss of spectral efficiency. But for the pseudo pilot method, as analyzed in Section 2, it does not lose any spectral efficiency except the only 1 pilot. When compared with 3% pilot aided method in Figure 6, the pseudo pilot method can improve the spectral efficiency about 3%.

4 Conclusion

In this paper, a new pseudo pilot-aided OFDM system mainly used for high performance coaxial transmission is proposed. Compared to conventional pilot-aided OFDM system, we utilize a novel and almost blind phase noise compensation method and puncture scheme to achieve high spectral efficiency. Simulation results show that the number and modulation formats of the pseudo pilots have significant effects on the system performance. We need try to find the optimum tradeoff according to the channel condition. Although the only 1 pilot will be inserted to solve the phase ambiguity problem when the phase noise is severe, the spectral efficiency is also much higher than the pilot-aided counterpart.

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Conflict of interest The authors declare that they have no conflict of interest.

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