A New Type of Comb Pilot in FBMC/OQAM

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Abstract—Scattered pilot-aided channel estimation in offset QAM-based filter bank multicarrier (FBMC/OQAM) systems has so far been only considered for slow fading channels. In more demanding scenarios, the classical auxiliary pilot (AP) idea has been shown to result in a severe error. This paper proposes novel channel estimation techniques for FBMC/OQAM systems for fast fading channels. Unlike the conventional auxiliary pilot, the FBMC/OQAM systems’ transmitter adopts the proposed comb pilot arrangement mode based on auxiliary pilot. Meanwhile feedback interference estimation algorithms and feedback interference calculation algorithms are proposed at receiver, which can eliminate the imaginary interference of all the pilot symbols. Numerical results show that the FBMC/OQAM systems with the proposed channel estimation algorithms based on the proposed pilot have a better bit error rate (BER) performance compared to that with the auxiliary pilot algorithm. And compared with AP, the greater the Doppler frequency is, the greater performance superiority the proposed channel estimator achieves.

Index Terms—Filter-Bank Multi-Carrier, Offset Quadrature Amplitude Modulation, Channel Estimation, Pilot Design

I. INTRODUCTION

Multicarrier communication system can transmit high-speed data flow by many parallel low-speed data flows simultaneously over many orthogonal subcarriers, so multicarrier communication system has better flexibility and high resistance to frequency selective fading channel. One of the most widely adopted multicarrier communication systems is OFDM, famous for its high spectrum efficiency, low computational complexity and easiness to combine with MIMO.

The fifth generation mobile communication technology (5G) requires the physical layer waveform technology to be more flexible and have higher frequency utilization efficiency. However the conventional OFDM adds cyclic prefix (CP) in order to increase the systems resistance to multipath interference, which has side effects as a waste of spectrum resources, and a large side lobe of the filter, resulting in a less flexibility of the system. FBMC is a candidate for 5Gs waveform technology. Compared with OFDM, FBMC’s prototype filter has a better time-frequency characteristic, so it does not need CP to resist channel fading, which makes FBMC systems to be more spectrum efficient, and has more flexibility to take advantage of some of the existing non-continuous spectrum resources[1]. Further more, FBMC has a good compatibility with OFDM, which means some of the techniques in OFDM can be applied directly to FBMC. But in order to obtain better time-frequency characteristics, FBMC sacrifices orthogonality between subcarriers[2].

Fading channel estimation and equalization techniques are crucial for coherent symbol detection at the receiver. In the framework of multicarrier systems, many channel estimation techniques were proposed in the literature particularly for OFDM systems [3–6], which can be classified as training sequence/pilot symbols based techniques and blind methods. In this paper, with a faster convergence speed and a lower computational complexity compared with blind methods, we will focus our attention on the former.

In recent years, many researchers have studied the problem of channel estimation of FBMC/OQAM systems. Focusing on pilot-based channel estimation schemes, [7] proposed an auxiliary pilot scheme (AP), which applies an auxiliary pilot to neutralize the interference on the prime pilot. Mestre X studied the auxiliary pilot design in a highly frequency selective fading channel, which approximates the signal model with the Taylor series to simulate various scenarios, and the resulted channel estimates can be considered to be multiple parallel analysis filters linear combination[8]. Cui W proposed a coded auxiliary pilot method that linearly encodes the auxiliary pilot to carry information, thereby further improving the spectral utilization of the FBMC systems[9]. Because the value of the auxiliary pilot depends on the main pilot in the original auxiliary pilot algorithm, Yu B proposed a dual correlation pilot design algorithm, by sending two related pilots to neutralize the respective interference[10]. Nissel R proposed a linear precoding of the symbols around the pilot symbols to eliminate the interference of the surrounding symbols to the pilot symbols[11].

Through the analysis of the current research situation, it is clear that almost all of the researches on channel estimation are focused on channel estimation in slow fading channels. This motivates that a fast fading pilot design scheme and channel estimation algorithms for FBMC.

This paper proposes a new comb pilots of FBMC/OQAM in fast fading channel. On the basis of the original auxiliary pilot algorithm, we insert pilots in the interval of auxiliary pilots to form comb pilots. Corresponding channel estimation algorithms are proposed simultaneously, which are named feedback interference estimation algorithm and feedback interference calculation algorithm respectively and introduced to calculate the imaginary interference of pilots without auxiliary pilot. We also proved that the BER performance of the proposed feedback channel estimation algorithms are better than AP algorithm.
The paper is organized as follows. In Section II, the conventional FBMC/OQAM system and AP algorithm are introduced. Section III presents the proposed new comb pilot arrangement and feedback channel estimation algorithms. Simulation results are presented in Section IV. Section V concludes this paper.

II. FBMC/OQAM COMMUNICATION SYSTEM

The generalized block diagram of the FBMC/OQAM transmitter is illustrated in Fig.1.

In the Fig.1, \( c_k (l) \) represents the complex symbol after the process of constellation mapping, and \( C2R \) represents the transformation of a complex to real. Introducing a phase rotation operation \( \theta_k (n) = j^{k+n} \) to ensure the interference between neighboring subcarriers is pure imaginary. The overlap factor is \( K \), and the number of subcarriers is \( M \). The length of the prototype filter is \( L \), and \( L = KM \). In the modulated filter banks, the number of prototype filter branches depends on the periodic of modulation function \( \varepsilon_k (m) \).

\[
\varepsilon_k (m) = (-1)^{kn} e^{j\frac{2\pi}{KL} (m - \frac{L}{2})} \nonumber
\]

(1)

where

\[
\gamma_k (m) = e^{j\frac{2\pi km}{L}} \quad (2)
\]

\[
\beta_k = (-1)^{kn} e^{-j\frac{2\pi k}{2} (\frac{m}{L})} \quad (3)
\]

The existence of \((-1)^{kn}\) in (3) leads to the frequency offset of all subcarrier signal near the zero frequency, in favor of further process.

The output of a synthesis filter bank can be expressed by:

\[
s (m) = \sum_{k=0}^{M-1} \sum_{n=-\infty}^{\infty} d_k (n) \theta_k (n) p (m - \frac{Lk}{2}) \varepsilon_k (m) \quad (4)
\]

where \( d_k (n) \) is the collection of real-valued data symbols at subcarrier \( k \), \( d_k (n) \) is transmitted at a rate of \( 2/T \), with the signaling period \( T = 1/\Delta f \) where \( \Delta f \) denotes the subcarrier spacing. The pair of symbols \( d_k (n) \) and \( d_k (n+1) \) represent the in-phase and quadrature parts of the complex-valued input symbol \( c_k (l) \), respectively.

\[
d_k (n) = d_k (2l) = \begin{cases} 
\text{Re} (c_k (l)), & k \text{ even} \\
\text{Im} (c_k (l)), & k \text{ odd}
\end{cases}
\]

(5)

where \( l \) is the sample index at OQAM mapping input.

In order to achieve high spectral efficiency, complex modulated filter banks are usually used, which means that all subchannel filters are frequency shifted versions of the prototype filter \( p (m) \). So, the synthesis subchannel filters are:

\[
g_k (m) = p (m) \varepsilon_k (m) \quad (6)
\]

with \( m = 0, 1, \ldots, L - 1 \).

As shown in Fig.2, the conjugate multiplicative factors \( \theta_k (n) \) and \( \beta_k (n) \) of the receiver correspond to \( \theta_k (n) \) and \( \beta_k (n) \) of the transmitter.

The analysis subchannel filters can be expressed as:

\[
f_k (m) = g_k (L - 1 - m) \quad (7)
\]

It should be noted that the design of the prototype filter must satisfy perfect reconstruction (PR) conditions or at least provide nearly perfect reconstruction (NPR) characteristics. However, the PR property is only achieved under the condition of ideal transmission channel. As interferences in the wireless channel are unavoidable, there is no way to meet PR conditions. Thus, prototype filters are designed to satisfy NPR characteristics. In this paper, we take PHYDYAS prototype filter[12] as NPR prototype filter. The finite impulse response (FIR) of the low-pass prototype filter can be expressed as:

\[
p (t) = 1 + 2 \sum_{k=1}^{K-1} (-1)^k P_k \cos \left( \frac{2\pi k t}{K} \right) \quad (8)
\]

where \( K \) is overlap factor, \( P_k \) is the filter coefficient, satisfying the following conditions.
where
\[
P_0 = 1
\]
\[
P_k^2 + P_{L-k}^2 = 1; P_{L-k} = P_k; 1 \leq k \leq K - 1
\]
\[
P_k = 0; K \leq k \leq L - K
\]
where \(1 \leq k \leq K - 1\). When \(K = 4\), the prototype filter frequency response is shown in Fig.3.

![Fig. 3. K = 4 The prototype filter frequency response](image)

![Fig. 4. Auxiliary pilot arrangement](image)

Because there is interference between adjacent filters in the FBMC, there will be interference information leaked to useful information after the complex channel. Meanwhile there will also be data leakage to interference. Thus it can not distinguish between signal and interference. With complex channel response, channel estimation algorithms, such as auxiliary pilot based algorithm, are needed to obtain accurate channel information. Fig.4 shows the arrangement of auxiliary pilots and the AP window selection is shown in Fig.5.

The interference generated between adjacent filters can be represented by an interference filter. The time domain interference coefficients of the interference filter are shown in Fig.5.

![Fig. 5. Interference weights and AP window choice](image)

In Fig.5, the red part represents the dominant pilot position \((k_p, n_p)\), and the gray represents the optional position of auxiliary pilot \((k_a, n_a)\). The black frame is the window for calculating the auxiliary pilot, i.e \(\Omega_{k_p, n_p}\).

\[
d_{k_a, n_a} = - \sum_{(k,n)} d_{k,n} \hat{i}_{k_p-k, n_p-n}
\]

(10)

where \((k, n) \in \Omega_{k_a, n_a}, (k, n) \neq (k_a, n_a), (k, n) \neq (k_p, n_p), d_{k_a, n_a}\) represents the auxiliary pilot at the position \((k_a, n_a)\), and \(t_{k_p-k, n_p-n}\) is interference weights in Fig.5.

III. A NEW TYPE OF COMB PILOT

Since the prototype filter is an approximate reconstruction filter, regardless of the frequency offset and time delay of the
channel, the output of transform block can be written as (11).

\[ y_{k,n} = \sum_{i=k-1}^{k+1} \sum_{l=-\infty}^{\infty} x_{i,l} q_{i,k,n-l} + w_{k,n} \]

(11)

where \( x_{i,n} = d_{i,n} \theta_{i,n} \) represents the signal after the OQAM mapping, and \( w_{k,n} \) represents channel additive noise. \( q_{i,k,n-l} \) represents a two-dimensional impulse response that depends on subcarriers, including the influence from the subcarrier \( k-1 \) to the subcarrier \( k+1 \) and the influence of the channel. Since the frequency domain characteristics of the filter in FBMC are excellent, only adjacent subcarriers will generate interference with each other. The receiver’s signal through the phase deflection at the receiver can be written as (12).

\[ \hat{y}_{k_0,n_0} = \theta_{k_0,n_0}^* y_{k_0,n_0} = d_{k_0,n_0} + j u_{k_0,n_0} + \theta_{k_0,n_0}^* w_{k_0,n_0} \]

(12)

where the imaginary interference is

\[ u_{k_0,n_0} = \sum_{(k,n) \in \Omega_{k_0,n_0}} d_{k,n} \hat{t}_{k_0-k,n_0-n} \]

(13)

In (13), \( \hat{t}_{k,n} = \text{Im} \left( \theta_{k,n}^* t_{k,n} \right) \). \( t_{k,n} \) represents the interference coefficient of each symbol on the surrounding symbol, and \( \Omega_{k_0,n_0} \) represents the range of symbols that interfere with the symbols around \( d_{k_0,n_0} \). At the receiver, the estimated channel response of \((k_p, n_p)\) is

\[ \hat{h}_{k_p,n_p} = \frac{\theta_{k_p,n_p}^* u_{k_p,n_p}}{d_{k_p,n_p}} \]

(14)

The above analysis shows that FBMC subcarriers are orthogonal to each other only in real part, which means there is imaginary interference between subcarriers.

The high relative velocity of the transmitter and the receiver will lead to a large Doppler frequency, resulting in a rapid change in the channel, i.e. the channel response is different on different symbols of the same subcarrier. The higher the Doppler frequency is, the faster the change will be. In general, in order to combat the rapid changes in such channel, the auxiliary pilot need to be adopted. Obviously, when the dominant pilot interval is too small, the window that calculates the auxiliary pilot will overlap, resulting in an infinite recursion of auxiliary pilot calculation. Meanwhile, the 5G scenario requires communication support velocity over 300km/h, so the auxiliary pilot method cannot be applied to fast fading channel. This paper presents an AP method based comb pilot arrangement, as shown in Fig.6.

As shown in Fig.6, the pilot with the auxiliary pilot is called the dominant pilot. The secondary pilot does not have the auxiliary pilot to help it eliminate interference. In order to obtain more accurate channel information, it is necessary to get the interference information of the secondary pilots. So feedback interference estimation algorithm and feedback interference calculation algorithm are proposed in this paper. The algorithm flow charts are shown in Fig.7 and Fig.8 separately.

The true channel response can be expressed by equation (15).

\[ \hat{h}_{k,n} = \frac{y_{k,n}}{x_{k,n} + j u_{k,n}} = \hat{h}_{k,1} + \frac{j}{y_{k,n}} \]

(15)

where \( k, n \) are the time domain and frequency domain label respectively. \( \hat{u}_{k,n} \) represents the estimate of the imaginary interference \( u_{k,n} \). From (15) it is evident that the smaller of the difference between \( \hat{u}_{k,n} \) and \( u_{k,n} \), the better the estimated effect is. The traditional auxiliary pilot cannot obtain \( \hat{u}_{k,n} \), so the \( \hat{h}_{k,n} \) is different from the real value. Feedback interference estimation algorithm and feedback interference calculation algorithm obtain approximately interference information through the proposed comb pilot.

In feedback interference estimation algorithm, the entire channel information is obtained by AP algorithm and interpolation in the first place. The channel response of the secondary pilots can be obtained by interpolating the channel response of the dominant pilots. For example, if linear interpolation is used, the channel response can be expressed as

\[ \hat{h}_{k,n} = \frac{y_{k,n}}{x_{k,n} + j u_{k,n}} = \hat{h}_{k,1} + \frac{j}{y_{k,n}} \]

(15)

where \( n_{d-1} < n < n_d \). \( \hat{h}_{k,n_d} \) is the dominant frequency channel response of the preceding time near the \((k, n)\), while the \( \hat{h}_{k,n_d} \) is the dominant frequency channel response at the posterior time near the \((k, n)\). Of course, other interpolation
algorithms can be used. For simplicity, linear interpolation is adopted as an example in this paper.

Then in the secondary pilots position, the corresponding transmission signal and the estimation of the interference information are obtained by using the received signal and the estimated channel information, which can be expressed as

\[ \hat{d}_{k,n} + j\hat{u}_{k,n} = \frac{y_{k,n}}{\hat{h}_{k,n}} \]  
\[ (17) \]

Since the pilot signal \( d_{k,n} \) is known, the estimation of the transmission signal obtained in (17) is corrected by \( d_{k,n} \). And then the feedback to the received signal is used to correct the estimated channel information, as shown in (18).

\[ \hat{h}_{k,n}^{(2)} = \frac{y_{k,n}}{d_{k,n} + j\hat{u}_{k,n}} \]  
\[ (18) \]

In (16) and (18), \( \hat{h}_{k,n}^{(1)} \) and \( \hat{h}_{k,n}^{(2)} \) represent the first and second estimation of the channel response respectively. Finally, the channel information acquired by the second estimation is interpolated to obtain the response of the whole channel estimation, with equalization and demodulation followed.

In feedback interference calculation algorithm, the entire channel information by AP algorithm and interpolation is firstly achieved. The channel response of the secondary pilots can be obtained by interpolating the channel response of the dominant pilots.

Then the interference information of the secondary pilots is calculated by using the estimated transmission signal after equalization and demodulation, which uses the estimated symbol around the secondary pilot symbol and the interference coefficients, as shown in equation (19). Thus, we can get \( d_{k,n} + \hat{u}_{k,n} \).

\[ \hat{u}_{k,n} = \sum_{(k',n') \in \Omega_{k,n}} \hat{d}_{k,n} \hat{t}_{k-k',n-n'} \]  
\[ (19) \]

where \( \hat{t}_{k-k',n-n'} \) represents the interference coefficient, and \( \hat{d}_{k,n} \) represents the symbol after demodulation, \( \Omega_{k,n} \) represents the interference calculation window around the secondary pilot, and \( \hat{u}_{k,n} \) represents the estimation of the interference information of the secondary pilot symbol.

After getting \( d_{k,n} + \hat{u}_{k,n} \), the channel response can be estimated once again by using (18). The channel response of the pilot subcarrier at each moment can be obtained, and then the channel information is acquired by re-interpolation, with the equalization and demodulation are carried out again. The feedback interference calculation algorithm is a recursive process, which can be conducted incessantly until a satisfactory performance. Since the focus of this article is not the number of feedback, but in the algorithm itself, and it can be seen once the feedback has a better performance, so this article does not discuss the number of feedback.

IV. SIMULATION RESULTS

In this section, we carry out a comparative study on the estimation performance of FBMC/OQAM in fast fading channel implementing the proposed the feedback channel estimate algorithms and the AP method. After simulation analysis, there are not many performance improvements in iterative feedback interference calculation, so the feedback interference calculation is followed by a feedback iterative simulation.

In all simulations, a Rayleigh multipath channel is adopted, with the multipath delay as \((0 1 2 3 4)T_s \), where \( T_s \) represents the sampling time, and the fading of each path as (-2.274 -4.413 -11.052 -18.500 -18.276)dB. The channel estimation uses LS estimation and linear interpolation algorithm. In all simulations, no channel coding is added. The remaining simulation parameters are shown in the table I.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SIMULATION PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subcarrier spacing</td>
<td>10.94kHz</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>11.2MHz</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>3.5GHz</td>
</tr>
<tr>
<td>Subcarrier number</td>
<td>1024</td>
</tr>
<tr>
<td>System bandwidth</td>
<td>10MHz</td>
</tr>
<tr>
<td>Baseband modulation order of OQAM</td>
<td>4</td>
</tr>
<tr>
<td>Overlap factor</td>
<td>4</td>
</tr>
<tr>
<td>Time domain interval of the pilot distribution</td>
<td>8</td>
</tr>
<tr>
<td>Frequency domain interval of the pilot distribution</td>
<td>4</td>
</tr>
</tbody>
</table>

Fig.9 shows the performance comparison at the speed on 300km/h. It is obvious that feedback interference estimation algorithm and feedback interference calculation algorithm based estimator provide much better estimation than Auxiliary Pilot based estimator. This is due to the insertion of pilot-intensive channel information obtained more, secondary pilots also use the inherent interference will reduce the interference error, so the performance becomes better.

Fig.10 shows the performance comparison at different speeds. It can be seen that the BER performance has significantly improvement after adding feedback compared with that using AP. At low speeds, the channel Doppler frequency is small and the channel change rate is low. The feedback channel estimation algorithms only calculate the interference of some
signals beside it, and the symbols far from it also interfere with it. Only relatively small, but there is also a superposition, so the differences between AP and the feedback channel estimate algorithms are small. However the performance improves with the increase of the speed of movement, i.e. the augment of Doppler frequency. This confirms that the feedback channel estimate algorithms can track the variation of rapidly fading channels status.

![Comparison of BER of Auxiliary Pilot and feedback channel estimate algorithms at different speeds](image)

As shown in all figures, the proposed feedback channel estimate algorithms have a better BER performance compared with AP. For the computational complexity, it is assumed that the number of total permissible pilots is $N_P$. Compared with the auxiliary pilot, feedback interference estimation algorithm adds $2N_P$ multiplication. Feedback interference calculation algorithm need to adds $20N_P$ multiplication, $18N_P$ addition, as well as one time-frequency interpolation, one equalization and one demodulation operation. And there is an output delay of the $K−1$ symbols since the interference of the pilot symbols is to be estimated in the both proposed algorithms. As a result, the computational complexity of the auxiliary pilot is less than that of the feedback interference estimation algorithm, and the most complexity is the feedback interference calculation algorithm.

For the spectrum utilization, it is assumed that the number of total permissible pilots for auxiliary pilot is $N_P$. Feedback interference estimation algorithm and feedback interference calculation algorithm use the same pilot insertion mode, and total pilots are $4N_P$, so the spectral utilization of the two are the same. It can be seen from Fig.4 and Fig.6, the comb pilot based on auxiliary pilot inserts more pilots than the auxiliary pilots, but there is no data loss, so its spectrum utilization is less than that of the auxiliary pilot algorithm.

In practice, the appropriate algorithm should be selected according to the specific application scenario. According to simulation results, as well as the analysis of computational complexity and spectrum utilization, the specific options are shown in the table II.

<table>
<thead>
<tr>
<th>Algorithm Selection</th>
<th>No Doppler frequency</th>
<th>Auxiliary Pilot</th>
<th>Small Doppler frequency</th>
<th>Feedback Interference Estimation</th>
<th>High Doppler frequency</th>
<th>Feedback Interference Calculation</th>
</tr>
</thead>
</table>

V. CONCLUSIONS

In this paper, a comb pilot based on auxiliary pilot and two corresponding feedback channel estimation algorithms are proposed for the estimation of FBMC/OQAM systems in the fast fading process. The simulation results showed that the BER performance of the proposed two feedback channel estimation algorithms based on the proposed pilot arrangement outperforms auxiliary pilot at Doppler frequency.

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