Channel Estimation in Next Generation LEO Satellite Communicastion Systems

Zheng Pan[1], Zhenyu Na[1(✉)], Xin Liu[2], and Weidang Lu[3]

[1] School of Information Science and Technology, Dalian Maritime University, Dalian 116026, China
nazhenyu@dlmu.edu.cn
[2] School of Information and Communication Engineering, Dalian University of Technology, Dalian 116024, China
[3] College of Information Engineering, Zhejiang University of Technology, Hangzhou 310058, China

Abstract. Low earth orbit (LEO) satellite communication systems are the key parts of Space-Air-Ground networks. In order to deal with the scarcity of spectrum source, generalized frequency division multiplexing (GFDM) becomes a candidate for next generation LEO satellite systems. In LEO satellite communication systems, channel estimation is an indispensable technique to adapt to complex satellite channel environment. Because of the non-orthogonality between GFDM subcarriers, conventional channel estimation techniques can't achieve the desired performance. We propose a Turbo receiver channel estimation method with threshold control to improve the channel estimation performance by utilizing the feedback information from Turbo decoder. The numerical and analytical results show that the proposed method can achieve better performance over LEO satellite channel.

Keywords: LEO · Satellite communication · GFDM
Channel estimation · Turbo coding · Threshold control

1 Introduction

Recently, satellite communication systems are used in almost every area all over the world. The global satellite industry revenues have doubled in last decade. According to the height of satellite orbit, the satellites can be divided into three categories: geostationary earth orbit (GEO), medium earth orbit (MEO) and low earth orbit (LEO). Compared with GEO and MEO, LEO satellites have the advantages of lower delay, lower Doppler frequency shift and lower cost of launch and manufacture. SpaceX and OneWeb both propose the projects of worldwide LEO satellite constellations, they determine to launch thousands of LEO satellites to build Space-Air-Ground networks [1–3].

Since more and more LEO satellites are launched for satellite communication, the scarcity of spectrum source has become one of the most important problems.

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In order to improve spectrum utilization, orthogonal frequency division multiplexing (OFDM) is used to supersede code division multiple access (CDMA) in many satellite systems [4,5]. As a key physical layer technology in 4th generation (4G) mobile communications, there are still many shortcomings need to be solved. With the development of mobile communications, some improved candidate waveforms for 5th generation (5G) are proposed [6–8]. Among these waveforms, the generalized frequency division multiplexing (GFDM) is considered as one of the optimal technique for LEO satellite communication systems. In GFDM systems, adjacent subcarriers are non-orthogonal. The modulation is based on data blocks, which contain several subsymbols and subcarriers. The non-orthogonality makes GFDM can achieve better spectrum efficiency than OFDM [9,10]. The structure of GFDM data blocks can be adjusted flexibly to adapt to different application scenarios. For the application of GFDM in satellite communication systems, the complicated satellite channel is one of the most serious obstacles. Channel estimation is the indispensable technique in satellite communication systems. In OFDM based satellite systems, channel estimation techniques have been well studied [11,12]. In [13], a general idea of separating pilot symbols from data symbols has been proposed. However, both of the pilot and data are known as the prior knowledge at the transmitter. Moreover, their channel estimation method is only suitable for nearly flat fading channels. In [14,15], an interference free pilot insertion is proposed to handle the interference from data to pilot symbols. In our prior works [16], a Turbo receiver channel estimation method is proposed in GFDM based cognitive radio networks. But as far as we know, there is no exact channel estimation technique in GFDM based LEO satellite systems. Our main contribution in this paper is to modify the Turbo receiver and calculate the threshold for channel estimation. Based on the LEO satellite channel, the performance of the least square (LS) channel estimation and the Turbo receiver channel estimation (TRCE) with threshold control (TC) is theoretically analyzed and verified by simulation.

The rest of this paper is arranged as follows: Sect. 2 describes the basic GFDM system model and the frequency domain signal processing. The TRCE with TC is proposed in Sect. 3. The orthogonal pilot insertion and LS channel estimation are also introduced in this section. Section 4 demonstrates and discusses the simulation results of the proposed channel estimation method. Section 5 is the conclusion of the paper.

2 System Model

The block diagram of GFDM-based satellite communication system is shown in Fig. 1. The binary source is coded by Turbo encoder to get the encoded binary source $\mathbf{b}_c$. Then $\mathbf{b}_c$ is mapped to 2^{μ}-valued complex constellation symbols by a mapper, e.g. quadrature amplitude keying (QAM) or phase shift keying (PSK). A GFDM block contains K subcarriers and M subsymbols, the $N = K \times M$ mapped symbols in vector $\mathbf{s}$ are given as

$$\mathbf{s} = (s_{0,0}, s_{1,0}, \cdots, s_{K-1,0}, s_{0,1}, s_{1,1}, \cdots, s_{K-1,M-1})^T. \tag{1}$$

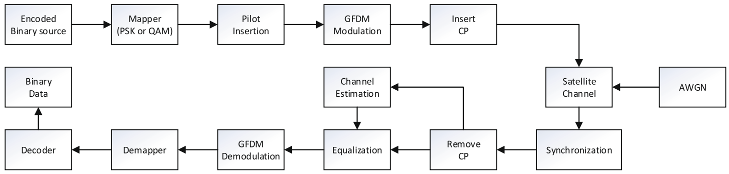

Fig. 1. Block diagram of GFDM-based satellite communication system.

The individual symbols $s_{k,m}$ are the transmission data symbols in mth subsymbol and on kth subcarrier. Each data symbol $s_{k,m}$ is pulse shaped by a filter impulse response

$$g_{k,m}[n] = g[(n, mK)modN]e^{-j2\pi \frac{k}{K} n}, \tag{2}$$

where $n = 0, \cdots, N-1$ denotes the sampling index. The filter impulse response $g_{k,m}[n]$ is the time and frequency shifted version of prototype filter $g[n]$. The transmission sample of GFDM signal is given as

$$x[n] = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} g_{k,m}[n] s_{k,m}. \tag{3}$$

The time and frequency shifting of prototype filter can be integrated into a $KM \times KM$ transmission matrix as

$$\boldsymbol{A} = (\mathbf{g}_{0,0}, \mathbf{g}_{1,0}, \cdots, \mathbf{g}_{K-1,0}, \mathbf{g}_{0,1}, \cdots, \mathbf{g}_{K-1,M-1}), \tag{4}$$

where $\mathbf{g}_{k,m} = (g_{k,m}[0], g_{k,m}[1], \cdots, g_{k,m}[N-1])^T$. Based on the transmission matrix $\boldsymbol{A}$, all the GFDM modulation operations can be rewritten into

$$\mathbf{x} = \boldsymbol{A}\mathbf{s}. \tag{5}$$

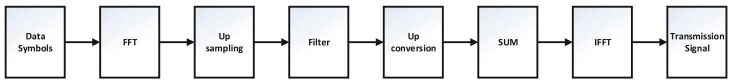

Fig. 2. Block diagram of GFDM modulation in frequency domain.

Based on the time and frequency 2-dimensional structure of GFDM blocks, the modulation process can be implemented in frequency domain or time domain. In this paper, we focus on the frequency domain modulation mainly because the channel estimation is applied in frequency domain. As shown in Fig. 2, the modulation process is given by

$$\mathbf{x} = \boldsymbol{W}_N^H \sum_{k=0}^{K-1} \boldsymbol{C}^{(k)} \Gamma^{(L)} \boldsymbol{R}^{(L)} \boldsymbol{W}_M \mathbf{s}_k, \tag{6}$$

where $\mathbf{s}_k$ are the data symbols on the kth subcarrier. The fast Fourier transformation (FFT) and inverse fast Fourier transformation (IFFT) processes are realized by FFT matrix $\boldsymbol{W}_M$ and IFFT matrix $\boldsymbol{W}_N^H$. Then the frequency domain data is upsampling by the repetition matrix $\boldsymbol{R}^{(L)}$. $\boldsymbol{R}^{(L)} = (\boldsymbol{I}_M \ \boldsymbol{I}_M \cdots \boldsymbol{I}_M)^T$ consists of L identity matrices with the size of $M \times M$. Each upsampled subcarrier is filtered by the filter matrix $\Gamma^{(L)} = \boldsymbol{diag}(\boldsymbol{W}_{LM}\mathbf{g}^{(L)})$. Subsequently, each subcarrier is upconverted to its respective frequency with the cyclic matrix $\boldsymbol{C}^{(k)}$. The higher and the lower spectrum components of the baseband subcarrier are converted into the passband components by the matrix $\boldsymbol{C}^{(k)}$. Similar to OFDM, CP is inserted to GFDM block before transmission to combat the inter block interference and multipath fading. Transmission over the satellite channel is modelled as $\tilde{\mathbf{y}} = \tilde{\boldsymbol{H}}\tilde{\mathbf{x}} + \tilde{\mathbf{w}}$, where $\tilde{\mathbf{y}}$ is the received signal, $\tilde{\boldsymbol{H}}$ is a $N + N_{CP} + N_{ch} - 1$ by $N + N_{CP}$ satellite channel convolution matrix. N_{CP} is the length of CP and N_{ch} is the length of channel impulse response $\mathbf{h} = (h_0, \cdots, h_{N_{ch}-1})^T$. Finally, $\tilde{\mathbf{w}}$ is the additive white Gaussian noise (AWGN). At the receiver side, we assume that the time and frequency synchronization is perfectly performed. Based on the cyclic prefix, the transmission model of the satellite channel can be simplified to

$$\mathbf{y} = \boldsymbol{H}\mathbf{x} + \mathbf{w}, \tag{7}$$

where $\boldsymbol{H}$ is the circular convolution channel matrix with the size of $N \times N$. This circular convolution matrix allows GFDM to employ zero forcing (ZF) equalization as in OFDM. The ZF channel equalization can be performed as

$$\mathbf{z} = IFFT\left(\frac{FFT(\mathbf{y})}{FFT(\hat{\mathbf{h}})}\right), \tag{8}$$

where $\hat{\mathbf{h}}$ is the channel impulse response obtained by channel estimation. Based on the prior knowledge of noise variance σ_w^2, the linear minimum mean square error (MMSE) makes a trade-off between noise enhancement and compute complexity. The MMSE frequency channel equalization is performed as

$$\mathbf{z} = IFFT[(\hat{\mathbf{H}}^H\hat{\mathbf{H}} + \sigma_w^2\boldsymbol{I}_N)^{-1})\hat{\mathbf{H}}^H], \tag{9}$$

where $\hat{\mathbf{H}}$ is the estimated channel frequency response. Derived from (6), the GFDM demodulation process can be written as

$$\hat{\mathbf{d}}_k = \boldsymbol{W}_M^H(\boldsymbol{R}^{(L)})^T\Gamma_R^{(L)}(\boldsymbol{C}^{(k)})^T\boldsymbol{W}_N\mathbf{z}, \tag{10}$$

where $\Gamma_R^{(L)}$ is the receiver filter matrix. At last, $\hat{\mathbf{d}}$ is demapped and decoded to get the binary data stream.

3 Channel Estimation

3.1 Least Square Channel Estimation

Pilot based channel estimation is to insert known pilot sequence into transmission block. Based on the received signal and known pilot sequence, the channel frequency response at pilot location can be estimated. In GFDM based LEO satellite communication system, the pilots are inserted into the first subsymbol with a specific interval Δk. In this paper, we use an orthogonal pilot insertion method. By moving the pilots to the pilot subcarriers which are orthogonal to data subcarriers, the pilots can avoid the interference from data subcarriers. The orthogonal pilot modulation is shown as follows:

$$\mathbf{x}_p = \boldsymbol{W}_N^H \sum_{k=0}^{K-1} \boldsymbol{C}^{(k)} \mathit{\Gamma}^{(L)} \boldsymbol{R}^{(L)} \mathit{\Lambda} \hat{\mathbf{s}}_k \tag{11}$$

$$\mathit{\Lambda} = blkdiag(\boldsymbol{I}_n, \boldsymbol{W}_{M-n}), \tag{12}$$

$\mathbf{s} = \hat{\mathbf{s}} + \check{\mathbf{s}}$ and $\hat{\mathbf{s}} \circ \check{\mathbf{s}} = \mathbf{0}_N$ is the Hadamard product of $\hat{\mathbf{s}}$ and $\check{\mathbf{s}}$. The permutation matrix $\mathit{\Lambda}$ can allocate the first n pilot subsymbols to the subcarriers orthogonal to data subcarriers. Because of (11) and (12), the pilot can totally kept away from the inter carrier interference (ICI). The transmission signal $\mathbf{x}$ can be defined as $\mathbf{x} = \mathbf{x}_p + \mathbf{x}_d$ based on (6) and (11), where $\mathbf{x}_d$ denotes the modulated subsymbols on data subcarriers. The transmission model (7) can be written into frequency domain as

$$\mathbf{Y} = \mathbf{H}(\mathbf{X}_d + \mathbf{X}_p) + \mathbf{W}, \tag{13}$$

where $\mathbf{Y}$ is the received signal in frequency domain. $\mathbf{X}_d$ and $\mathbf{X}_p$ are the frequency domain transmission symbols on data and pilot subcarriers. The received pilot symbols $\mathbf{Y}_{pilot}$ can be segregated from the received symbols without ICI. The LS channel estimation is used to minimize the cost function $||\mathbf{Y} - \mathbf{H}\mathbf{X}||^2$. The LS channel estimation can be expressed as:

$$\check{\mathbf{H}}_{pilot} = \frac{\mathbf{Y}_{pilot}}{\mathbf{X}_{pilot}} = \mathbf{H}_{pilot} + \mathbf{W}_{LS}, \tag{14}$$

where $\mathbf{W}_{LS} = \frac{\mathbf{W}_{pilot}}{\mathbf{X}_{pilot}}$ is the enhanced AWGN on pilot subcarriers. In order to get the whole channel frequency response (CFR) of the satellite channel, $\check{\mathbf{H}}_{pilot}$ will be interpolation filtered at last.

3.2 Turbo Receiver Channel Estimation with Threshold Control

Turbo code is widely used in LEO satellite communication systems. In normal Turbo decoder, the feedback soft information is only used for iterative decoding, so the soft information is not fully utilized. We propose a TRCE with TC to make full use of the feedback soft information. The block diagram of the TRCE with TC is shown in Fig. 3. The TRCE with TC can be divided into a three-stage process.

The first stage is initial channel estimation. The CFR is initially estimated by pilot-aided channel estimation based on (14). After the equalization, the equalized symbols will enter into next stage.

The second stage is iterative channel estimation. In Turbo decoder, the external soft information is fed back in each iteration. The output log-likelihood ratio

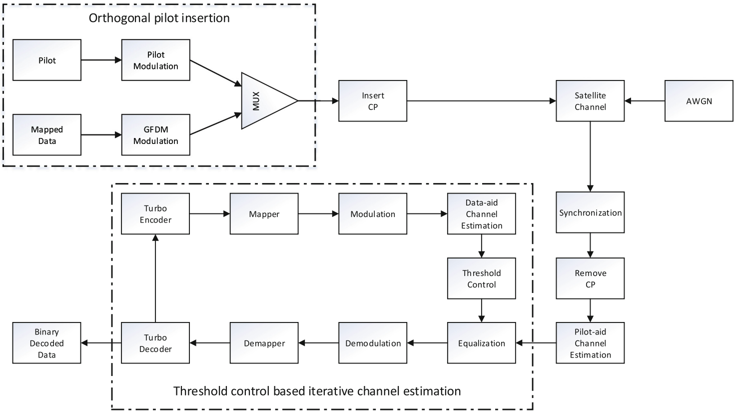

Fig. 3. Block diagram of Turbo receiver channel estimation with threshold control in GFDM based LEO satellite communication system.

from maximum a posteriori (MAP) decoder is encoded again for iterative channel estimation. In this stage, the rebuilt GFDM data symbols $\hat{\mathbf{X}}_{data}$ are treated as known training symbols. By applying data-aided channel estimation, the CFR at data position can be expressed as:

$$\check{\mathbf{H}}_{data} = \frac{\mathbf{Y}_{data}}{\hat{\mathbf{X}}_{data}}. \tag{15}$$

Although the data-aided channel estimation in iteration can utilize the external soft information, the imperfect decoded data will lead the estimation to a bias. If the estimated CFR is used for next iteration directly without any judgement, the accuracy of the channel estimation will deteriorate evidently. Thus, the threshold control is necessary to judge the reliability of the estimated CFR. The mean square error (MSE) of the data-aided channel estimation is given as:

$$MSE_{data} = \mathbb{E}\left[|\mathbf{H} - \check{\mathbf{H}}_{data}|^2\right] = \frac{\sigma_w^2}{|\hat{\mathbf{X}}|^2} \tag{16}$$

where $\mathbb{E}[\cdot]$ means the expectation. And the MSE of the pilot-aided channel estimation can be expressed as:

$$\begin{aligned} MSE_{pilot} &= \mathbb{E}\left[|\mathbf{H} - \check{\mathbf{H}}_{pilot}|^2\right] \\ &= \frac{1}{N}\boldsymbol{Tr}\left\{R_{hh} + F_{in}(R_{pp} + \frac{\sigma_w^2}{\sigma_x^2}\boldsymbol{I}_{N_p}F_{in}^H) - 2\boldsymbol{Re}[F_{in}R_{hp}^H]\right\}, \end{aligned} \tag{17}$$

where $\boldsymbol{Tr}[\cdot]$ denotes the trace of matrix. R_{hh}, R_{pp} and R_{hp} represent the channel correlation matrices. F_{in} is the interpolation filter matrix with the size of N by N_p.

Based on the compare between MSE_{pilot} and MSE_{data}, the reliability of data-aided channel estimation can be judged and the threshold λ can be defined.

$$MSE_{pilot} \gtrless MSE_{data}$$

$$\lambda \triangleq \sqrt{\frac{\sigma_w^2}{\frac{1}{N}\boldsymbol{Tr}\left\{R_{hh} + F_{in}(R_{pp} + \frac{\sigma_w^2}{\sigma_x^2}\boldsymbol{I}_{N_p}F_{in}^H) - 2\boldsymbol{Re}[F_{in}R_{hp}^H]\right\}}}. \quad (18)$$

By means of this judgement, (14) and (15) can be integrated into:

$$\check{\mathbf{H}}^i(n) = \begin{cases} \dfrac{\mathbf{Y}_{data}(n)}{\hat{\mathbf{X}}_{data}^{(i)}(n)} & |\hat{\mathbf{X}}_{data}^{(i)}(n)| > \lambda \\ \check{\mathbf{H}}^{(i-1)}(n) & |\hat{\mathbf{X}}_{data}^{(i)}(n)| < \lambda \end{cases}, \; n = 0, 1, \cdots, N-1, \quad (19)$$

where i means the ith iteration. $\check{\mathbf{H}}^{(i-1)}$ denotes the estimated CFR of the previous iteration. Based on (19), the data-aided channel estimation is judged by TC strategy. Subsequently, the estimated CFR is fed back to equalizer for the next iteration. With the increase of the iteration number, the veracity of the channel estimation will be improved obviously.

4 Simulation Results

This section provides simulation results to demonstrate the validity of the TRCE with TC in the GFDM based LEO satellite communication systems. The simulation parameters are listed in Table 1. According to [17], we select the L-band LEO satellite channel in urban environment as the simulation environment. The bit error rate (BER) and MSE performances are evaluated through Monte-Carlo simulations.

Table 1. Simulation parameters

Parameter	Value
Modulation mode	QPSK
Structure of GFDM block	K = 96, M = 7
Pilot spacing	3
Pilot sequence	Zadoff-Chu
Channel coding	Turbo coding
Generating matrix	(1,1,1,1;1,1,0,1)
Coding rate	1/3
Number of decoder iteration	8

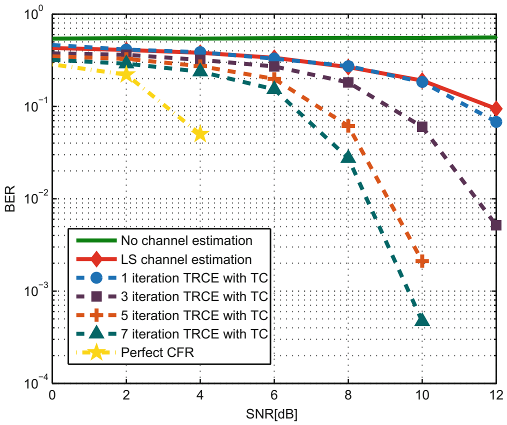

Fig. 4. BER performance of TRCE with TC in GFDM based LEO satellite systems.

The BER performance of the proposed TRCE with TC is shown in Fig. 4. Without channel estimation, the BER performance of GFDM based LEO satellite systems is terrible. When performing the basic LS channel estimation, the BER performance becomes better. But even when the SNR is 12 dB, the BER is still nearly 10^{-1}. The proposed TRCE with TC has better performances within any iteration number. When only one iteration is utilized for TRCE, the BER performance only has tiny improvement than LS channel estimation. The BER performance is improved gradually as more iteration is used for TRCE.

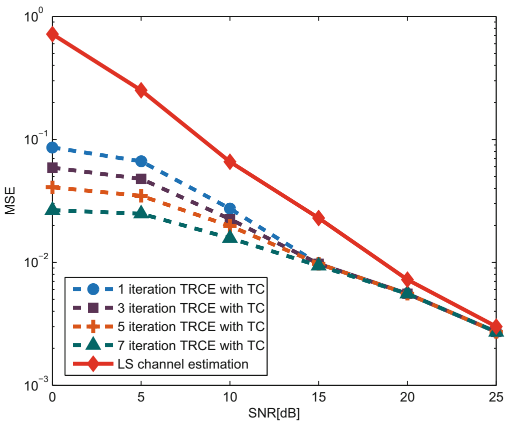

Fig. 5. MSE performance of TRCE with TC in GFDM based LEO satellite systems.

In Fig. 5, the MSE performances of LS channel estimation and the proposed method are evaluated. The proposed TRCE with TC significantly improves the

MSE performance compared with basic LS channel estimation. The increase of iteration number leads to better MSE performance of TRCE. When SNR is above 15 dB, the reliability of rebuilt symbols is high. Therefore, the MSE performances of TRCE with different iteration number are nearly the same.

5 Conclusion

We have proposed a TRCE method with TC in GFDM based LEO satellite communication systems. The LS channel estimation is used to cope with the LEO satellite channel. The GFDM receiver is modified for data-aided iterative channel estimation. A TC strategy is added to verify the credibility of rebuilt data symbols before equalization. From the simulation results we observed that TRCE with TC outperforms the basic LS channel estimation in LEO satellite channel. The BER and MSE analysis have shown that, the performance can be improved significantly by increasing the iteration number. The number of iteration which is used for TRCE can be selected flexibly to meet different demands.

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