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Non Data-Aided SNR Estimation for UAV OFDM Systems

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Abstract: Signal-to-noise ratio (SNR) estimation is essential in the unmanned aerial vehicle (UAV) orthogonal frequency division multiplexing (OFDM) system for getting accurate channel estimation. In this paper, we propose a novel non-data-aided (NDA) SNR estimation method for UAV OFDM system to overcome the carrier interference caused by the frequency offset. First, an absolute value series is achieved which is based on the sampled received sequence, where each sampling point is validated by the data length apart. Second, by dividing absolute value series into the different series according to the total length of symbol, we obtain an output series by stacking each part. Third, the root mean squares of noise power and total power are estimated by utilizing the maximum and minimum platform in the characteristic curve of the output series after the wavelet denoising. Simulation results show that the proposed method performs better than other methods, especially in the low synchronization precision, and it has low computation complexity.

Keywords: unmanned aerial vehicle; orthogonal frequency division multiplexing; signal-to-noise ratio; parameter estimation; non data-aided

1. Introduction

Unmanned aerial vehicle (UAV), as a groundbreaking technology, has been widely used in many applications such as delivery, surveillance, video streaming and so on [1]. In UAV communication systems, high-speed data rate is required based on many actual scenarios. For example, considering that UAV collects high-resolution images to describe the geometry of objects, we are expected to establish reliable data transmission links and provide enough bandwidth to ensure stable and accurate image transmissions. Orthogonal frequency division multiplexing (OFDM), as a high-speed data transmission method, splits the data stream across several separate narrowband channels at different frequencies to reduce interference and crosstalk [2,3]. Leveraging OFDM into UAV communication requires the knowledge of exact UAV communication channels which have the following characteristics. First, since a UAV is on a certain flight height and the ground station uses directional control antennas, there are a strong direct signal component and a Gaussian white noise [4]. Second, as UAV usually has a flight speed, the Doppler effect is generated accordingly [5]. Third, there are multipath components caused by different propagation paths and the frequency selective fading in such air-to-ground channels [6]. According to these characteristics, the amplitude and the phase of each subcarrier will change more randomly with carrier frequency offset, timing offset and frequency selective fading, which leads to the fading in both time and frequency domains and the inter-symbol interference (ISI).

Therefore, how to accurately detect the changed factors and demodulate the original signals at ground receiver under such UAV OFDM system is of great significance in UAV communication systems [7–9].

To ensure a desired communication performance, signal-to-noise ratio (SNR) needs to be well estimated, since accurately estimating SNR value guarantees the adaptive adjusted communication rate, modulation and coding schemes [10,11]. In addition, the forward error correction coding and decoding code rate also requires real-time SNR estimation value. Affected by the fluctuated amplitude and phase of each subcarrier in UAV OFDM systems, SNR can be time-varying and thus is difficult to be estimated. There are two SNR estimation methods for OFDM system, that is, data-assisted (DA) estimation and non-data-assisted (NDA) estimation. Specifically, DA estimation method utilizes transmitted pilot symbols to obtain estimated value. However, the redundant pilot symbols decrease system throughput. NDA estimation method allows an in-service and inter-systems SNR estimation without the prior transmitted signals [12]. In existing works, some NDA SNR estimation methods have been proposed. References [2,12,13] estimated the SNR by utilizing the characteristic of OFDM symbols. However, high complexity of multi-path channel order estimation algorithm leads to high computation complexity and low estimation accuracy. Reference [14] proposed an algorithm for signal reconstruction by utilizing the auto-correlation functions of the received signal and the reconstructing signal. However, it had high computation complexity and was hard to achieve. In contradiction to the traditional maximum likelihood (ML) SNR estimation, the problem of finding the roots of a polynomial of third degree was avoided by a convenient approximation proposed in Reference [15]. Also, in Reference [16], a method for estimating the order and SNR of NDA channel based on time-varying autocorrelation function was designed for OFDM systems. A new closed-form expression of the time-varying autocorrelation function (TVAF) for the received signals was obtained. The proposed estimation method achieved significant performance gains in low SNR region while maintaining satisfactory performance gain in high SNR region. Reference [17] showed the feasibility of utilizing zero subcarrier to measure noise power and verified its performance through simulations. Reference [18] proposed a novel SNR estimation algorithm for OFDM system in the doubly selective channels by inserting special preambles. The noise variance was estimated by one preamble symbol in time domain. A modified ML method was proposed in Reference [19], which uses the redundant information of the cyclic prefix to work directly in the time domain and can be applied to any unary or non-unitary constellation. Reference [20] proposed a NDA estimation method for estimating primary signal transmission parameters in OFDM overlay system, using only the available fast Fourier transform (FFT) component of the secondary user. The method did not need any prior knowledge of the primary signal or the environmental noise. In Reference [21], the joint ML estimation of SNR was established by using the representation structure of the training preamble consisting of multiple identical parts. A new expression of Cramer-Rao bound for the joint estimation of all unknown parameters was given to evaluate the final accuracy of ML method. In Reference [22], the SNR estimation utilized two identical semi-characteristics of time synchronization preambles in OFDM system and depended on their autocorrelation. The existing estimator was compared with the normalized mean square error (NMSE) in single-input-single-output (SISO) SNR estimation method. Heretofore, lots of SNR estimation methods have been put forward but most of them still have not considered the effect of frequency offset. In Reference [23], the influence of frequency offset on SNR was analyzed. Under the premise of prior information, the SNR was estimated when the signal has frequency offset. However, it had high computation complexity. Therefore, we study the SNR estimation in UAV OFDM system with the frequency offset.

In this paper a novel low-complexity NDA SNR estimation method is proposed for UAV OFDM system, consisting of three main components, an absolute value series, the maximum and minimum platform in the characteristic curve of the output series and the root mean squares. The main innovative contributions of the proposed method are summarized as follows—first, an absolute value series is achieved which is based on the sampled received sequence, where each sampling point is validated by the data length apart. Second, by dividing absolute value series into the different series according to the total length of symbol, we obtain an output series by stacking each part. Third, the root mean squares of noise power and total power are estimated by utilizing the maximum and minimum platform in the characteristic curve of the output series after the wavelet denoising. Simulation results show that the proposed method is effective and feasible conditioned on the poor synchronization precision (containing residual frequency offset) with lower computation complexity and better performance compared with other methods.

The rest of this paper is organized as follows. The signals model of UAV OFDM system is presented in Section 2. The proposed NDA SNR estimation method is introduced in Section 3. Section 4 shows the numeric simulation and discussion to verify the estimation performance. Finally, in Section 5, we conclude the main work of this paper.

2. Signals Model of UAV OFDM

2.1. UAV Channel Model

The UAV OFDM system model is shown in Figure 1. We consider the NDA SNR estimation for UAV OFDM with ground station in multipath propagations. The transmitted OFDM signals can be reflected by the urban barriers, such as buildings, and OFDM subcarrier signal bandwidth is relatively small and generally smaller than channel coherent bandwidth, which belongs to narrowband signal. Thus, multipath channel model can be used as a UAV downlink channel model where the OFDM narrowband signal experiences multiple impulse responses at ground station. The channel impulse response [24] is given as

$$h = [h_0, h_1, \ldots, h_l], \tag{1}$$

where $h_l(l = 0, 1, \ldots, L)$ and L are the the gain of the l-th path and the channel order, respectively. And l-th is assumed to be equal to the maximum delay of the multipath channel.

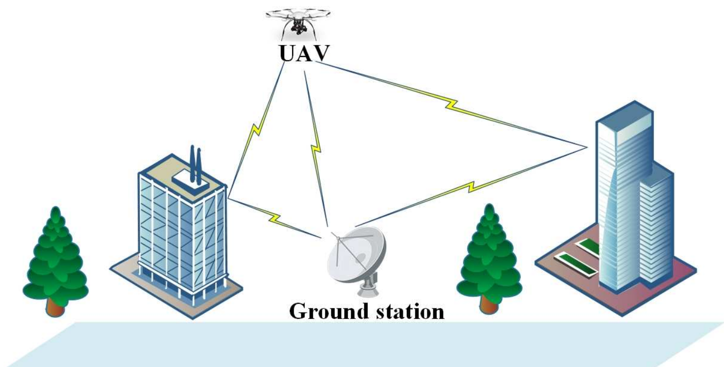

Figure 1. Unmanned Aerial Vehicle (UAV) Orthogonal frequency division multiplexing (OFDM) system model.

2.2. The OFDM Model over UAV Channel

In an OFDM system, the mth transmitted signal sample [25] is given by

$$x_m(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_m(k) e^{j\frac{2\pi k}{N}(n-N_c)}, \qquad n = 0, 1, \ldots, N + N_c - 1, \tag{2}$$

where $X_m(k), k = 0, 1, \ldots, N-1$, is modulated data of the m-th OFDM symbol, N and N_c are the total number of sub-carriers and the size of cyclic prefix (CP), respectively. Suppose $X_m(0), \ldots, X_m(N-1)$ are independent and identically distributed random variables.

The OFDM model under UAV channel conditions is shown in Figure 2. To avoid the ISI, L is assumed to be less than N_c. Now supposing that the symbol timing and frequency offset have been synchronized, then the received sampling signal transmitted through multipath channel can be given by

$$\begin{aligned} y_m(n) = &\sum_{l=1}^{L} h_l x_{m-1}(N_c + N + n - l)U(l - n - 1) + \sum_{l=0}^{L} h_l x_m(n-l)U(n-l) + v_m(n), \\ &n = 0, 1, \ldots, N + N_c - 1, \end{aligned} \tag{3}$$

where $U(\cdot)$ is the step function, $v_m(n) \sim N(0, \sigma^2)$ represents additive white Gaussian noise (AWGN) with mean 0 and variance σ^2 and $E\left[v_m(n)v_m^*(n+\tau)\right] = \sigma_v^2 \delta(\tau)$.

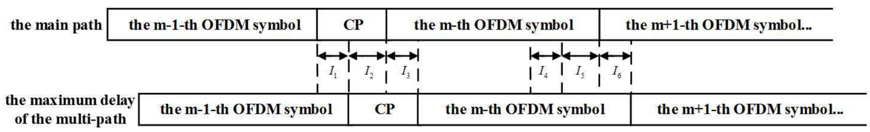

Figure 2. OFDM model signals over UAV channel.

3. The Proposed NDA SNR Estimation Method

Suppose the sample sequence of the received OFDM signal is $r(k), k = 1, \ldots, N_r$, where k and N_r are the k-th sampling point and the total number of sampling points, respectively. Provided that the parameters have been estimated accurately and N is the length of the valid signal data. Define $y(k)$ as

$$y(k) = r(k) - r(k-N). \tag{4}$$

It is assumed that the frequency offset has been perfectly estimated and compensated without considering the influence of the dispersion channel, then, the received signal are given as

$$y(k) = s(k) + n(k) - s(k-N) - n(k-N), \tag{5}$$

where $s(k)$ and $n(k)$ represent the signal component and noise component of the k-th slot, respectively. According to the characteristics of the OFDM signal with CP, there are two different situations. When $s(k) = s(k-N)$, $s(k)$ and $s(k-N)$ represent the copied OFDM symbol and CP symbol, respectively. When $s(k) \neq s(k-N)$, $s(k)$ and $s(k-N)$ represent two samples from different systems, respectively.

In addition, the transmitted signal, which is composed of a large number of independent information flows, can be accurately modeled as a complex Gaussian process. Since each term of $y(k)$ obeys Gaussian distribution, $|y(k)|$ obeys Rayleigh distribution. Suppose that the power of the desired signal is σ_s^2 and the noise power is σ_n^2 in $y(k)$ and the power of the complex Gaussian variable z is σ^2, then, (6) can be established.

$$E\left[|z|\right] = \sqrt{\frac{\pi}{2}}\sigma. \tag{6}$$

When $\tilde{v}_m(n) = v_m(n+N) - v_m(n)$, it can be easily proved that $\tilde{v}_m(n)$ is a Gaussian noise with mean zero, variance $\sigma_{\tilde{v}}^2 = 2\sigma_v^2$ and the proof process is

$$\begin{aligned} E\left[|\tilde{v}_m(n)|^2\right] &= E\left[|v_m(n+N) - v_m(n)|^2\right] \\ &= E\left[(v_m(n+N) - v_m(n))(v_m(n+N) - v_m(n))^*\right] \\ &= E\left[|v_m(n+N)|^2\right] + E\left[|v_m(n)|^2\right] = 2\sigma_v^2. \end{aligned} \tag{7}$$

Therefore, when $s(k) = s(k-N)$, we can get

$$y_{abs}(k) = E\left[|y\left(k\right)|\right] = \sqrt{\frac{\pi}{2}} \cdot \sqrt{2}\sigma_n = \sqrt{\pi}\sigma_n, \tag{8}$$

otherwise, when $s\left(k\right) \neq s\left(k-N\right)$, we obtain

$$y_{abs}(k) = E\left[|y\left(k\right)|\right] = \sqrt{\frac{\pi}{2}} \cdot \sqrt{2\left(\sigma_s^2+\sigma_n^2\right)} = \sqrt{\pi} \cdot \sqrt{\sigma_s^2+\sigma_n^2}, \tag{9}$$

provided that $y_{abs}(k)$ is a periodic sequence and its period is the symbol total length. The total length is known before estimating SNR. Divide the sequence according to the symbol total length and stacking each part. This stacking method can get a better statistical result based on little intercepting data. y_{acc} is expressed as

$$y_{acc}(i) = \frac{1}{M}\sum_{j=1}^{M} y_{abs}\left(i + j \cdot N_T\right), \tag{10}$$

where M is the complete intercepted OFDM symbolic number, N_T is the OFDM symbol total length. Therefore, the sequence length of y_{acc} always equals the symbol total length.

Owing to the influence caused by multipath channel, there is a transition part between the maximum and minimum platforms. This part is caused by the CP with ISI. Figure 3 illustrates the characteristic curve of y_{acc} after the fourth-order Haar wavelet denoising. From Figure 3, we observe that the maximum and minimum platforms are attained by utilizing the characteristic curve after the wavelet denoising. There is a minimum platform in the characteristic curve after wavelet denoising, which also exists in the original characteristic minimum platform part. Therefore, this method can not only extract the mean square of the noise power but also can avoid estimating the maximum delay of the multipath channel of the signals. For extracting the maximum platform, first calculate the average of the data sequence after denoising, then all the parts being larger than the average are supposed to be the maximum platform parts.

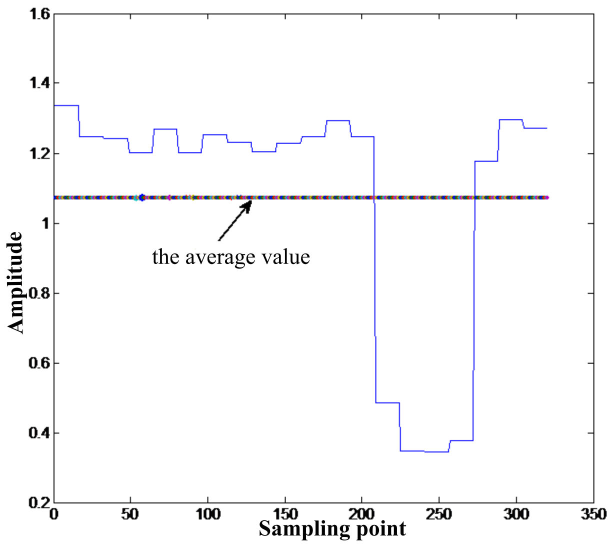

Figure 3. The characteristic curve of y_{acc} sequence after the wavelet transform.

The maximum platform and the minimum platform extracted by the proposed method are corresponding to the root mean square of real noise power and total power in Figure 3. Hence, the proposed method is effective. In order to use less data and get more accurate results, averaging y_{acc} relative to the minimum and maximum platforms to get the root mean square of the noise power and total power.

The smaller values represents the root mean square of the noise power and the larger values represents the root mean square of the power of the signal plus noise. Define $y_{acc\_\max}$ as the maximum values and $y_{acc\_\min}$ as the minimum values, then the root mean square of noise power and total signal power root mean square are given by

$$\hat{\sigma}_n = mean\left(y_{acc}\left(i\right)\right), i \in y_{acc\_min}, \tag{11}$$

$$\hat{\sigma}_t = mean\left(y_{acc}\left(i\right)\right), i \in y_{acc\_max}, \tag{12}$$

where $\hat{\sigma}_n$ and $\hat{\sigma}_t$ are the the root mean square of the noise power and the total signal power, respectively.

Thus, the estimated SNR for UAV OFDM system can be derived from the (11) and (12) as

$$\widehat{SNR} = \left(\frac{\hat{\sigma}_t}{\hat{\sigma}_n}\right)^2 - 1. \tag{13}$$

In conclusion, the steps of the NDA SNR estimation of UAV OFDM are as follows:

Step 1: Sample the received OFDM signals with a sampling sequence $r\left(k\right), k = 1, \ldots, N_r$ and then get a difference sequence $y(k)$, where each point in $y(k)$ is valid data length sampling points apart;

Step 2: Divide $y_{abs}(k)$ according to the symbol total length and get an output series y_{acc} by stacking each part. Then, obtain the characteristic curve of y_{acc} after the Haar wavelet denoising and extract the maximum and minimum values platforms $y_{acc\_\max}$ and $y_{acc\_\min}$;

Step 3: Calculate the root mean square of the noise power based on (11);

Step 4: Calculate the root mean square of the total signal power based on (12);

Step 5: Calculate the $\widehat{SNR}$ of UAV OFDM based on (13).

4. Numeric Simulation and Discussion

In this section, the effectiveness of the proposed method is verified by simulation. Suppose that the OFDM model is 802.16e OFDM, with the CP of 1/4 and the size of IFFT is 256. The downlink channel of UAV models are SUI-1, GSM TU6 and 9-path fading channel. The gain [25] of each path is

$$E\left(|h_l|^2\right) = e^{-l/3} \Bigg/ \left(\sum_{l=0}^{8} e^{-l/3}\right), \qquad l = 0, 1, \ldots, 8. \tag{14}$$

Performance is evaluated in terms of the estimation bias G_{bias} defined as $G_{bias} = E\left[\widehat{SNR} - SNR\right]$, where $\widehat{SNR}$ is the estimated SNR and SNR is the corresponding input SNR.

4.1. SNR Estimation Performance with Different Number of Symbols

Figure 4 illustrates the performance of the estimated SNR under three different multipath channel conditions. It can be seen from the Figure 4 that the proposed estimation method performs well for SUI-1 channel and exponential fading channel but a little bit dissatisfied for the TU6 channel due to its large maximum delay and attenuation factor of each path. However, even if the input SNR is −2 dB, the maximum estimation error does not exceed 1.2 dB, so the SNR estimation is effective.

Figure 5 illustrates the performance of the estimated SNR when using different numbers of OFDM symbols under the different multipath channel conditions. The dotted line indicates the estimation performance when using 400 OFDM symbols while the solid line shows the estimated performance when using 100 OFDM symbols. It can be seen from Figure 5 that more OFDM symbols result in better estimation performance.

The NDA SNR estimation performs well in SUI-1 and exponential fading channel, with low estimation bias (less than 0.4 dB). For TU6 channel, even if the estimation bias becomes slightly larger (about 1 dB) due to its large attenuation coefficient, the method is also effective for SNR estimation.

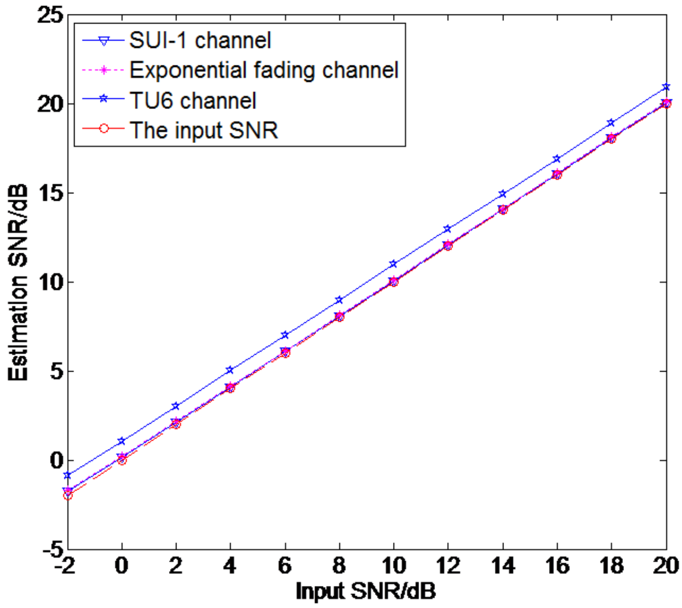

Figure 4. Comparison of the Input Signal-Noise-Ratio (SNR) with the Estimated SNR.

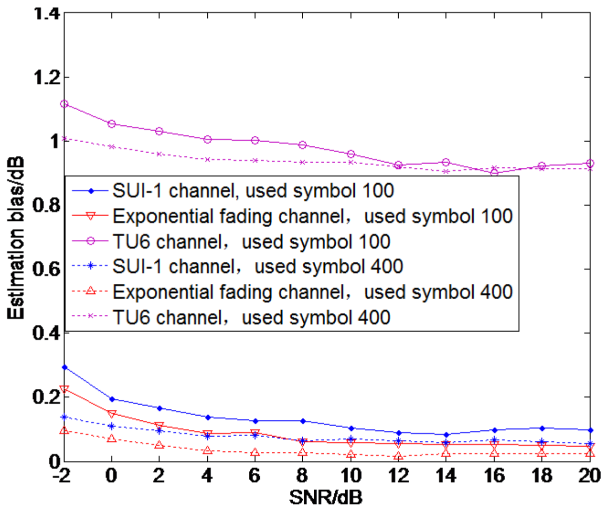

Figure 5. Estimation performance with different number of symbols.

4.2. SNR Estimation Performance with Different Frequency Offsets

In order to verify the SNR estimation performance of the proposed method with different frequency offsets. Figure 6 illustrates the effect of different normalized frequency offsets on the estimated SNR under different SNRs. In Figure 6, we observed that the estimation bias increases with the frequency offset due to the increasing introduced interference. As the SNR increases, the influence of the frequency offset on the estimated value increases gradually. The interference introduced by the frequency offset is handled as noise. Under the condition of knowing the signal power, the estimation deviation increases with the SNR since the total noise power becomes enlarge with the frequency offset [26].

In order to verify that the proposed method is still feasible after effective frequency offset estimation and frequency offset compensation, this paper uses the frequency offset estimation method introduced in Reference [27] to estimate the frequency offset and the frequency offset compensation. Then, the compensated received sequence is used to estimate SNR. Figure 7 describes the comparison of the estimation performance between the circumstances of compensating frequency offset (solid line) and no frequency offset (dashed line). After the frequency offset has been estimated and compensated, the proposed method still performs well (no more than 0.1 dB compared to no frequency offset).

As a result, the proposed SNR estimation method is still effective after the frequency offset has been estimated and compensated.

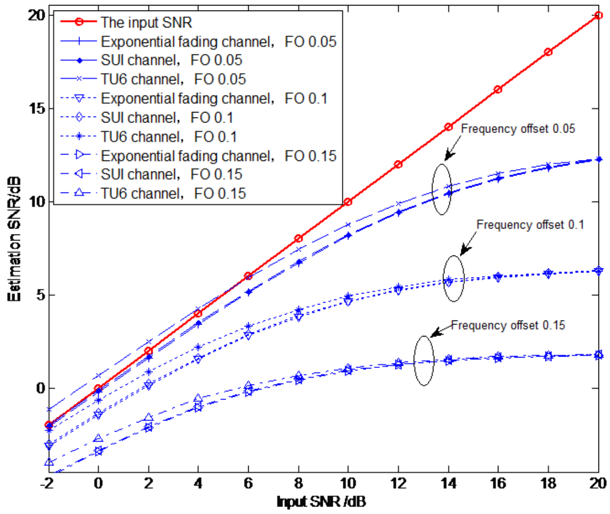

Figure 6. Estimation performance with different frequency offsets.

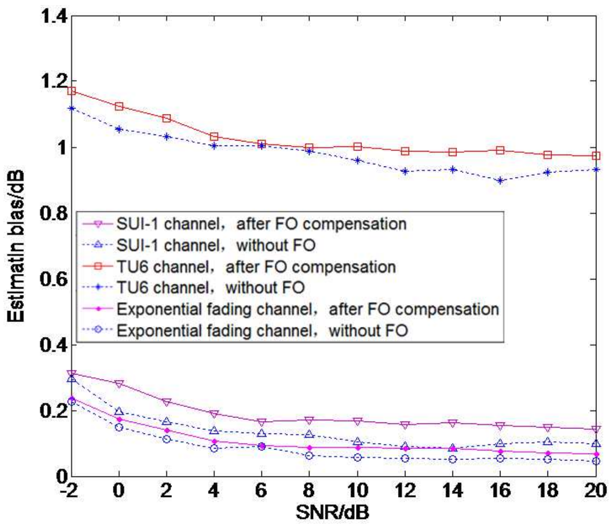

Figure 7. Comparison of compensating frequency offset with no frequency offset.

4.3. Estimation Performance Comparison of Different SNR Estimation Methods

Figure 8 describes the comparison between the improved method and the method in Reference [2] under three different multipath channels. The two methods are both effective for exponential fading channel and SUI-1 channel. For TU6 channel, the estimation bias of the method in Reference [2] becomes larger when SNR lies in 5 dB and 18 dB and this characteristic is presented in SUI-1 channel. The main reason is that Reference [2] used the minimum description length (MDL) to estimate the maximum delay in multipath to obtain the non-inter-symbol interference data interval. However, once the delay of multipath channel becomes longer, this method will obtain a large estimation bias under low SNR and thus part of the used data will have the ISI when estimating the SNR. When the SNR is low (less than 2 dB), the bias caused by the inter-symbol interference is not so obvious compared to the noise power, therefore, the SNR estimation bias is not so large. However, when having the middle SNR (between 4 dB and 18 dB), compared to the noise power, the bias caused by ISI becomes larger, thus the estimation bias becomes enlarged. When the SNR is greater than 18 dB, the MDL achieves a higher accuracy when estimating the maximum delay of multipath channel. There is no ISI in the data used to estimate the SNR, as a result, the estimation bias declines again. This problem does not exist in the proposed method due to it does not need to estimate the maximum delay of multipath channel.

Besides, the main computation complexity lies in the wavelet denoising, the computation complexity of the wavelet denoising is $O(N)$, where N is the data length of denoising. In this paper, we have $N = 320$ and the computation complexity of [2] is $N_c(N_c - 1)M/2 + (N_c - 1)^3/6$, where $N_c = 64$. It can be seen clearly from this comparison, the computation complexity of this paper is lower than that of Reference [2]. In conclusion, when the delay of multipath channel is large, the method in Reference [2] are not available enough, while the proposed method is still effective and well-performed with lower complexity. As a result, the proposed method is more suitable for UAV OFDM system than method in Reference [2].

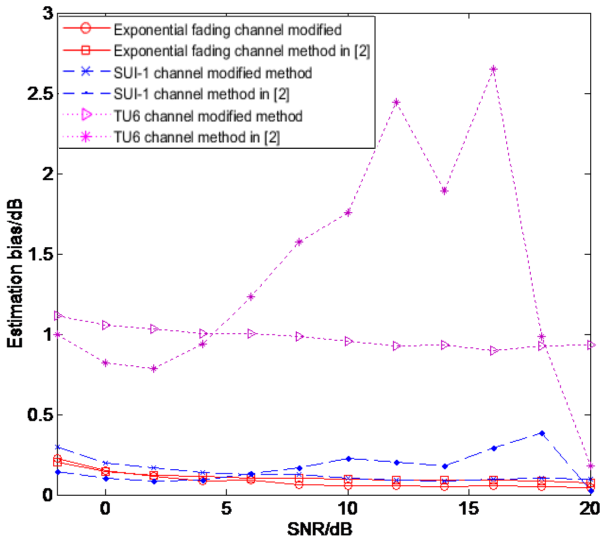

Figure 8. Comparison of different SNR estimation methods.

5. Conclusions

In this paper, we proposed a novel NDA SNR estimation method for UAV OFDM systems. Due to the method does not need to estimate the maximum delay of multipath channel, the method is still effective in multipath fading channels after the frequency offset has been estimated and compensated. When the number of OFDM symbols is increased, better estimation performance can be obtained. Simulation results demonstrate that the proposed method is well-performed in the condition of poor synchronization precision (containing residual frequency offset) and has a lower computation complexity compared with other method, which is more suitable for UAV OFDM system. It should be noted that the proposed method is a time-domain estimation method and its performance is not as well as the frequency-domain estimation method. We will further study the frequency-domain estimation method.

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