Post-Print: Weighted Channel Estimation Algorithm Based on Preamble Interference Cancellation for FBMC Systems

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Abstract

Aiming at the problem of imaginary interference in channel estimation for FBMC systems, a novel channel estimation algorithm is proposed. First, the algorithm employs a new pilot structure based on imaginary interference cancellation; then, two pilot columns are utilized to perform coarse channel estimation respectively; finally, a weighted approach is applied to the coarse channel estimation for fine channel estimation, further improving the channel estimation performance. Simulation results show that, compared with the conventional imaginary interference cancellation algorithm (IIE), the new pilot structure algorithm can achieve a performance gain of 1dB-2dB at a bit error rate of 1%.

Full Text

Preamble

Title: Weighted Channel Estimation Algorithm for FBMC Systems Based on Preamble Interference Cancellation

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Abstract: To address the imaginary interference problem in channel estimation for FBMC systems, this paper proposes a novel channel estimation algorithm. First, the algorithm employs a new pilot structure based on imaginary interference cancellation. Then, two columns of pilots are used for coarse channel estimation respectively. Finally, weighted processing is applied to the coarse channel estimates to perform refined channel estimation, further improving channel estimation performance. Simulation results demonstrate that compared with the conventional imaginary interference elimination (IIE) algorithm, the proposed pilot structure algorithm achieves a performance gain of 1-2 dB at a bit error rate of 1%.

Keywords: FBMC; interference cancellation; preamble sequence; channel estimation

0 Introduction

Future communication systems require higher spectral efficiency to accommodate the rapid growth of mobile traffic. Although Orthogonal Frequency Division Multiplexing (OFDM) offers advantages such as resistance to frequency-selective fading and narrowband interference, and has been widely adopted in various wireless communication systems, it requires a cyclic prefix (CP) as a guard interval to ensure system robustness, which reduces data transmission efficiency. Additionally, the rectangular window filter employed in the time domain of OFDM systems generates large side lobes in the frequency domain, causing severe spectral leakage. Filter Bank Multi-Carrier (FBMC) utilizes filters with excellent time-frequency localization properties that can improve spectral efficiency without requiring guard intervals to guarantee system stability. Consequently, FBMC has attracted significant attention from academia and industry as a candidate to replace OFDM in next-generation wireless communication systems [**?**, **?**, **?**, **?**].

FBMC only achieves orthogonality in the real domain, which causes imaginary interference between adjacent symbols. Therefore, FBMC employs Offset Quadrature Amplitude Modulation (FBMC/OQAM), where OQAM modulation ensures orthogonality between the real and imaginary parts at time-frequency lattice points to avoid imaginary interference. Accurate channel estimation is crucial for the reliability of FBMC/OQAM systems. Numerous scholars have conducted extensive and in-depth research on this problem. Reference [**?**] proposed the IDPOP algorithm, which utilizes rather than eliminates imaginary interference for channel estimation. Reference [**?**] adopted scattered pilots and introduced auxiliary pilots; the received dominant pilots use auxiliary pilots to cancel imaginary interference for channel estimation. This method has high complexity and is difficult to apply for channel estimation with high-density pilots. References [**?**, **?**] proposed blind channel estimation algorithms, where [**?**] exploits the statistical properties of received OQAM signals and interference components for channel estimation, requiring extremely high computational complexity as spatial symbols must be calculated at each subcarrier position. Preamble-based pilot structures are identical to block-type pilot structures in OFDM systems, with main channel estimation methods including Interference Elimination Method (IEM), Interference Approximation Method (IAM), and Pair of Pilots (POP) algorithm. Reference [**?**] proposed the POP algorithm, which derives channel frequency response by leveraging the property that the channel remains approximately constant across adjacent positions. Reference [?] proposed the New Pilot Structure (NPS) algorithm, which combines interference cancellation and interference utilization to create new preamble combinations and uses symmetric patterns to eliminate interference for channel estimation. Reference [?] employed the Auxiliary Pilot Method (APM), which uses data and auxiliary pilots to eliminate imaginary interference for channel estimation. Reference [?] proposed the Imaginary Interference Elimination (IIE) algorithm, which uses two identical columns of FBMC pilot symbols with opposite filter symbols at the first and second column pilot positions. The imaginary interference from the first column pilot' s received signal can be eliminated using the interference from the second column pilot' s received signal, and the first column pilot is used for channel estimation. Reference [?] proposed a new IAM algorithm that improves system estimation performance by increasing the power of pseudo-pilots, but this incurs large pilot overhead and reduces data transmission efficiency. In summary, the aforementioned preamble-based channel estimation algorithms do not fully utilize pilots for channel estimation, and their system performance remains to be improved.

This paper focuses on preamble-based channel estimation algorithms in FBMC/OQAM systems. The proposed new pilot structure utilizes two columns of pilots for mutual interference cancellation, employs both columns for coarse channel estimation respectively, and then applies a weighted algorithm to the coarse estimates for refined channel estimation. This algorithm considers both pilot-to-pilot interference and data-to-pilot interference, and finally uses linear weighted combination to further enhance channel estimation performance.

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1 FBMC/OQAM System Signal Model

The FBMC/OQAM baseband equivalent signal can be expressed as

$$s(t) = \sum_{m=0}^{M-1} \sum_{n} a_{m,n} g(t - nT_0) e^{j2\pi m F_0 t} e^{j\varphi_{m,n}}$$

where $a_{m,n}$ represents the real-valued symbol on the m-th subcarrier at the n-th time instant, M is the number of subcarriers, and $g(t)$ is the filter bank derived from the prototype filter through time-frequency offsets. F_0 denotes the subcarrier spacing, where $F_0 = 1/T_0$, with T_0 representing the OFDM symbol period and τ_0 representing the orthogonal offset between the real and imaginary parts of OQAM symbols. $\varphi_{m,n}$ is the phase generated by the orthogonality property, which can be any value; this paper takes $\varphi_{m,n} = \frac{\pi}{2}(m+n)$. The prototype filter $g(t)$ has excellent time-frequency characteristics, and its time-frequency transform yields the orthogonality property

$$\Re\{\int g_{m,n}(t)g^{*}_{p,q}(t)dt\} = \delta_{m,p}\delta_{n,q}$$

where δ is the Dirac delta function. From equation (3), when $(m,n) \neq (p,q)$, all values are purely imaginary. This indicates that the FBMC/OQAM system only satisfies orthogonality in the real domain, and perfect reconstruction can only be achieved when equation (3) holds. Assuming the channel experiences flat fading on each subcarrier, when the output is located at the p-th subcarrier and q-th FBMC/OQAM symbol, it can be expressed as

$$y_{p,q} = H_{p,q}a_{p,q} + \sum_{(m,n)\neq(p,q)} H_{m,n}a_{m,n}\zeta^{m,n}_{p,q} + \eta_{p,q}$$

where $H_{p,q}$ represents the channel frequency response, $\zeta^{m,n}_{p,q}$ denotes the imaginary interference, and $\eta_{p,q}$ represents additive white Gaussian noise.

2.1 Traditional Pilot Structure Algorithms

References [**?**, **?**] proposed two-column pilot structure algorithms that primarily employ imaginary interference cancellation. The main interference to the first column pilot symbols comes from the second column pilot symbols. However, through specific structural design of the second column pilot symbols and combining with filter interference coefficient weights, the primary interference can be eliminated. The main interference to the second column pilots comes not only from the first column pilot symbols but also from transmitted data symbols. The interference from the first column pilot symbols can be eliminated through the specific pilot structure, but the remaining data interference can be utilized. The prototype filter function and its interference coefficient weights are shown in Figure 3 [Figure 3: see original paper].

In reference [**?**], the filter corresponding to the first column pilot is shown in equation (2); the filter for the second column pilot is shown in equations (6) and (7). As shown in equation (8), different filters are used at pilot symbol positions in odd and even rows. The interference elimination principle for the first column pilot is as shown in equation (10). By combining the two columns of pilots at the receiver, the imaginary interference from the preceding column pilot can be eliminated and channel estimation can be performed.

The pilot structure in reference [**?**] is shown in Figure 1 [Figure 1: see original paper]. The relationship between data symbols and pilot symbols is expressed as

$$a^{0}_{m-2M,n} = a^{1}_{m-2M,n} = a^{2}_{m-2M,n} = a^{3}_{m-2M,n} = a^{4}_{m-2M,n} = d_{m-2M,n}$$

where $d_{m-2M,n}$ represents the transmitted data at time instant n, and $a^0_{m-2M,n}$ is the reference signal at even subcarriers at time instant n.

Although the second column pilot suffers from data interference, useful information for channel estimation exists. Therefore, coarse channel estimation is performed using both columns of pilots respectively, and weighted processing is applied to the coarse estimates to further improve performance. The flow structure of the new algorithm is shown in Figure 4 [Figure 4: see original paper].

2.2 New Pilot Structure Algorithm

The new pilot structure considers both pilot-to-pilot interference and data-to-pilot interference, while fully utilizing both columns of pilots for channel estimation. The new pilot structure is shown in Figure 2 [Figure 2: see original paper].

The data-to-pilot imaginary interference is expressed as

$$\rho_{m,n} = \sum_{d \neq m} d_{d,n} \cdot \text{interference coefficient}$$

where $\rho_{m,n}$ represents the imaginary interference from data $d_{d,n}$ to pilot $a_{m,n}$. The average interference across M pilot points is calculated as

$$\bar{\rho} = \frac{1}{M} \sum_{i=0}^{M-1} \rho_i$$

From equation (11), the first column pilot experiences almost no imaginary interference, so traditional LS channel estimation can be used to obtain relatively accurate channel frequency response. From equation (12), although the second column pilot suffers from right-side data imaginary interference, LS channel estimation yields relatively poor channel frequency response.

Since data interferes with both columns of pilots but the interference to the first column is small while interference to the second column is large, proportional weighting is applied to the channel estimates to improve accuracy. The refined channel estimate using weighted estimation is

$$\hat{H} = \lambda \hat{H}_0 + (1 - \lambda)\hat{H}_1$$

where $\hat{H}_0$ and $\hat{H}_1$ are the coarse estimates from the first and second pilot columns respectively. The weighting coefficient λ can be expressed as

$$\lambda = \frac{\rho_1}{\rho_0 + \rho_1}$$

where ρ_0 and ρ_1 represent the interference on the first and second column pilots respectively. The value of λ adapts with changing data.

Therefore, the new channel estimation algorithm can be transformed into solving for the proportional coefficient λ, whose value changes adaptively with the data.

3 Performance Analysis of New Pilot Structure Algorithm

To highlight the advantages of the proposed algorithm, its computational complexity is analyzed as follows:

a) **POP Algorithm**: The POP algorithm obtains channel frequency response through mathematical logic operations. Channel estimation requires $3M$ multiplications, M subtractions, and M LS channel estimation divisions. No filter information is needed.

b) **APM Algorithm**: The APM algorithm uses interpolation in channel estimation. It requires $4M$ multiplications, M subtractions, M channel estimation divisions, and $M/2$ interpolation calculations. Its complexity is higher than POP but provides better estimation performance.

c) **NPS Algorithm**: The NPS algorithm calculates equivalent pilots during channel estimation, requiring $4M$ multiplications, M additions, and M divisions. Its computational load is slightly lower than APM but with better estimation performance.

d) **IIE Algorithm**: The IIE algorithm inverts the filter at the second column pilot positions to handle interference from the first column pilot. It requires $4M$ multiplications, M filter inversion multiplications, M interference cancellation subtractions, and M channel estimation divisions. The algorithm complexity increases but performance improves.

e) **New Algorithm**: The proposed algorithm requires $4M$ multiplications, M inherent interference accumulation summations, two averaging operations, and M channel estimation divisions. Although its complexity is slightly higher than POP, similar to APM and NPS, and lower than IIE, it achieves optimal channel estimation performance within an acceptable complexity range.

4 Simulation and Analysis

To verify the performance of the proposed algorithm, the new pilot structure algorithm was simulated and validated for FBMC systems in MATLAB. The simulation parameters are shown in Table 1 .

Table 1 Simulation Parameter Settings

Parameter	Value
FFT Points	ITU-VA, ITU-PA
Filter Length L_g	(a)

As shown in Figure 5, five algorithms were simulated and compared under Gaussian channel for 4-OQAM, 16-OQAM, and 64-OQAM modulation schemes. Figure 5(a) demonstrates that the proposed algorithm achieves superior bit error rate (BER) performance across all modulation schemes. Figure 5(b) shows mean square error (MSE) simulation results, where MSE represents the error between ideal and estimated channels, indicating channel estimation quality. The MSE expression is

$$\mathrm{MSE} = \frac{1}{M}\sum_{i=0}^{M-1}\frac{\|H-\hat{H}_i\|^2}{\|H\|^2}$$

where H is the ideal channel value and $\hat{H}_i$ is the LS-estimated value. The proposed algorithm' s MSE is clearly superior to POP, APM, and NPS algorithms. Although its MSE is similar to IIE, the new algorithm has lower complexity. Overall, MSE and BER performance trends are consistent.

Although both algorithms use two-column pilots, reducing pilot overhead compared to traditional IAM algorithms, they only consider pilot-to-pilot interference without accounting for data-to-pilot interference, and utilize only one column for channel estimation. To address these issues, the new pilot structure algorithm is proposed.

Figure 6 shows BER simulation comparisons of the algorithms with different pilot columns under ITU-VA and ITU-PA channel models. In both PA and VA channel models, the second column pilot suffers significant data interference, resulting in the worst channel estimation performance. The first column pilot experiences less data interference and achieves better performance. The proposed weighted algorithm fully utilizes both pilot columns to obtain the best performance. Additionally, different channel parameters in various channel models cause performance variations.

Figure 7 presents BER performance comparisons under different channel models. The proposed algorithm achieves optimal BER performance in both VA and PA multipath channels. Traditional POP algorithm performs worst due to unreasonable pilot structure and poor noise immunity. APM algorithm' s auxiliary pilots are derived from transmitted first-column data with alternating odd-even symbols, and interpolation is used for channel estimation. Since interpolation cannot fully capture channel characteristics, its performance is only slightly better than POP. NPS algorithm uses three pilot columns, considering imaginary interference weights in symmetric structures for interference cancellation, showing improved performance over POP and APM but with increased pilot overhead. IIE algorithm reduces one pilot column while improving performance over NPS, but its pilot structure is susceptible to pilot value selection. The new pilot structure algorithm achieves optimal system performance through coarse and refined channel estimation using only two pilot columns.

Figure 8 shows MSE performance comparison curves for the pilot algorithms under VA and PA multipath channels. POP algorithm' s MSE performance is poor because its pilot structure design neglects noise and other interferences, resulting in large errors between estimated and true channel values. APM algorithm' s interpolation during channel estimation cannot fully represent the true channel, yielding poor performance. NPS algorithm increases equivalent pilot power but introduces data interference through its pilot structure. IIE algorithm does not fully utilize pilot symbols for channel estimation, losing some useful information. The new algorithm not only designs a special pilot structure for interference cancellation but also fully utilizes pilot symbols for channel estimation, achieving excellent MSE performance in Figures 8(a) and 8(b).

In summary, the proposed pilot structure fully utilizes both pilot columns for channel estimation. Through extensive simulation and comparative analysis, the algorithm achieves superior performance at low SNR. The correctness, feasibility, and superiority of the new algorithm are verified from various aspects.

5 Conclusion

With 5G approaching commercial deployment, FBMC systems are among the candidate technologies, making accurate channel estimation a key technology for 5G. Conventional channel estimation algorithms have limitations. This paper proposes a new pilot structure algorithm. Theoretical analysis and simulation results demonstrate that the proposed pilot structure uses mutual interference cancellation and weighted algorithms to obtain accurate channel estimation, achieving significant performance improvements compared to traditional POP, APM, and IIE algorithms. Therefore, the proposed pilot structure and algorithm are effective and feasible.

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