The Influence of ISI and an Improved Algorithm of Channel Estimation in the Chirp System

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Abstract. Chirp signal is widely used in communication, radar, sonar and ultrasonic systems. The impulse response of channel must be estimated in PSK chirp spread spectrum modulation systems which is a chirp signal multiplied by the PSK modulated signal. Due to the influence of filters and multipath channel, the received signal of current symbol will be affected by the interference of the previous symbol and the next symbol, the interference which is called intersymbol interference (ISI) can degrade the performance of channel estimation and demodulation. In this paper, based on BPSK chirp spread spectrum modulation system, we describe the received model, the channel estimation based on FFT and channel estimation of matched filtering, analyze the impacts of ISI on channel estimation. And we simulate the MSE of channel estimation and the simulation results are consistent with the analysis, then an improved method of channel estimation is proposed based on the analysis of the impact of ISI on channel estimation.

1. Introduction

Chirp signal that is also called Linear Frequency Modulation(LFM) signal is widely used in communication [1], radar systems for pulse compression [2], sonar systems for range and Doppler estimation [3] and ultrasonic system [4]. A chirp spread spectrum(CCS) modulation was introduced by Winkler in 1962 [1] in which a pair of linear chirps having opposite chirp rates were used for binary signalling. The CCS systems were adopted as a physical layer technology of the IEEE 802.15.4a standard for low-rate wireless personal area networks in 2007 [5].

The CSS systems are classified into the following two categories [6] - direct modulation (DM)-CSS and binary orthogonal keying (BOK)-CSS. In the DM-CSS systems, DM is a chirp signal multiplied by PSK modulation signals to achieve the purpose of spread spectrum, which is also called PSK chirp spread spectrum (PSK-CCS) modulation system.

The impulse response of the multipath channel must be estimated before chirp equalization for PSK-CCS modulation system. So we use the pilot symbols inserted into the data symbols to estimate the channel impulse response. Various channel estimation methods are described in [7-11]. The matched filtering which is one of the classic methods of multipath parameter estimation is proposed by Bell et al [7]. A matched filter algorithm is presented to determine the time shifts and amplitudes for each path in [7]. The least square (LS) method is used for channel parameter estimation, because not only it is simple, but also its performance is not subject to statistical properties of the channel [8] ~ [9]. A joint improved algorithm of multipath parameter estimation based on matched filtering and least square method is proposed in [10]. The channel estimation method based on FFT is described in [11],
the channel estimation based on FFT uses FFT to reduce the computational complexity, and it can obtain channel impulse responses of all paths simultaneously.

The received signal of the current symbol will be affected by the next symbol and the previous symbol because of the effects of transmitted filter, received filter and multipath channels, the interference which is called inter symbol interference (ISI) will degrade the performance of channel estimation and equalization. However, the influence of ISI on channel estimation is not mentioned in [7-11]. In this paper, we analyzed the influence of ISI on the channel estimation of matched filtering (MF) and FFT, and verified the analysis results through the simulation. Finally, we proposed an improved method for channel estimation based on the impact of ISI on channel estimation.

The rest of the paper is arranged as follows. In Section 2, we introduce the received model of the BPSK-CSS modulation system, then describe the channel estimation method of MF and FFT. In Section 3, we derive and analyze the impact of ISI based on the channel estimation of MF and FFT. Then, we simulate the influence of ISI on the channel estimation performance of MF and FFT under different channel and different SF. In Section 4, an improved method of channel estimation is proposed. Finally, we conclude the paper.

2. The Received Model and Channel Estimation of MF and FFT

2.1. The Received Model of PSK-CSS System

In the PSK-CSS system, we suppose that the bandwidth of the channel for the transmission is B, SF is called the spreading factor with \( SF \in \{3,4,\ldots,12\} \). A is the PSK modulation value of the transmitted bits, A = 1 or -1 for BPSK. So the transmitted signal can be written as follow.

\[
s(t) = Ae^{j2\pi(Bt^3/3Tc^3)} \quad |t| < \frac{Tc}{2}
\]

where \( Tc = \frac{2SF}{B} \) denotes the duration of the chirp signal, \( \mu \) called the chirp rate, denotes the instantaneous frequency change rate of the chirp signal and \( |\mu| = \frac{B}{2SF}, T_1 \) is initial phase.

When considering the discrete-time baseband equivalent signal, we transmit a sample every \( T = \frac{1}{B} \), then \( t = \frac{k}{B}, T_1 = \frac{K}{B}, K = -2SF - 1 \) and k is the discrete sampling index, so the discrete transmitted signal can be expressed as \( s(k) \).

\[
s(k) = Ae^{j2\pi\frac{2^{2}B^2}{3SF^2} \cdot \frac{k}{B}} = Ae^{j2\pi\frac{(k+k)^{2}}{3SF^2}}, k = -2SF - 1, \ldots, 0, 1, \ldots, 2SF - 1 - 1
\]

We define the convolution result of the transmitted filter, multipath channel and received filter as the time domain channel \( h(t, \tau) \), which is expressed as follows.

\[
h(t, \tau) = \sum_{l=-L_2}^{L_2} h_1 e^{j2\pi hl \delta (t - \tau)}
\]

where \( h_1 \) is the channel impulse response of path l, \( \tau_1 \) is the time delay of path l, \( L_2 - 1 \) is the maximum value of path l, \( L_3 \) is the maximum value forward of path l after passing the filter. And \( \lambda_l \) is the offset caused by the doppler of path l, in the static channel, \( \lambda_l = 0 \).

The discrete received signal is \( r(k) \)

\[
r(k) = \sum_{l=-L_1}^{L_2} h_1 s(k-l) + w(k) = \sum_{l=-L_1}^{L_2} Ah_1 e^{j2\pi(k+k-l)^{2}} + w(k)
\]

where \( w(k) \) is a zero-mean complex white Gaussian noise random process with variance \( E\{|w(k)|^2\} = \sigma^2 \) and is assumed independent with respect to \( s(k) \).

Equation (4) can also be expressed as a matrix.

\[
R = XH + W
\]

where \( R = [r_0, r_1, r_2, \ldots, r_{N-1}] \), \( N = 2SF \), \( r_i \) is the received signal of the i-th sampling in a chirp symbol. \( W = [w_0, w_1, w_2, \ldots, w_{N-1}] \) is Gaussian white noise vector. \( H = [h_{-L_2}, \ldots, h_{-1}, h_0, h_1, h_2, \ldots, h_{L_3-1}] \), \( X \) is the matrix of the transmitted signal.
where \( s_n^m \) is the transmission signal of the \( n \)-th sampling of the \( m \)-th chirp symbol.

### 2.2. Channel Estimation of MF

According to the principle of [7], the matched filter can be expressed as follows.

\[
m(k) = A^H e^{-j2\pi\frac{(k+K)^2}{2SF^2 + 1}}
\]

(7)

The channel estimation of matched filtering is the convolution of \( R(k) \) and \( m(k) \). If the transmitted signals of the previous symbol, current pilot symbol and the next symbol are the same, it can be expressed as cyclic convolution, we can get the channel estimation \( \hat{h}_{MF}(n) \).

\[
\hat{h}_{MF}(n) = \sum_{k=0}^{2SF-1} \left( \sum_{l=-L_1}^{L_2-1} A h_l e^{j2\pi\frac{2n(k+K-n)^2}{2SF^2 + 1}} + w(k) \right) A^H e^{j2\pi\frac{2n(k+K-n)^2}{2SF^2 + 1}} = h_{MF} + \tilde{w}(n)
\]

(8)

\[
h_{MF} = \sum_{k=0}^{2SF-1} \left( \sum_{l=-L_1}^{L_2-1} h_l e^{j2\pi\frac{2n(k+K-n)^2}{2SF^2 + 1}} \right)
\]

(9)

\[
\tilde{w}(n) = \sum_{k=0}^{2SF-1} \left( A^H w(k) e^{-j2\pi\frac{(k+K-n)^2}{2SF^2 + 1}} \right)
\]

where \( \tilde{w}(n) \) is the noise and the power is \( 2SF \sigma^2 \). When \( n = l \), \( h_{MF} \) is \( h_l 2SF \), otherwise \( h_{MF} \) is 0. So the channel estimation can be written as \( \hat{h}_{MF}(l) \).

\[
\hat{h}_{MF}(l) = h_l + \frac{1}{2SF} \tilde{w}(l)
\]

(10)

Equation (10) can also be expressed as a matrix \( \bar{H}_{MF} \).

\[
\bar{H}_{MF} = \frac{1}{2SF} \bar{X} \bar{H}
\]

(11)

where \( R \) is the received data of one chirp symbol, \( \bar{H}_{MF} = [h_0, h_1, h_2, ..., h_{L_2-1}]^T \) and \( \bar{X} \) is as follows.

\[
\bar{X} = \begin{bmatrix}
    s_n^m & s_n^{m-1} & \cdots & s_n^{-L_2+1} \\
    s_n^{m+1} & s_n^{m} & \cdots & s_n^{-L_2+1} \\
    \vdots & \vdots & \ddots & \vdots \\
    s_n^{m+L_2-2} & s_n^{m+L_2-3} & \cdots & s_n^{-1}
\end{bmatrix}
\]

(12)

However, if the transmitted signals of the previous symbol, the current pilot symbol and the next symbol are different, the received signal is \( \bar{R} = [r_0^m, r_1^m, r_2^m, ..., r_{N-1}^m, r_0^{m+1}, ..., r_{L_2}^{m+1}]^T \). \( r_i^m \) represents the received signal of the \( i \)-th sampling of the \( m \)-th chirp symbol, \( H = [h_{-L_1}, ..., h_{-1}, h_0, h_1, h_2, ..., h_{L_2-1}] \). \( \bar{X} \) is as follows.

\[
\bar{R} = \bar{X} H + W
\]

(13)

\[
\bar{X} = \begin{bmatrix}
    s_n^m & s_n^{m-1} & \cdots & s_n^{-L_2+1} \\
    s_n^{m+1} & s_n^{m} & \cdots & s_n^{-L_2+1} \\
    \vdots & \vdots & \ddots & \vdots \\
    s_n^{m+L_2-2} & s_n^{m+L_2-3} & \cdots & s_n^{-1}
\end{bmatrix}
\]

Then the channel estimation \( \bar{H}_{MF} \) is as follows.
\[ \hat{H}_{MF} = \frac{1}{2^{SF}} \hat{X}^H_{MF} \tilde{R} \]  

(14)

\[ \hat{X}^H_{MF} = \begin{bmatrix} (s_n^*)' & (s_n^*)' & \cdots & (s_{n-L}^*)' \\ 0 & (s_n^*)' & \cdots & (s_{n-L}^*)' \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & (s_{n-L+2}^*)' & (s_{n-L+1}^*)' & \cdots & (s_{n-L})' \end{bmatrix} \]

The channel estimation of MF needs to do a correlation for each path. If the number of multi-path is large, the complexity of MF is very high.

### 2.3. Channel Estimation based on FFT

The channel estimation based on FFT uses FFT to reduce the computational complexity, and it can obtain channel impulse responses of all paths simultaneously. If the transmitted signal of the previous symbol, the current pilot symbol and the next symbol are the same, firstly, the received data \( r(k) \) is despread, that is, the conjugate of the transmitted signal is multiplied to obtain \( \text{DesR}(k) \).

\[ \text{DesR}(k) = r(k) \text{conj}(s(k)) = \sum_{l=-L}^{L-1} h_l e^{j\frac{2\pi l^2}{2^{SF+1}}} e^{-j\frac{2\pi k(l+1)}{2^{SF+1}}} + A^H w(k) e^{-j\frac{2\pi k^2}{2^{SF+1}}} \]  

(15)

Then taking the FFT of vector \( \text{DesR}(k) \).

\[ \tilde{h}(n) = \sum_{k=0}^{2^{SF}-1} \left( \sum_{l=-L}^{L-1} h_l e^{j\frac{2\pi l^2}{2^{SF+1}}} e^{-j\frac{2\pi k(l+1)}{2^{SF+1}}} + A^H w(k) e^{-j\frac{2\pi k^2}{2^{SF+1}}} \right) e^{j\frac{2\pi kn}{2^{SF+1}}} \]  

(16)

For equation (16), when \( l = n \), the first item is not 0, otherwise it is 0, so

\[ \tilde{h}(n) = 2^{SF} h_n e^{j\frac{2\pi n^2}{2^{SF+1}}} + \tilde{w} \]  

(17)

The channel estimation based on FFT is \( \hat{H}_{FFT}(n) \).

\[ \hat{g}_{FFT}(n) = \frac{1}{2^{SF}} \tilde{h}(n) e^{-j\frac{2\pi n^2}{2^{SF+1}}} = h_n + \frac{1}{2^{SF}} e^{-j\frac{2\pi n^2}{2^{SF+1}}} \tilde{w} \]  

(18)

The process of equations (15), (16) and (18) can be expressed in the form of a matrix.

\[ \hat{H}_{FFT, ALL} = \text{diag} \left( e^{-j\frac{2\pi (0^2+0)}{2^{SF+1}}}, e^{-j\frac{2\pi (1^2+k)}{2^{SF+1}}}, \ldots, e^{-j\frac{2\pi ((2^{SF}-1)^2+k((2^{SF}-1)))}{2^{SF+1}}} \right) \cdot \text{IFFTW} \]  

(19)

where \( \text{IFFTW} \) is the IFFT matrix, and we can deduce that \( B \) is as follows.

\[ B = \begin{bmatrix} s_0^* & s_{n-1}^* & \cdots & s_n^* \\ s_1^* & s_{n-2}^* & \cdots & s_{n-1}^* \\ \vdots & \vdots & \ddots & \vdots \\ s_{n-L+2}^* & s_{n-L+1}^* & \cdots & s_{n-L}^* \end{bmatrix} \]

If only \( \hat{H}_{FFT} = [\hat{h}_0, \hat{h}_1, \hat{h}_2, \ldots, \hat{h}_{L-1}]^T \) is calculated, the channel estimation based on FFT can also be expressed as follows.

\[ \hat{H}_{FFT, ALL} = \frac{1}{2^{SF}} \hat{X}^H_{FFT} R \]  

(20)

where \( \hat{X}^H_{FFT} \) is taken from the rows 1 to \( L_2 \) of matrix \( B \), which is equal to \( X \) in equation (12). So, if the transmitted signals of the previous symbol, the current pilot symbol and the next symbol are the same, \( \hat{H}_{FFT} = \hat{H}_{MF} \).
If the transmitted signals of the previous symbol, the current pilot symbol and the next symbol are different, \( \tilde{X}_{\text{FFT}} \neq \begin{bmatrix} 0 \\ 1 \end{bmatrix} \), so there is ISI in \( \tilde{H}_{\text{FFT}} \).

3. The Impact of ISI on Channel Estimation

From the above analysis, if the transmitted signals of the previous symbol, the current pilot symbol and the next symbol are different, there will be ISI which degrades the performance of channel estimation and chirp demodulation.

3.1. The Impact of ISI on the Channel Estimation of FFT

The matrix \( X \) in the received signal of in equation (6) can be written as

\[
X = X_{\text{FFT, ideal}} + I_{\text{FFT,1}} + I_{\text{FFT,2}} - I_{\text{FFT,3}} - I_{\text{FFT,4}}
\]  
(21)

\[
X_{\text{FFT, ideal}} = \begin{bmatrix}
 s_{l_1}^m & \ldots & s_{l_1}^m & s_{l_1}^m & \ldots & s_{l_1}^m \\
 s_{l_1+1}^m & \ldots & s_{l_1+1}^m & s_{l_1+1}^m & \ldots & s_{l_1+1}^m \\
 \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
 s_{l_1}^m & \ldots & s_{l_1}^m & s_{l_1}^m & \ldots & s_{l_1}^m \\
 s_{l_2}^m & \ldots & s_{l_2}^m & s_{l_2}^m & \ldots & s_{l_2}^m \\
 \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
 s_{l_2}^m & \ldots & s_{l_2}^m & s_{l_2}^m & \ldots & s_{l_2}^m \\
 \end{bmatrix}
\]

\[
I_{\text{FFT,1}} = \begin{bmatrix}
 0 & \ldots & 0 & s_{n-1}^m & \ldots & s_{n-1}^m \\
 0 & \ldots & 0 & 0 & \ldots & s_{n-1}^m \\
 \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
 0 & \ldots & 0 & 0 & \ldots & 0 \\
 \end{bmatrix}
\]

\[
I_{\text{FFT,3}} = \begin{bmatrix}
 0 & \ldots & 0 & 0 & \ldots & 0 \\
 0 & \ldots & 0 & 0 & \ldots & 0 \\
 \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
 0 & \ldots & 0 & 0 & \ldots & 0 \\
 \end{bmatrix}
\]

Then the received signal in equation (5) can be written as follows.

\[
R = (X_{\text{FFT, ideal}} + I_{\text{FFT,1}} + I_{\text{FFT,2}} - I_{\text{FFT,3}} - I_{\text{FFT,4}})H + W = X_{\text{FFT, ideal}}H + I_{\text{FFT}}H + W
\]  
(22)

\[
X_{\text{FFT, ideal}}H \text{ indicates the received signal when the transmission signals of the previous symbol, the current pilot symbol and the next symbol are the same, then the channel estimation based on FFT of equation (20) can be written as}
\]

\[
\tilde{H}_{\text{FFT}} = \frac{1}{2SF} \tilde{X}_{\text{FFT}}R = \frac{1}{2SF} \left( \tilde{X}_{\text{FFT}}^H (X_{\text{FFT, ideal}}H + I_{\text{FFT}}H + W) \right) = \frac{1}{2SF} \left( H + \tilde{X}_{\text{FFT}}^H I_{\text{FFT}}H + \tilde{X}_{\text{FFT}}^H W \right)
\]  
(23)

\[
\text{ISI}_{\text{FFT}} = \frac{1}{2SF} \tilde{X}_{\text{FFT}}^H I_{\text{FFT}}H = \frac{1}{2SF} \left( \tilde{X}_{\text{FFT}}^H (I_{\text{FFT,1}} + I_{\text{FFT,2}} - I_{\text{FFT,3}} - I_{\text{FFT,4}})H \right)
\]  
(24)

\[
\tilde{X}_{\text{FFT}}^H I_{\text{FFT,1}}H \text{ and } \tilde{X}_{\text{FFT}}^H I_{\text{FFT,2}}H \text{ are the interference of the previous symbol and the next symbol to the current symbol respectively.}
\]

\[
\tilde{X}_{\text{FFT}}^H I_{\text{FFT,3}}H \text{ and } \tilde{X}_{\text{FFT}}^H I_{\text{FFT,4}}H \text{ are interferences caused by signals that are missing from the current symbol.}
\]

3.2. The Impact of ISI on the Channel Estimation of MF

The same to the channel estimation based on FFT, for the channel estimation of MF, the received signal in equation (13) can be written as follows.

\[
\tilde{R} = (X_{\text{MF, ideal}} + I_{\text{MF,1}} + I_{\text{MF,2}} - I_{\text{MF,3}} - I_{\text{MF,4}})H + W = X_{\text{MF, ideal}}H + I_{\text{MF}}H + W
\]  
(25)

\[
I_{\text{MF}} = I_{\text{MF,1}} + I_{\text{MF,2}} - I_{\text{MF,3}} - I_{\text{MF,4}}
\]

\[
X_{\text{MF, ideal}}, I_{\text{MF,1}}, I_{\text{MF,2}}, I_{\text{MF,3}} \text{ and } I_{\text{MF,4}} \text{ as is follows.}
\]
Then the channel estimation of matched filtering of equation (14) can be written as
\[
\hat{H}_\text{MF} = \frac{1}{2SF} (\hat{X}^H_{\text{MF,ideal}} + I_{\text{MF}})H + W = \frac{1}{2SF} (H + \hat{X}^H_{\text{MF,ideal}} + I_{\text{MF}} H + \hat{X}^H_{\text{MF,W}}) \quad (26)
\]
So the ISI of MF is
\[
I_{\text{ISI,MF}} = \frac{1}{2SF} (\hat{X}^H_{\text{MF,ideal}} + I_{\text{MF,2}} - I_{\text{MF,3}} - I_{\text{MF,A}})H \quad (27)
\]

3.3. Analysis of ISI Impact on Channel Estimation

From the above analysis, the effect of ISI decreases as SF increases, and the performance comparison of both channel estimation methods can be obtained according to the relationship between the transmitted symbols of the previous symbol(\(s_{m-1}\)), the current pilot symbol(\(s_m\)) and the next symbol(s_{m+1}).

1) If \(S_{m-1} = S_m = S_{m+1}\), there is no ISI and \(I_{\text{FFT,i}} = I_{\text{MF,i}} = 0, i = 1 \sim 4\), so the channel estimation of MF and FFT are the same.

2) If \((S_{m-1} = S_{m+1}) \neq S_m\), so \(I_{\text{FFT,i}} \neq 0, I_{\text{MF,i}} \neq 0, i = 1 \sim 4\). For \(h_0\), the ISI is the same for both methods. But for \(h_i (i > 0)\), the influence of ISI on FFT is the same for all path, while for MF, the influence of \(h_i (i < 0)\) increases with the increase of \(i\); the influence of \(h_i (i > 0)\) decreases with the increase of \(i\). For channels with large delay spread, the energy is mainly concentrated in \(h_i (i > 0)\) (such as ETU), so the channel estimation performance of MF is better. For channels with small delay spread, the energy is concentrated in \(h_i (i = 0)\) (such as AWGN), so the channel estimation based on FFT is better.

3) If \((S_{m-1} = S_m) \neq S_{m+1}\), \(I_{\text{FFT,i}} = I_{\text{MF,i}} = 0, i = 1 and 3, I_{\text{FFT,i}} \neq 0, I_{\text{MF,i}} \neq 0, i = 2 and 4\). For \(h_i (i > 0)\), the influence of ISI on FFT is the same for all path, while for MF, the influence of \(h_i (i < 0)\) increases with the increase of \(i\), so the channel estimation based on FFT is better.
4) If $S_{m-1} \neq S_m = S_{m+1}$, $I_{FFT,i} = I_{MF,i} = 0, i = 2$ and $4$, $I_{FFT,i} \neq 0, I_{MF,i} \neq 0, i = 1$ and $3$. For $\hat{h}_i (i > 0)$, the influence of ISI on FFT is the same for all path, while for MF, the influence of $\hat{h}_i (i > 0)$ decreases with the increase of $i$, so the channel estimation of MF is better.

We simulate the influence of ISI on the channel estimation of MF and FFT under different channels and different SFs. We suppose the system bandwidth is $B=3.6\text{MHz}$, and the simulation results of SF $= 3 \sim 5$ under different channels are shown in Fig. 1–3.

From Fig. 1, we can see that the gap between the MSEs of both methods become smaller with the increasing of SF. So we only consider SF $= 3$ when we compare the MSE performance of both methods under different relationships of the transmitted signal in Fig. 2–3.

From Fig. 2, we can see that, for a large time delay spread channel, the channel estimation performance based on FFT is better than MF when the transmitted signals of the previous symbol and the current pilot symbol are the same, otherwise, channel estimation of MF is better or the same. From Fig. 3, we can see that, for a small time delay spread channel, the channel estimation performance of MF is better than FFT when the transmitted signals of the next symbol and the current pilot symbol are the same, otherwise channel estimation based on FFT is better or the same. The simulation results are the same as the above analysis conclusions.

According to the results, we can choose the channel estimation method according to the time delay spread or the transmitted signals of the previous symbol and the next symbol.

![Fig.1 MSE comparison of both channel estimations for different SFs when channel is ETU](image1.png)

![Fig.2 MSE comparison of both channel estimations with different relationship of transmitted signal when SF is 3 under ETU channel and EVA channel.](image2.png)
4. Improved Method of Channel Estimation

We propose an improved method of the channel estimation according to the above analysis and the simulation results about the impact of ISI on channel estimation. The transmitted signals of the previous symbol and the next symbol and the time delay spread can affect the performance of channel estimation, so we can estimate root-mean-squared (RMS) delay spread ($\tau_{\text{RMS}}$) and the transmitted signals first, and then choose the channel estimation method according to the estimated signals and $\tau_{\text{RMS}}$.

Step 1. Firstly, $\tau_{\text{RMS}}$ is estimated according to the power delay profile (PDP) of preamble or pilot symbol [12].

Step 2. For each pilot symbol, we estimate the channel impulse response based on the channel estimation of MF and FFT respectively, $\hat{H}_{\text{MF1}}$ and $\hat{H}_{\text{FFT1}}$.

Step 3. When the first data symbol is equalized, we use the the channel estimation value of MF ($\hat{H}_{\text{MF1}}$) by default, and the equalization of the following data symbols use the selected channel estimation value.

Step 4. The channel estimation value of the pilot symbol is selected according to the signals of the data symbols estimated in step6 (the first time is step3), and the method is as follows.

If $\tau_{\text{RMS}}$ is greater than the threshold (configurable 0.2us), when the estimated value of the previous symbol is the same as the transmitted signal of the current pilot symbol, we choose the channel estimation of FFT, otherwise, choose the channel estimation of MF.

If $\tau_{\text{RMS}}$ is smaller than the threshold, when the estimated value of the next symbol is the same as the transmitted signal of the current pilot symbol, we choose the channel estimation of MF, otherwise, choose the channel estimation of FFT.

Step 5. Filter the selected channel estimation value to get $\hat{H}_{\text{Filter}}$.

Step 6. The filtered channel estimation value $\hat{H}_{\text{Filter}}$ is used to estimate the transmitted signals of the following data symbols, and then perform step 4.

Step 7: Perform steps 4, 5 and 6.

It can be seen from the simulation results in FIG. 4 that the MSE performance of the improved channel estimation is better than the channel estimation of MF and FFT.
5. Conclusion

For the PSK-CCS modulation system, the impulse response of channel must be estimated, but the channel estimation of the current pilot symbol will be affected by the ISI of the previous symbol and the next symbol because of the impact of the filters and multipath channel. In this paper, we analyzed and simulated the impact of ISI on channel estimation. From the analysis and simulation, we can get that the transmitted signals of the previous and next symbol and the time delay spread can affect the performance of channel estimation, and we proposed the improved method based on the transmitted signals and the time delay spread to improve the MSE performance of the channel estimation.

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