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Performance analysis of broadband satellite communication system based on OFDM/TDM

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Abstract

Orthogonal frequency division multiplexing (OFDM) is attracting more attention for its capability of high speed transmission. However, the OFDM possesses an obvious shortage in its high ratio of the peak power to the average power (PAPR), which has become the main issue holding it back to be applied to the broadband satellite communication system. OFDM combined with time division multiplexing (TDM), dividing the subcarriers of OFDM into some blocks in time tune, can decrease the high PAPR of OFDM. Meanwhile, the advantages of OFDM can be preserved. In this paper, OFDM/TDM is applied to the broadband satellite communication system. This paper theoretically analyses OFDM/TDM system model as well as its restraining effect on PAPR, and proposes frequency domain multiplexing-pilot (FDM-Pilot) channel estimation algorithm. Simulation results show OFDM/TDM in broadband satellite communication system has approving performance and decreased the PAPR.

Keywords OFDM/TDM, broadband satellite communication system, PAPR, channel estimation

1 Introduction

The broadband satellite communication system, which has been dramatically developed to meet a fast growing demand of its using, is going to play an important role in the future air-space-ground of integrated communication network. In the past few years, OFDM is successfully applied in various wireless communication systems, e.g. digital video broadcasting (DVB), wireless local area networks (WLAN) [1]. OFDM has the advantages of high spectrum efficiency, robustness to the interference and fitness for the frequency-selective fading, et al. For above reasons, OFDM became one of the key technologies in beyond the 3rd generation mobile communication (B3G) system, the 4th generation mobile communication (4G) system [2]. However, it has not been included in the broadband satellite standards. Many researches are being considered for the development of a satellite radio interface using OFDM and the study results are being standardized in various standardization bodies [3–5]. So the research of the key technologies using OFDM for the broadband satellite system is essential.

On the other hand, as multicarrier modulation system, OFDM signal is generated from the addition of many of orthogonal subcarrier signals modulated. If the phases of the subcarrier signals are consistent, the instantaneous power of the signal will be far greater than its average power, and it causes large PAPR. The peak power is proportional to the number of subcarriers [1]. High PAPR is the main defect of OFDM, which affects its application in broadband satellite communication system. In the implement, the nonlinear high power amplifier (HPA) with a large dynamic range should be used. Otherwise the peak is in the nonlinear range to lead to the spectrum spread and the increase of the bit error code ratio (BER) caused by signal distortion in band. Therefore, to apply OFDM to

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broadband satellite communication and make it work well, PAPR of the signal must be reduced.

In order to overcome the PAPR problem of OFDM and ensure the system performance and reduce the system complexity, Gacanin et al. proposed to combine OFDM with TDM to form OFDM/TDM system [6–7], which is also called generalized OFDM (GOFDM), this system divides the long inverse fast Fourier transform (IFFT) operation time window of OFDM signal into several blocks, each block contains the reduced the number of subcarriers to reduce the PAPR. Considering the characteristics of OFDM/TDM, OFDM/TDM applied to the broadband satellite communication system can take advantage of OFDM, improve system performance and efficiently utilize the spectrum, and reduce the PAPR of OFDM. This paper theoretically analyses the OFDM/TDM system model and its inhibitory effect of the PAPR, at the same time, proposed a channel estimation method to improve system performance. The computer simulation results are given later, which indicates OFDM/TDM in broadband satellite communication system has approving performance and decreases the PAPR.

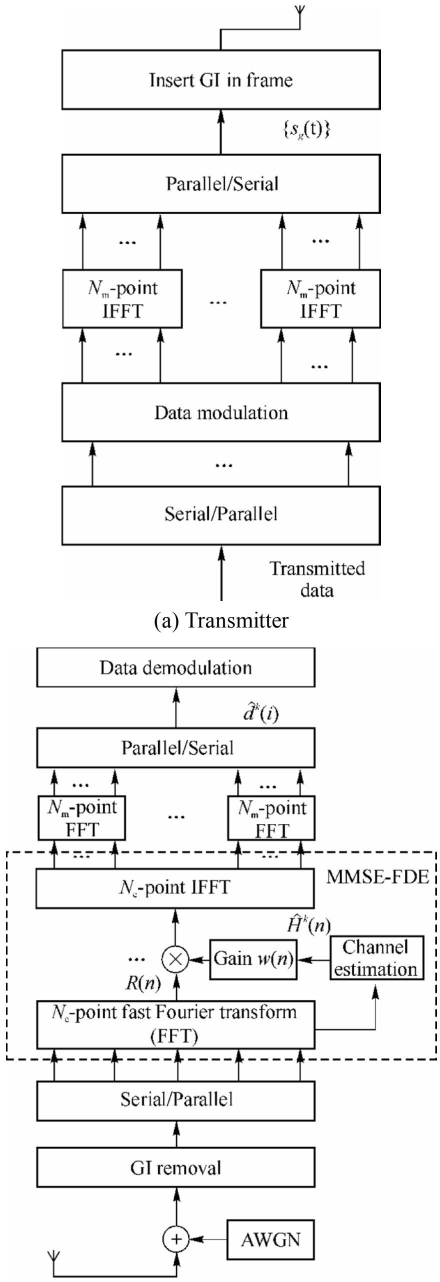
2 OFDM/TDM system

2.1 OFDM/TDM system model

OFDM/TDM system model is proposed based on conventional OFDM system model. OFDM/TDM divides the long IFFT operation time window of OFDM signal into K blocks, each block contains the reduced the number of subcarriers, at the receiver the demodulation of OFDM/TDM signal is a reverse process. Fig. 1 illustrates the configuration of an OFDM/TDM transmitter/receiver respectively.

In the transmitter, the transmitted data is first converted into parallel data to N_c subchannels, where the conventional OFDM signal with N_c subcarriers. Then, the transmitted data of each parallel subchannel is modulated by PSK-based or QAM-based modulation. The sequence of N_c data-modulated symbols $\{d(i); i=0 \quad N_c-1\}$ with $|d(i)|=1$ is to be transmitted during one OFDM/TDM frame. Data-modulated sequence $\{d(i)\}$ is divided into K blocks of $N_m = N_c/K$ symbols each. The kth block symbol sequence is denoted as $\{d_g^k(i); i=0 \quad N_m-1\}$ for the gth OFDM/TDM frame, where $d_g^k(i)=d_g(kN_m+i)$. The N_m-point IFFT is applied to each data block to generate a sequence of K OFDM symbols with N_m subcarriers during one IFFT time window. The transmission data rate of one OFDM/TDM frame is kept the same as that of one conventional OFDM signal. The OFDM/TDM signal can be expressed using the equivalent lowpass representation as

$$s_g(t)=\sum_{k=0}^{K-1} s_g^k(t-kN_m)u(t-kN_m) \tag{1}$$



(b) Receiver

Fig. 1 The configuration of an OFDM/TDM transmitter/receiver for t=0~N_c – 1, where $s_g^k(t)$ is the kth OFDM signal with N_m subcarriers, given by

$$s_g^k(t)=\sqrt{\frac{2E_s}{T_s}\frac{1}{N_m}}\sum_{i=0}^{N_m-1}d_g^k(i)\mathrm{e}^{\frac{\mathrm{j}2\pi ti}{N_m}} \tag{2}$$

for t=0~N_m – 1, where E_s and T_s represent the total signal energy per symbol and the sampling interval. Since this paper only considers one OFDM/TDM frame situation, the following sections ignore the index subscript g, i.e. $s(t)$ and $s^k(t)$.

To overcome the multipath fading, before transmitting, the last N_g samples in the OFDM/TDM frame with N_c samples are copied as a cyclic prefix and inserted at the beginning of the frame as the guard interval (GI). Fig. 2 illustrates the OFDM/TDM frame structure.

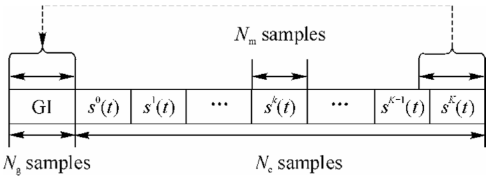


Fig. 2 OFDM/TDM frame structure

The OFDM/TDM signal propagates through the fading channel. At the receiver, GI is removed at first and the received data $r(t)$ is converted into parallel data. Then N_c-point FFT are applied over the entire OFDM/TDM frame to decompose the received signal into N_c frequency components represented by $\{R(n); n=0 \quad N_c-1\}$. $R(n)$ is used to make channel estimation to gain the channel frequency response $\hat{H}(n)$. The equalization weight of one tap MMSE-FDE is got from $\hat{H}(n)$ as

$$w(n)=\frac{\hat{H}^*(n)}{\left|\hat{H}(n)\right|^2+\left(\frac{E_s}{N_0}\right)^{-1}} \tag{3}$$

where N_0 denote the single-sided additive white Gaussian noise (AWGN) power spectrum density (PSD). And then this equalization is applied to $R(n)$ as

$$\hat{R}(n)=R(n)w(n) \tag{4}$$

The time-domain OFDM/TDM signal is recovered by applying N_c-point IFFT to $\{\hat{R}(n); n=0 \quad N_c-1\}$, the OFDM demodulation is carried out using N_m-point FFT to obtain decision variables $\{\hat{d}^k(i); i=0 \quad N_m-1\}$. Those variables are demodulated and decoded subsequently.

2.2 The PAPR of OFDM/TDM

The OFDM signal is generated from the addition of all the modulated orthogonal subcarrier signals. If the phases of the subcarrier signals are consistent, the instantaneous power of the resulting superimposed signal will be far greater than the average power of it, and it causes large PAPR. Studies have shown that PAPR is proportional to the number of subcarriers [1]. High PAPR is the main defect of OFDM, and affect its application in broadband satellite communication system. However, One OFDM/TDM symbol with reduced subcarrier has the low PAPR. For this reason, we apply OFDM/TDM into the broadband satellite system in order to meet the power requirement of the satellite system. In this section, the inhibitory effect of the PAPR in OFDM/TDM is theoretically analyzed and the CCDF model of OFDM/TDM is derived follow-up in this section.

The equivalent lowpass representation of the OFDM/TDM signal as given in Eq. (1), the PAPR of one OFDM/TDM frame can be defined as the ratio of the peak power to the ensemble average power and can be expressed as

$$\lambda_{\mathrm{PAPR}}=\frac{\max\left\{\left|s(t)\right|^2\right\}_{t=0\sim JN_c-1}}{E\left\{\left|s(t)\right|^2\right\}} \tag{5}$$

Assumed the JN_m-point IFFT size is large enough so that the real and the image of kth slot OFDM signal $s^k(t)$, for t=0~N_m – 1, are samples of zero-mean statistically independent Gaussion process with unint variance. JN_m represents oversampleing and J>1. From this assumption, the above PAPR expression can be derived. Therefore, the amplitude $\{a(t)(=|s^k(t)|); \quad t=0 \quad JN_m-1\}$ is independent-and-identically distribution (i.i.d) Rayleigh random variables [7].

Cumulative distribution function (CDF) $F(\lambda_k)$ of the PAPR λ_k for the kth slot is given as

$$F(\lambda_k)=\left(1-\mathrm{e}^{-\lambda_k}\right)^{JN_m} \tag{6}$$

Then complementary cumulative distribution function (CCDF) $F_{\mathrm{CCDF}}(\lambda_k)$ of the PAPR λ_k for the kth slot can be derived from above Eq. (6)

$$F_{\mathrm{CCDF}}(\lambda_k)=1-\left(1-\mathrm{e}^{-\lambda_k}\right)^{JN_m} \tag{7}$$

We assume that the modulated data blocks $\{d^k(i); i=0 \quad N_m-1\}$, for $k=0 \quad K-1$, are statistically independent, one OFDM/TDM frame is composed of K statistically independent OFDM symbols. Hence, the CCDF of one OFDM/TDM frame PAPR can be given by

$$F_{\text{OFDM/TDM-CCDF}}(\lambda_k)=\left[1-\left(1-\mathrm{e}^{-\lambda_k}\right)^{JN_\mathrm{m}}\right]^K \tag{8}$$

From above expression, we can see that the PAPR of the OFDM/TDM is decreasing with the increasement of K. In the simulation section, the CCDFs of OFDM/TDM PAPR are presented which include the theoretical calculation results based on Eq. (8) and the simulation results from a large number of OFDM/TDM signals.

3 Channel estimation algorithm for OFDM/TDM

Channel estimation is one of the key technologies in OFDM/TDM system. Channel estimation and the channel equalization will affect on the system performance. Through the channel estimation results the equalization weight can be gained. So the effect of the equalization relies on the accuracy of channel estimation. For the existing OFDM/TDM channel estimation algorithms, the channel estimation algorithm based on TDM-Pilot with interpolation operation need estimate the Doppler frequency shift and noise variance with the high computational complexity [8]; the channel estimation algorithm based on FDM-Pilot with DFT degrade estimation accuracy caused by aliasing errors [9]. In this system, the channel estimation algorithm based on FDM-Pilot with improved discrete cosine transform (DCT) is applied to OFDM/TDM with the low computational complexity. Although DCT combined estimation algorithm is not the new one, the channel estimation for OFDM/TDM has not adopted this algorithm before this paper. For the broadband satellite communication system, a large number of data with high-speed is transmitted and the channel varies rapidly. The system needs one method to get the channel information quickly. The proposed method in this paper has the quick trace ability to respond to the channel variance.

DCT is a novel technology widely applied to the image processing [10]. For DCT and DFT, they have the different transform idea. For a N-point sequence, it is made signal process as a periodic signal with the length of N in DFT, so the boundary signals between the two adjacent periodic signals are not consecutive and then the obvious high frequency components appear. But in DCT, the transform of N points equals that N points are became $2N$ points through mirror image and operated. Obviously the mirror image extend operation of DCT can resolve the boundary discontinuousness effect in the DFT and then decrease the high frequency components in the transform domain. Through these two methods comparison, we can see that the channel estimation with DCT can make the signals energy focus on the low frequency field, reduce the aliasing errors and get the channel response results which is close to the original response.

3.1 The implement of the algorithm

Considering the OFDM/TDM frame structure as illustrated in Fig. 2. In one OFDM/TDM frame, there are K OFDM/TDM symbols with N_m subcarriers in each symbol. The last one OFDM/TDM inserts in the front of the frame and works as pilot at the same time to make channel estimation (let N_g=N_m). Let T_c represent the duration of one OFDM/TDM frame and it is the interval between the two pilots too. Assuming that the interval between the pilots is shorter than the channel coherent time, the channel parameters between the pilots are constant and the channel is flat fading. Since the pilots insert the each frame, the channel trace ability of this pilot construction is stronger than that one adopted in the paper [8]. At the same time, the long delay is the one characters of the satellite communication system, the system need the estimation finished quickly. The proposed algorithm operates in one OFDM/TDM frame and can satisfy this requirement.

Since FDM-Pilot is the one symbol of the one OFDM/TDM frame, the pilot is not consecutive in both time and frequency domain. To get the whole channel information in frequency domain, the interpolation method is needed to aid the channel estimation algorithm. This algorithm contains two ports. At first, least square (LS) method is used to get the frequency channel response of the pilots; then, use DCT to get the whole channel response of the frequency domain. The details of the algorithm are described as follow.

Step 1 LS method is used to get the frequency channel response of the pilots.

$$\tilde{H}_\mathrm{p}(k)=\frac{R_\mathrm{p}(k)}{X_\mathrm{p}(k)};\quad k=0\sim N_\mathrm{m}-1 \tag{9}$$

where $X_\mathrm{p}(k)$ presents the frequency domain expression of the transmitted pilot, $R_\mathrm{p}(k)$ presents the frequency domain expression of the received pilot.

Step 2 Make N_m-point DCT to $\tilde{H}_p(k)$.

$$\hat{h}_{DCT}(n) = w_{N_m}(n)\sum_{k=0}^{N_m-1}\tilde{H}_p(k)\cos\left\{\frac{\pi(2k+1)n}{2N_m}\right\};$$
$$n = 0,1,2,\dots,N_m-1 \tag{10}$$

where $w_{N_m}(n)=\begin{cases}1/\sqrt{N_m}; & n=0\\ \sqrt{2/N_m}; & n\neq 0\end{cases}$.

Step 3 In the transfom domain pad zeros to get the signal $\hat{h}_{N_c-DCT}(n)$ with N_c length.

$$\hat{h}_{N_c-DCT}(n)=\begin{cases}\hat{h}_{DCT}(n); & 0\leqslant n\leqslant N_m-1\\ 0; & N_m\leqslant n\leqslant N_c-1\end{cases} \tag{11}$$

Step 4 Considering the characteristics of the multipaths channel and DCT, through DCT the channel impulse response will be concentrated on the low-frequency region and the noise will be spread into the whole frequency region from low to high. If the index of the impulse response is higher than N_{max}, it can be omitted, that is

$$\hat{h}_{N_c-DCT}(n)=\begin{cases}\hat{h}_{N_c-DCT}(n); & 0\leqslant n\leqslant N_{max}-1\\ 0; & N_{max}\leqslant n\leqslant N_c\end{cases} \tag{12}$$

N_{max} is decided by the energy distribution. When the ratio of the energy of the impulse response with a certain length to the whole energy get to the predefined value, the impule response behind it will not be considered, the certain length is N_{max}.

Step 5 $\hat{h}_{N_c-DCT}(n)$ is transformed to frequency domain using N_c-point EIDCT.

$$\hat{H}_{N_c}(k)=\sum_{n=0}^{N_c-1}w_{N_c}(n)\hat{h}_{N_c-DCT}(n)\cos\left\{\frac{\pi\left(2k+\frac{N_c}{N_m}\right)}{2N_c}\right\};$$
$$k=0,1,\dots,N_c \tag{13}$$

4 Simulation results

This section presents the computer simulation results and the discussion on the results. At first, the PAPR of OFDM/TDM is simulated in this section to verify OFDM/TDM has the lower PAPR than OFDM and the PAPR of OFDM/TDM reduces with the decrease of the number of the subcarriers. Then, the system performance simulations are presented.

As described in Sect. 2, when we select different K value, the number of subcarriers (N_m) of OFDM/TDM symbol changes correspondingly. For the number of all subcarriers is 2 048, when K selects 1, 8, 32, the number of subcarriers is 2 048, 256, 64, respectively. Obviously, we can see when K equals to 1, no dividing is operated to OFDM, and it is the conventional OFDM. K is chosen by the requirement of the application system. The smaller K is, the lower the spectrum efficiency would be, since OFDM/TDM symbol in frequency domain is not continuous. So there is a trade-off between low PAPR and high spectrum efficiency.

Fig. 3 illustrates the simulation of the CCDF of OFDM/TDM PAPR. In the figure, the theoretical calculation results based on Eq. (8) and the simulation results are presented together. The simulation results are got from 20 000 OFDM/TDM signals. From this figure, we can see the OFDM/TDM has the low probability of the appearance of high PAPR. With the K increases the probability of the appearance of high PAPR decreases. So applying OFDM/TDM to broadband satellite communication system has the low risk of the high PAPR.

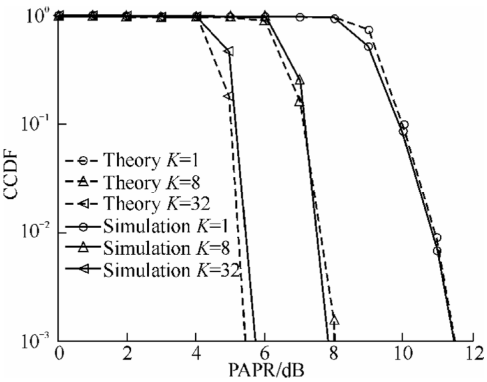


Fig. 3 The simulation of CCDF of OFDM/TDM PAPR (N_c=2 048)

GEO satellite communication system is considered in the simulation. Between the gateway station and the satellite, Ka band is used; between the satellite and the user terminal, L/S band is selected. In this system one needs to take account of the effects of weather conditions as well as the effects of fading and shadowing [11]. The weather effect can be modeled with Gaussian distribution [12]. Corazza model describes the fading and shadowing which can be constructed by Rice distribution combines with Lognormal distribution [13]. The composite channel model is present in Fig. 4. In the simulation, quadrature phase shift keying (QPSK) is selected as modulation method and MMSE is used as frequency equalization. One OFDM/TDM frame has 8

OFDM symbols (K=8) and each symbols has 256 subcarriers (N_m=256). The transform points of FFT is 2 048 (N_c=2 048) and the samples of GI is 256 (N_g=256).

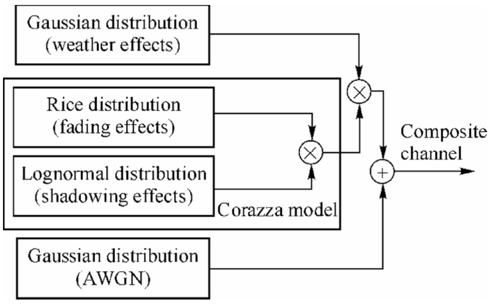


Fig. 4 The composite channel for GEO satellite communication system

Fig. 5 presents the bit error ratio (BER) of performance comparison. In this figure, three cases are compared: the system with no MMSE-FDE, the system with QPSK, and the system with QPSK and OFDM/TDM with MMSE-FDE. Obviously if the equalization is not applied to the system, the received data cannot be recovered. OFDM/TDM improves the system performance compared with the system not using it. Through the above theoretical analysis and the computer simulation, we can see, OFDM/TDM degrees the PAPR and hold the good system performance.

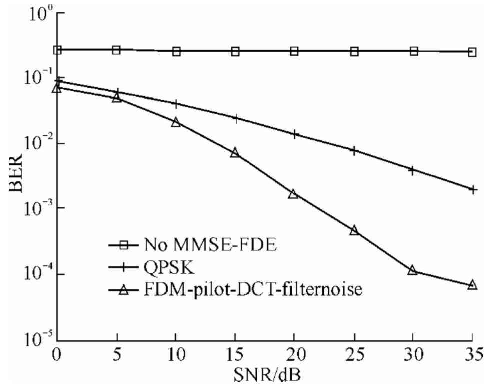


Fig. 5 BER performance comparison

Fig. 6 illustrates the BER comparison of the two FDM-Pilot channel estimation algorithms, one is with DFT interpolation and the other is with DCT interpolation proposed in this system. It can be seen, the channel estimation with DCT has the better performance than the algorithm with DFT.

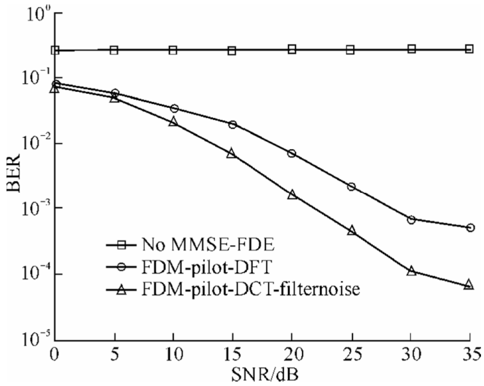


Fig. 6 BER comparison of the two FDM-Pilot channel estimation algorithms

5 Conclusions

In this paper, OFDM/TDM is applied to the broadband satellite communication system. OFDM/TDM system model and its restraining effect on PAPR are theoretically analyzed in this paper. Moreover, the FDM-Pilot channel estimation algorithm is described in details. At the end, the simulation results are presented. Through the simulation results, it can be seen that OFDM/TDM in broadband satellite communication system has the satisfied performance and make the PAPR decrease.

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