Preamble Design and Iterative Channel Estimation for OFDM/Offset QAM System

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***Abstract*—In present of multi-path effect, the inter symbol interference (ISI) always exists in the OFDM/OQAM system and the preamble based channel estimation for the conventional orthogonal frequency division multiplex with cyclic prefix (CP-OFDM) is not feasible any more. Considering the characteristic of the extended Gaussian function (EGF), we propose two modified preamble based channel estimation by adding zero-value guard symbols, which are located at both sides (method A) and the left side (method B) of preamble reference symbol. Compared with the CP-OFDM system, the proposed preamble based channel estimation achieves 2dB improvement. Furthermore, we shorten the preamble without zero-value guard symbol to improve the spectrum efficiency. Unfortunately, the residual inter symbol interference (ISI) from neighbor symbols degrade the channel estimation performance. We propose an iterative channel estimation method for OFDM/OQAM system to remove the residual ISI. Simulation results demonstrate that those proposed preamble design and iterative channel estimation methods are effective for OFDM/OQAM system.**

***Index Terms* — OFDM/Offset QAM, preamble, channel estimation, iterative channel estimation**

I. INTRODUCTION

Orthogonal frequency division multiplexing with cyclic prefix (CP-OFDM) is an efficient multicarrier modulation to fight against multipath fading channels. However its robustness to multipath propagation effect comes from the insertion of a cyclic prefix and is therefore obtained at the price of a reduced spectral efficiency. To remove cyclic prefix, the prototype function modulating each subcarrier must be very well localized both in the time and in the frequency domain, to limit the inter symbol interference (ISI) and inter carrier interferences (ICI). This function is also designed to guarantee orthogonality between subcarriers. Functions with this double characteristic exist as discussed in [1-3]. Moreover, various pulse shaping prototype functions with good time and frequency localization property have been proposed in [4-7] and implementation issues based on various filter banks have also been addressed in [8-11].

Indeed, the authors in [2] have presented the isotropic orthogonal transform algorithm (IOTA), which is a two-step orthogonalization algorithm applied to the Gaussian function, yields an orthogonal transform based on a continuous time function having nearly optimal time frequency localization. In addition, as shown by Bölcskei in [3], it can be also used to derive a closed-form expression that describes a new family of functions called extended Gaussian functions (EGF). However, the optimally localized ones with EGF only guarantee orthogonality on real values, hence an alternative multicarrier modulation scheme is proposed, i.e., orthogonal frequency division multiplex/offset QAM (OFDM/OQAM). OFDM/OQAM is a good candidate for next generation wireless communication, because of good time and frequency localization properties. To data, OFDM/OQAM system has already been introduced in the digital radio technical standards [12] and WRAN (IEEE 802.22) [13].

Compared with the CP-OFDM system, which transmits complex valued symbols at given symbol rate, the OFDM/OQAM modulation transmits real valued symbols at twice this symbol rate and therefore has a similar spectral efficiency. But, in practice, it provides a higher useful bit rate, since it operates without the addition of cyclic prefix. Furthermore its pulse shaping can be optimized according to given channel characteristics.

However, all the nice features of OFDM/OQAM come at the price of a relaxation of the orthogonality conditions that only hold in the real field. Consequently, the conventional channel estimation methods for CP-OFDM system cannot be directly applied in the case of OFDM/OQAM signals. Therefore how to implement channel estimation effectively becomes an open problem. Some researchers have proposed several channel estimation methods for the OFDM/OQAM system, focusing on preamble based [14-16] and scattered pilot based approaches [17]. In [14], it requires a priori knowledge of the pulse shaping function for channel estimation. In [15-16], the preamble based approach achieves 2dB better BER performance than that of the CP-OFDM system. However, effectiveness of preamble based channel estimation is still not investigated. In this paper, we investigate the effectiveness of different preamble designs for OFDM/OQAM channel estimation.

To improve the spectrum efficiency for OFDM/OQAM system, we shorten the preamble structure with 1 zero-value guard symbol. However, the residual ISI arising from the neighbor symbols degrade channel estimation performance of OFDM/OQAM system. Hence, how to eliminate the residual ISI is an important issue for channel estimation. In this paper, we present a kind of

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iterative channel estimation method to remove the residual ISI for the short preamble structure. Simulation results demonstrate that short preamble with iterative channel estimation is an effective method for OFDM/OQAM system.

In section II, we give a description of the extended Gaussian function and OFDM/OQAM modulation. Section III is devoted to the presentation of the different preamble designs for OFDM/OQAM channel estimation. Section IV is devoted to the short preamble structure without zero-value guard symbol and iterative channel estimation to eliminate the residual ISI. Finally, simulation results are demonstrated to verify advantages of the modified preamble based approach for the OFDM/OQAM system in section V and conclusion is drawn in Section VI.

II. OFDM/OQAM MODULATION

A. Extended Gaussian Function

In [18], a modulation procedure is proposed to build a novel orthogonal frequency division multiplex system. The method includes a family function as follows

$$z_{\alpha,v_0,\tau_0}(t) = \mathrm{O}_{\tau_0}\,\mathrm{F}^{-1}\,\mathrm{O}_{v_0}\,\mathrm{F}\,g_\alpha(t)\,, \qquad (1)$$

where **F** is the Fourier transform operator, Gaussian function $g_a(t) = (2a)^{1/4} e^{-\pi a t^2}$ with a, which denotes spreading parameter, τ_0 and v_0 are the time and frequency parameters of the modulation system. O_α is an orthogonalization operator to transforms a function $x(t)$ according to

$$\mathrm{O}_\alpha x = \frac{x(t)}{\sqrt{\alpha \sum_{k=-\infty}^{\infty} |x(t-k\alpha)|^2}}\,,\ a > 0\,. \qquad (2)$$

Moreover, the property $\mathrm{F} z_{\alpha,v_0,\tau_0}(t) = z_{1/\alpha,\tau_0,v_0}(t)$ leads to good time and frequency localization, as shown in Fig. 1.

In multipath fading channel environment, the CP-OFDM system can completely remove ISI and achieve the nearly perfect channel information by adding cyclic prefix. As shown in Fig. 1, the EGF function spreads to several neighbors OFDM symbols. Although EGF function with the property of fast attenuation, the OFDM/OQAM system with EGF function still brings strong ISI to the neighbor symbols in present of multipath channel, which is totally different with the CP-OFDM system.

B. OFDM/OQAM system

According to [2], the transmitted signal is expressed:

$$s(t) = \sum_n \sum_{m=0}^{M-1} a_{m,n}\, j^{m+n} e^{j2\pi m v_0 t} g(t - n\tau_0)\,, \qquad (3)$$

where $a_{m.n}$ denotes the real information value (offset QAM) on the m^{th} subcarrier at the n^{th} symbol, M is the number of subcarriers, v_0 and τ_0 denote the subcarrier spacing and OFDM/OQAM symbol duration, respectively, $g(t)$ denote pulse shape prototype function. An inner product of demodulation is defined as follows

$$\left\langle g_{m,n} \mid g_{m',n'} \right\rangle_R = \mathrm{Re}\left(\int_{\Re} g_{m,n}(t) g^*_{m',n'}(t)\,dt \right) = \delta_{m,m'}\delta_{n,n'}\,. \qquad (4)$$

At the receiver side, the demodulation can be expressed as:

$$\hat{a}_{m,n} = \sum_{m=0}^{N-1} a_{m,n} \left\langle g_{l,n}, g_{m,n} \right\rangle_R + \underbrace{\left\langle g_{l,n}, n(t) \right\rangle_R}_{n_0(t)} = a_{m,n} + n_0(t). \qquad (5)$$

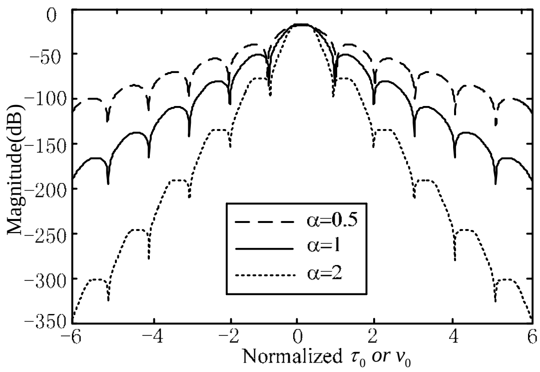


Figure 1. Robustness of time delay and frequency shift

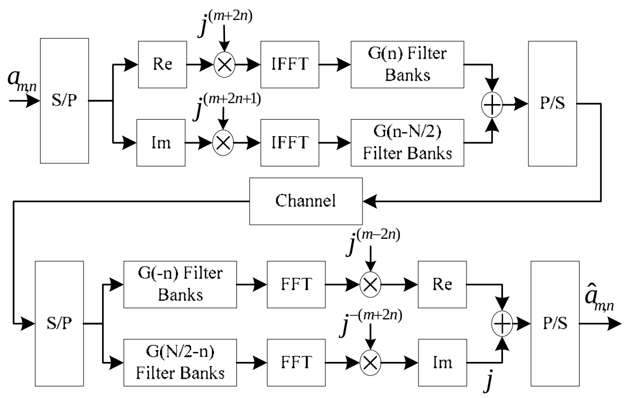


Figure 2. OFDM/OQAM system diagram

In order to use FFT/IFFT operation to implement the OFDM/OQAM system efficiently, let $s(t)$ be the output signal of OFDM/OQAM modulator [19-20]

$$\begin{aligned} s(t) = {} & \sum_n \sum_{m=0}^{M-1} a^R_{m,n} g(t - 2n\tau_0) j^{m+2n} e^{j2\pi m v_0 t} + \\ & j \sum_n \sum_{m=0}^{M-1} a^I_{m,n} g(t - (2n+1)\tau_0) j^{m+2n} e^{j2\pi m v_0 t} \end{aligned}\,, \qquad (6)$$

where $a^R_{m,n}$ and $a^I_{m,n}$ denote the real and imagine part of the complex transmitted symbol, respectively. By sampling $s(t)$ at rate $1/T_C$ during time interval [$nT_S - \tau_0$,

$nT_S + \tau_0$], the transmitted signal can be expressed as

$$s_k[n] = g_k[n] * A_N^k(a_{m.n}^R) + g_{k-N/2}[n] * A_N^k(ja_{m.n}^I), \quad (7)$$

where

$$\begin{aligned} A_N^k(x_{m.n}) &= \sum_{m=0}^{M-1} x_{m.n} e^{j\frac{\pi}{2}(m+2n)} e^{j2\pi\frac{mk}{M}} \\ s_k[n] &= s[nM+k] = s(nT_S + kT_C) \\ g_k[p] &= g[pM+k] = g(pT_S + kT_C) \end{aligned} \quad . \quad (8)$$

Observed from Fig.2, the OFDM/OQAM modulation can be easily implemented by an IFFT block followed by a pulse shaping filter bank. Importantly, the novel modulation separates the complex data streams into two branches--real part and imagine part branch. Fortunately, the structure of each branch is very similar to the conventional CP-OFDM system, only adding the filter bank after IFFT block. Therefore, the complex preamble based channel estimation approach is feasible for the OFDM/OQAM system.

III. Modified Preamble Based Channel Estimation

A. *Analysis of channel estimation under multipath fading channel for OFDM/OQAM system*

In this paper, there are some basic assumptions that the transmitted signals pass through the static multipath channel denoted $h(t)$ and the presence of an additive noise $n(t)$. The received signal of OFDM/OQAM system can be expressed as follows:

$$r(t) = \int_0^{\Delta} h(t,\tau) s(t-\tau) d\tau + n(t) . \quad (9)$$

Recall from (3), the received signals are rewritten as:

$$r(t) = \sum_n \sum_{m=0}^{M-1} a_{m,n} j^{m+n} e^{j2\pi m v_0 t} g(t - n\tau_0) H_m + n(t), \quad (10)$$

with

$$H_m = \int_0^{\Delta} h(\tau) e^{j2\pi m v_0 (-\tau)} d\tau . \quad (11)$$

Hence, the demodulated signal can be expressed as

$$\begin{aligned} y(t) &= \mathrm{Re}\{\sum_{n'} \sum_{m'=0}^{M-1} \left\langle r(t) \mid g_{m',n'} \right\rangle\} \\ &= \mathrm{Re}\{(\sum_n \sum_{n'} \sum_{m=0}^{M-1} \sum_{m'=0}^{M-1} a_{m,n} \left\langle g_{m,n} \mid g_{m',n'} \right\rangle H_m\} + n^*(t) \end{aligned} \quad . \quad (12)$$

From above equation, since the real operator is not linear, the demodulation process for OFDM/OQAM system is totally different with that for CP-OFDM system.

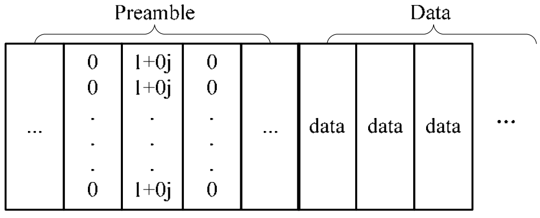
As discussed by Lélé in [18-19], for OFDM/OQAM system, a simple one-tap equalization is enough to compensate the frequency selective fading channel effect, if the prototype filter utilizing in OFDM/OQAM system has good time and frequency localization. It should be noticed that perfect or nearly perfect channel information is the basic element for effective equalization. Therefore, how to achieve perfect or nearly perfect channel information is the key issue for OFDM/OQAM system.

B. *Preamble design for OFDM/OQAM system*

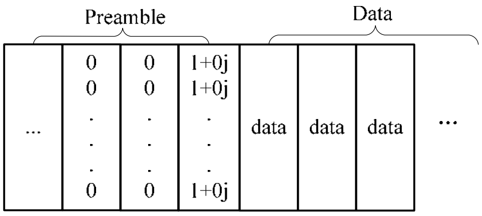
For the conventional CP-OFDM system, there is a simple and robust implementation against frequency selective fading channel, for example one-tap equalizer. It is necessary to notice perfect or nearly perfect channel information is the basic factor for equalization. However for OFDM/OQAM system, although the EGF function has good time and frequency localization, the ISI still exists in present of multipath channel environment. Therefore, the key point of channel estimation for the OFDM/OQAM system is how to remove or decrease the ISI to achieve the perfect channel state information in present of multipath channel environment.

In practical wireless communication systems, preamble based and pilot based channel estimations are feasible to achieve the perfect or nearly perfect channel information for multicarrier system. In this paper, only preamble based channel estimation is considered for the OFDM/OQAM system. According to above discussions, there are two ways to guarantee nearly perfect channel information for the OFDM/OQAM system—ISI avoidance and ISI cancellation. Our aim is to design effective preamble based channel estimations focusing on ISI avoidance, instead of the ISI cancellation. From the works in [16], the main ISI is from the neighbor symbols, therefore ignoring the negligible ISI from symbols far away from the preamble reference symbol.

Since the novel OFDM/OQAM implementation is similar to the conventional CP-OFDM system, two modified preamble base channel estimations are proposed. For ISI avoidance, the simplest way is to add guard symbols around the preamble reference symbol. There are two different ways to add guard symbols, which are located at both sides (method A) and the left side (method B) of preamble reference symbol as shown in Fig. 3. Compared with method A, method B utilizes left side guard symbols to guarantee ISI avoidance, therefore with higher system efficiency. Although adding guard symbols is available to protect the reference symbol, the effectiveness of method A and B still are open problems. In other words, how many guard symbols are required to guarantee the nearly perfect channel information? In the simulation results, effectiveness of the modified preamble based channel estimations is mainly investigated.



(a) Method A



(b) Method B

Figure 3. Modified preamble based channel estimations for the OFDM/OQAM system

IV. Iterative Channel Estimation For Short Preamble Based OFDM/OQAM System

A. *Short Preamble structure for OFDM/OQAM system*

Since the preamble structures require two zero-value guard symbols to guarantee ISI avoidance, the length of the long preamble structure is taken equal to $3\tau_0$, which is equivalent to 3/2 complex symbol for CP-OFDM system, hence leading to OFDM/OQAM system with low spectrum efficiency.

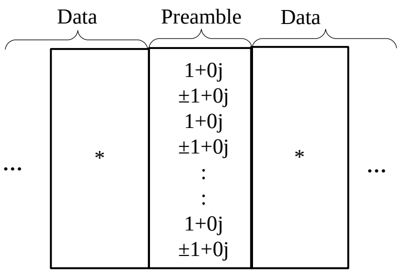


Fig. 4 Short preamble with $2\tau_0$ for the OFDM/OQAM system

To improve the spectrum efficiency for OFDM/OQAM system, we shorten the preamble structure without zero-value guard symbol (short preamble structure with $2\tau_0$). The short preamble for OFDM/OQAM system is shown in Fig. 4.

However, since the short preamble can not totally remove the ISI, the residual ISI arising from the neighbor symbols will degrade channel estimation performance of OFDM/OQAM system. And how to eliminate the residual ISI becomes an important issue for the short preamble based OFDM/OQAM system.

B. *Iterative channel estimation for OFDM/OQAM system*

In this paper, we propose iterative channel estimation method to improve the channel estimation performance for the short preamble case. The system diagram for iterative channel estimation is shown as Fig. 5.

For the iterative channel estimation method, the initial channel estimation is obtained from the short preamble symbol. And then, the receiver will demodulate the receiving data. However, after the first demodulation of transmitted signal, the output is fed back to the channel estimator which then produce a better channel estimation which is passed on to the demodulator. Moreover, this iteration can be performed a number of times.

Normally, there are two different ways for symbol detector (hard decisions and soft decisions), therefore leading to hard decision feedback and soft decision feedback iterative channel estimation. For simplicity, only the hard decision feedback and least square (LS) estimation discussed by Sandell in [21] are adapted. The LS algorithm depicted as follows:

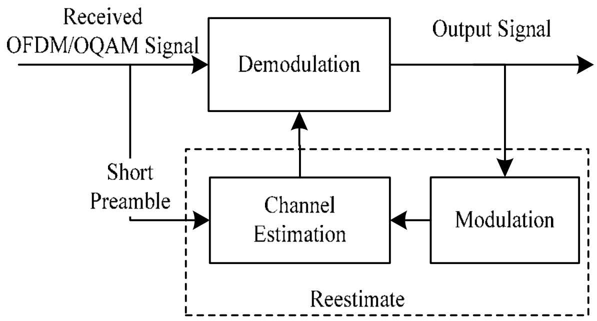


Fig. 5 System diagram for iterative channel estimation for short preamble based OFDM/OQAM system

$$H_I = E\{\hat{\boldsymbol{H}}\} = E\{(B^H B)^{-1} B^H r\}, \qquad (13)$$

where r is the received signal, B is the matrix with transmitted symbols including the short preamble symbol, $E\{.\}$ denotes expectation and $(\,.\,)^H$ denotes Hermitian transpose. The iterative channel estimation method for short preamble based OFDM/OQAM system is with following steps:

Step 1: Set initial condition: abstract the short preamble symbols a_n and data symbols s_n from the received OFDM/OQAM signal.

Step 2: Estimate the channel information $\tilde{H}$ by the short preamble symbol a_n.

Step 3: Demodulate the receive signal s_n by estimated channel information $\tilde{H}$.

Step 4: Restructure the transmitted symbols $\tilde{B}$ by (1).

Step 5: Reestimate the channel information H_I by (10).

Step 6: Repeat from step 3 to step 5 for the designed number of iteration.

Since the iteration can be performed a number of times, the channel estimation performance is gradually improved with the number increasing. Meanwhile, it is clear that the better channel estimation performance can be achieved if adapting minimum mean square error (MMSE) algorithm or other more complex algorithm instead of the LS method, but those issues are not considered in this paper.

V. Simulation Results

Simulation results have been carried out with a channel model and modulation parameters that are borrowed from the IEEE 802.22 standard. This standard aims at constructing wireless regional area network (WRAN) utilizing free TV bands. The channel profile and the main parameters of the system used are given in the Table I.

TABLE I. GENERAL LINK LEVEL PARAMETERS

Parameters	Values	
Bandwidth	4MHz	
Channel	Path delay	-3 0 2 4 7 11 (us)
	Power gain	-6 0 -7 -22 -16 -20 (dB)
Modulation	QPSK	
Channel coding	Convolutional code, K=7, [133,171]	

Considering the conventional CP-OFDM system will occupy extra time slots as cyclic prefix, it is of lower spectral efficiency than that of OFDM/OQAM system. For a fair comparison, OFDM/OQAM and CP-OFDM systems utilize different channel coding rate to keep the same spectral efficiency as discussed by Lacroix in [22]. The parameter for OFDM/OQAM and CP-OFDM system are in Table II.

TABLE II. PARAMETERS FOR THE OFDM/OQAM AND CP-OFDM SYSTEM

	OFDM/OQAM	CP-OFDM
Number of subcarriers	256	256
Pulse shaping filter	EGF, *a*=2, 8 taps	--
Cyclic prefix	--	1/4
Coding rate	1/2	2/3
Bandwidth efficiency (bits/sec/Hz)	1	1.06

A. *Different preamble design for OFDM/OQAM system*

Simulation results of different preamble designs are shown as following Fig. 5 and Fig. 6. To better explain the advantages of the modified preamble based channel estimation methods for OFDM/OQAM system, the BER performance of OFDM/OQAM system is compared with that of the CP-OFDM system and OFDM system without cyclic prefix.

BER performance of method A is demonstrated as Fig. 5. It's clear that with perfect channel information (perfect channel estimation), BER performance of OFDM/OQAM system is slightly worse than that of the CP-OFDM system. However for the preamble based channel estimation, the BER performance of the OFDM/OQAM system is 2dB better than that of the CP-OFDM system, which is same with the results in [15-16]. Furthermore, there is an interesting phenomenon that even increasing the number of guard symbols, the performance of method A remains same (the BER performance of nine guard symbols is identical with that of two guard symbols). The phenomenon is because of the propagation characteristic of EGF function, which contains most energy in adjacent two symbols as shown in Fig. 1.

For the method B, BER performances under different channel estimation methods are shown as Fig. 6. As same as the method A, the BER performance of method B is still better than that of the CP-OFDM system, only the performance of two guard symbol is slightly worse below BER 10^{-3} level. For the practical wireless communication system, the error correcting codes, such as LDPC and Convolution codes, is necessary to improve the system performance. Considering the correcting abilities of those codes, we always focus on BER performance above BER 10^{-3} for uncoded system. Compared simulation results from Fig. 5 with Fig. 6, method B achieves the same BER performance with method A above BER 10^{-3} level. Meanwhile, since only one guard symbol in the left side for method B instead of two guard symbols on both sides for method A, the preamble based channel estimation—method B is of higher efficiency and preferred for the practical OFDM/OQAM system.

For the OFDM system without cyclic prefix, the multipath fading channel will lead to serious ISI and deteriorated performance, while the CP-OFDM system can remove ISI through adding cyclic prefix. Therefore, the performance of the OFDM system without cyclic prefix is worse than that of the CP-OFDM and OFDM/OQAM system.

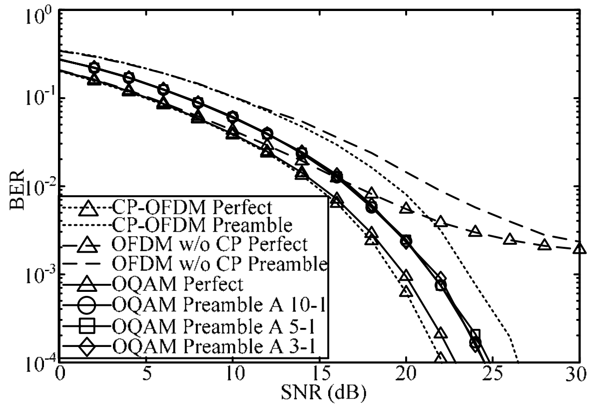


Fig. 5 BER performance of preamble based channel estimation--Method A

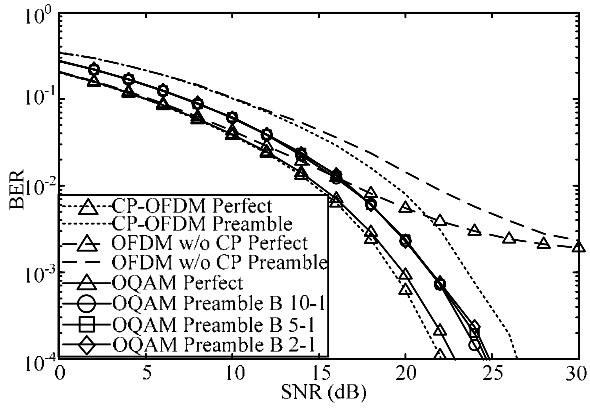


Fig. 6 BER performance of preamble based channel estimation--Method B

B. *Iterative channel estimation*

The performance evaluation of channel estimation is performed by mean square error (MSE) of estimated channel information and bit error rate (BER). The MSE is given by the following equation:

$$MSE = E\,|\,\tilde{H} - H\,|^2 , \quad (14)$$

where $\tilde{H}$ and H denote the estimated and ideal channel information respectively.

Simulation of MSE of estimated channel information and BER performance are shown as Fig. 7 and Fig. 8. There are three important results are manifested:

a) For the short preamble structure, although the ICI can be cancelled through specific preamble structure design, without zero-value guard symbol is not enough to guarantee preamble symbol without ISI, which leads to OFDM/OQAM system having weak channel estimation performance. Fig. 7 illustrates that without iterative channel estimation, the error floor of MSE is around 0.5. Moreover, it is same for BER simulation results as shown in Fig. 8. At the BER 10^{-2} level, long preamble structure is 10dB better than the short preamble structure. Therefore, it is necessary to remove the residual ISI for the short preamble structure to improve channel estimation performance.

b) Under iterative channel estimation case, Fig. 7 shows that MSE performance is largely improved through iterative channel estimation. For short preamble with 1 time iterative, the error floor of MSE increases from 0.5 to 0.05. For BER performance as shown in Fig. 8, short preamble structure with 1 time iteration can achieve closed performance with long preamble structure under low SNR zone. As the number of time iteration increasing, BER performance of the short preamble with iteration is always better than that of long preamble structure. For example, at the BER 10^{-4} level, BER performance of the short preamble with 2 time iteration is 1dB better than that of the long preamble structure, while short preamble with 3 time iteration is 2.4dB better. In other words, the short preamble with finite time iterative channel estimation has better performance than the long preamble structure.

c) As the number of iterative time increasing, BER performance of the short preamble with iterative channel estimation is gradually close to that of perfect channel estimation case. At the BER 10^{-4} level, there is only 1dB gap with the perfect channel estimation as the number of iterative time increasing up to 10. Therefore, it is clear that the short preamble with iterative channel estimation can achieve higher spectral efficiency and better performance for OFDM/OQAM system under the multipath fading channel environment.

VI. CONCLUSION

In present of multipath effect, the ISI always exists in the OFDM/OQAM system, therefore preamble based channel estimation methods for the conventional CP-OFDM are not feasible any more. Considering the characteristics of the EGF based OFDM/OQAM system, two modified preamble based channel estimations are proposed by adding guard symbols to guarantee the nearly perfect channel information. Compared with the CP-OFDM system, BER performance of both two preamble based channel estimation approaches (method A and method B) obtain 2dB improvement. Importantly, the EGF based OFDM/OQAM system achieve the highest system efficiency because of no any cyclic prefix,

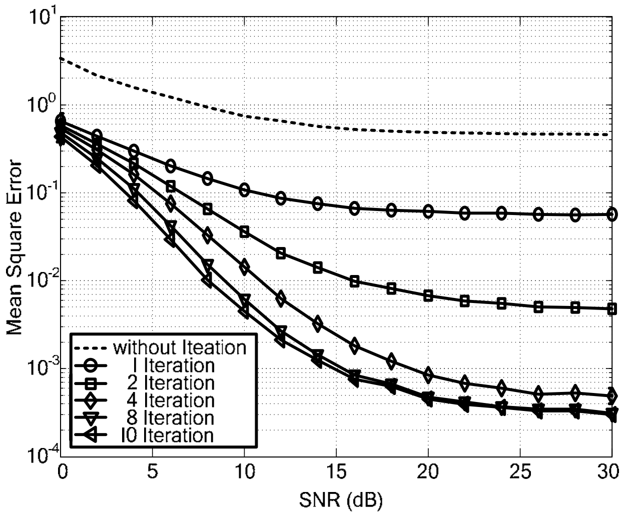


Fig. 7 MSE performance for short preamble with iterative channel estimation

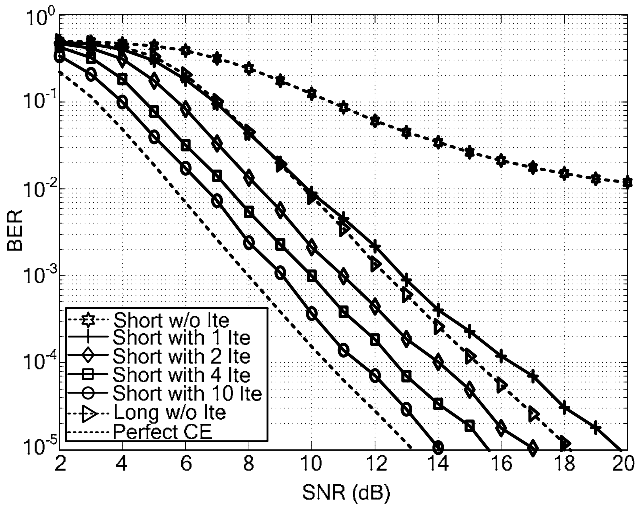


Fig. 8 BER performance for short preamble with iterative channel estimation

while the CP-OFDM system must require cyclic prefix to remove ISI. To improve the spectral efficiency of OFDM/OQAM system, we propose the short preamble without guard symbol. However, the residual ISI arising from the neighbor symbols degrade the channel estimation performance. Therefore we propose the short preamble structure with iterative channel estimation to decrease the residual ISI. After finite number of iterative time, the short preamble with iterative channel estimation has excellent channel estimation performance. Simulation results demonstrate the proposed preamble design and iterative channel estimation are effective for OFDM/OQAM channel estimation. In the future works, we will study effective pilot based channel estimation for the practical OFDM/OQAM system.

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