Second Order Time-Frequency Modulation in Satellite High-Mobility Communications

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***Abstract*—Providing reliable wireless communications for high-mobility terminals remains one of the main challenges faced by satellite high-mobility communication systems. Because the high Doppler frequency offset and Doppler rate caused by the high-mobility nature of the mobile terminal, and low signal-to-noise ratio (SNR) circumstances caused by limited satellites' link budgets degrade the system performance seriously. To solve such a problem in high-mobility satellite communications, we propose a novel modulation method named second order time-frequency (SOTF) modulation, which consists of index modulation (IM) and liner frequency modulation (LFM). Simulation results show that the bit error ratio (BER) performance of the proposed modulation method with different parameters is better than traditional modulation methods. Specially, the BER performance loss is about 0.05dB in high-mobility communication scenarios, which demonstrates that the proposed modulation method is insensitive to Doppler frequency offset and Doppler rate. Overall, the proposed method can be well applied in high-mobility satellite communication systems for its good performance with moderate complexity.**

***Index Terms*—Doppler frequency offset, Doppler rate, Low SNR, Index modulation, LFM signal.**

I. Introduction

SATELLITES communication systems can provide global coverage and various services for high-mobility terminals [1], which is a promising solution to extend the terrestrial communication networks in unserved areas and reduce vulnerability to physical attacks or natural disasters [2]. With the large scale development of high speed mobile terminals, wireless communications in high mobility environments are expected to be supported by satellite communication systems. But traditional satellite communication systems cannot be applied in high mobility scenarios directly, because lots of problems still remain to be solved in satellite high-mobility communication systems.

Unlike traditional satellite communications, the satellite high-mobility communication system faces more challenges. On the one hand, the high mobility nature of the mobile terminal usually causes high Doppler frequency offset and high Doppler rate, which inevitably causes the mismatch between the frequencies of the oscillators at the transmitter and receiver [3]. Generally, time-varying carrier frequency offset (CFO) is difficult to track and compensate, which usually degrades the performance of the satellite high-mobility communication system seriously without the perfect synchronization. On the other hand, limited link budgets in satellites usually make the communication system work in low SNR circumstances, which further degrades the BER performance. Therefore, how to reduce the influence of the Doppler effect in low SNR circumstances is rather challenging for satellite high-mobility communication systems.

In the literature, most of algorithms mainly focused on the estimation and compensation of Doppler frequency rate and Doppler frequency offset, rather than reducing the influence of Doppler effect in the communication system. In [4], the author proposed a Doppler frequency offset estimation method using broadcast ephemeris and phase-locked loop, but this method could not estimate Doppler rate effectively. Similarly, most Doppler frequency offset estimation methods such as [5]–[7] did not consider the influence of Doppler rate in high-mobility scenarios. The author in [8] proposed a joint-estimation algorithm for Doppler shift and Doppler rate based on pilot symbols, which could achieve the carrier synchronization effectively. But this method needed relatively large numbers of pilot symbols. Later, in [9], the author proposed a Doppler rate estimation algorithm based on the Zadoff-Chu (ZC) sequence in the satellite communication system but with the high SNR threshold, which was not appropriate for high-mobility communication systems in low SNR circumstances. Overall, traditional satellite communication technologies designed for satellite communications cannot be applied to satellite high-mobility communication systems directly. Therefore, it is significant to develop the new modulation method designed specially for the satellite high-mobility communication system, which can reduce the effect of Doppler frequency offset and Doppler rate in low SNR circumstances.

Different from date aided (DA) or code aided (CA) Doppler correction methods, in this paper, to cope with aforementioned challenges in satellite high-mobility communications, we propose a new modulation method comprised of IM and LFM, which can reduce the influence of the Doppler effect in low SNR circumstances effectively. The rest of the paper is organized as follows. We first introduce the system model in Section II, and then the proposed modulation method is

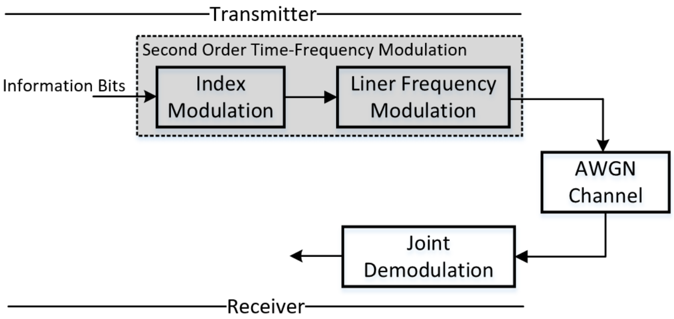


Fig. 1. System model for SOTF modulation.

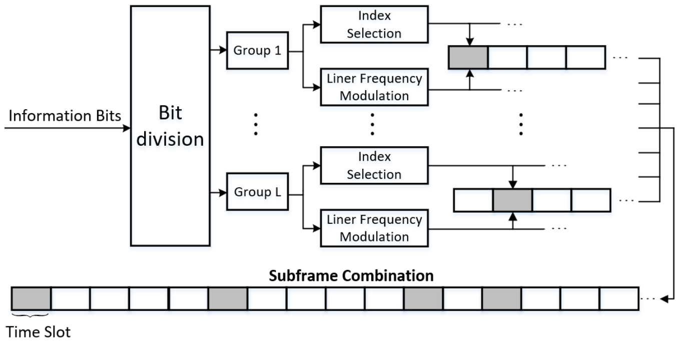


Fig. 2. The structure of SOTF modulation in the transmitter.

introduced in Section III. Later, simulation results are shown in Section IV. Finally, Section V gives the conclusion.

II. System model

Index modulation is a recent popular modulation technology that can implicitly convey information bits by activating a subset of indices [10]–[12], which is capable of modulating some specific information bits in the frequency, the space, and time domains to improve the system performance [13]. Due to the high-mobility nature of the mobile terminal, the Doppler frequency offset and Doppler rate caused by the mobile terminal is relatively high, which makes synchronization become the bottleneck in low SNR circumstances, especially for the phase-shift keying (PSK) modulation system. Compared with the PSK modulation, LFM is insensitive to the Doppler frequency offset and Doppler rate but with relatively poor BER performance. Therefore, binary information bits can be modulated into the chirp signal with different chirp rates, i.e., the chirp-BOK modulation, to reduce the influence of the Doppler frequency offset and Doppler rate. Specially, in order to further improve the BER performance in low SNR circumstances, SOTF modulation comprised of IM and LFM is proposed, which is able to reduce the influence of the high-mobility nature of mobile terminals in low SNR circumstances.

The system model considered in this paper is shown in Fig. 1. In the transmitter, information bits are modulated by SOTF. Then the transmitted frame $\mathbf{s}$ is passed through the up conversion, and corrupted by the additive white Gaussian noise (AWGN). Meanwhile, Doppler frequency offset and Doppler rate are also considered in the channel mode. In the receiver, the received signal $\mathbf{r}$ is passed to the joint demodulator, which extracts the transmitted information bits by means of the codebook match.

III. PROPOSED MODULATION METHOD

To reduce the influence of high Doppler frequency offset and Doppler rate in low SNR circumstances, we propose a new modulation method as shown in Fig. 1, which is able to cope with the challenges from the high-mobility scenarios and low SNR circumstances. In this section, SOTF modulation and demodulation are introduced in detail.

A. Transmitter Model

The structure of SOTF modulation is shown in Fig. 2. In the transmitter, N-length information bits are divided into L groups, which can be expressed as

$$\mathbf{s} = \left(\mathbf{s}^{(1)}, \mathbf{s}^{(2)}, \ldots, \mathbf{s}^{(L)}\right), \tag{1}$$

where $\mathbf{s}^{(l)}$, $l = 1, 2, \ldots, L$ represents the lth subframe.

Furthermore, each subframe in (1) spanning over M time slots can be written as follows:

$$\mathbf{s}^{(l)} = \left(s_1^{(l)}, s_2^{(l)}, \ldots, s_M^{(l)}\right), \tag{2}$$

where $N = L \cdot M$. In each subframe $\mathbf{s}^{(l)}$, K out of M time slots are selected for LFM, while the other time slots are set to zero without LFM.

Specially, information bits in the lth subframe are divided into two subsequences, i.e, the index sequence $\mathbf{b}_1^{(l)}$ and the modulation sequence $\mathbf{b}_2^{(l)}$. For the former, $\mathbf{b}_1^{(l)}$ is conveyed by activating specific time slots, which depends on the selection of K indices from M indices. Hence, the length of the index sequence can be expressed as

$$B_1 = \left\lfloor \log_2 \begin{pmatrix} M \\ K \end{pmatrix} \right\rfloor. \tag{3}$$

While for the latter, the number of modulation bits depends on the number of time slots K which can be activated to transmit the chirp signal. Thus, the length of the modulation sequence can be expressed as

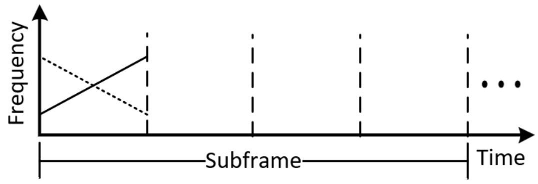
$$B_2 = K \cdot \log_2(Q), \tag{4}$$

where Q represents the number of different chirp rates in the chirp signal. Specially, Q=$2^v, v \in \mathrm{N}_+$.

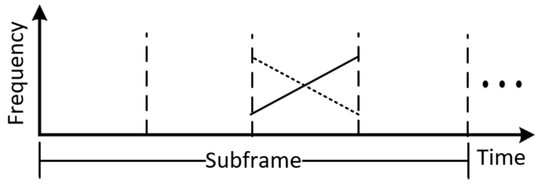
From the preceding analysis, the bit rate can be expressed as

$$R = \frac{\left\lfloor \log_2 \begin{pmatrix} M \\ K \end{pmatrix} \right\rfloor + K \cdot \log_2(Q)}{M}, \tag{5}$$

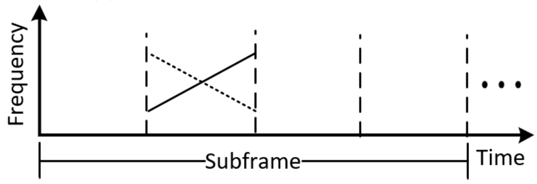
which is fixed for the given parameters K, M, and Q.



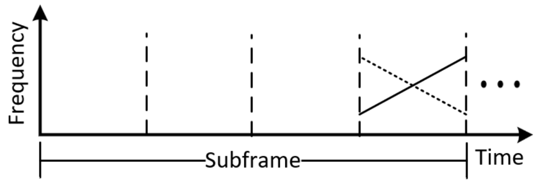
(a) The Structure of the subframe A.



(b) The Structure of the subframe B.



(c) The Structure of the subframe C.



(d) The Structure of the subframe D.

Fig. 3. The structure of the subframe when $(K, M, Q) = (1,\ 4,\ 2)$. (The dashed line and solid line represents the rising chirp signal and falling chirp signal respectively.)

The chirp signal in the lth subframe of the mth time slot can be written as

$$s_m^{(l)} = \exp\left[j\pi(2f_0 t + kt^2)\right], \tag{6}$$

where f_0 presents the center frequency, k refers to the chirp rate, and T_s is the signal time duration. Basically, the chirp signal is nonlinear and nonstationary. When $k > 0$, the frequency of the chirp signal varies from low frequency to high frequency, which is the rising chirp signal. Conversely, the falling chirp signal with $k < 0$, varies from high frequency to low frequency. Specially, the chirp rate k is determined by the information bit, where the rising chirp signal is assigned to 1-bit and the falling chirp signal is assigned to 0-bit, when $Q = 2$.

For example, when $(K, M, Q) = (1,\ 4,\ 2)$, one of four time slots is activated in the subframe, and LFM is employed in the activated time slot to modulate the modulation bit $\mathbf{b}_2^{(l)}$. In this case, legitimate subframe sequences can be expressed as

$$\mathbf{s}^{(l)} \in \left\{ \begin{bmatrix} s_1^{(l)} \\ 0 \\ 0 \\ 0 \end{bmatrix}^T, \begin{bmatrix} 0 \\ s_2^{(l)} \\ 0 \\ 0 \end{bmatrix}^T, \begin{bmatrix} 0 \\ 0 \\ s_3^{(l)} \\ 0 \end{bmatrix}^T, \begin{bmatrix} 0 \\ 0 \\ 0 \\ s_4^{(l)} \end{bmatrix}^T \right\}, \tag{7}$$

where T represents the transposition. The number of legitimate subframe sequences depends on preset parameters (K, M, Q), i.e., $Q^K \cdot \left\lfloor \log_2 \begin{pmatrix} M \\ K \end{pmatrix} \right\rfloor$. As shown in Fig. 3, information bits are conveyed in different time slots with different chirp rates. Based on the preset codebook, either the rising chirp signal or the falling chirp signal is activated in the specific time slot, which can represent different index sequences and modulation sequences.

B. Receiver Model

In the receiver, the successful acquisition of the chirp signal and perfect synchronization are assumed to be achieved. When the mobile terminal is in the line of sight (LOS), the received signal can be written as

$$r(t) = \mathbf{s} \cdot e^{j\pi\left[2f_d t + h_a t^2\right]} + n\left(t\right), \tag{8}$$

where f_d represents Doppler frequency offset, h_a is the Doppler rate, $n\left(t\right)$ is the complex additive white Gaussian noise with zero mean and variance $\sigma_n^2 = \frac{N_0}{2}$. Furthermore, the Doppler frequency offset f_d and Doppler rate h_a can be expressed as follows:

$$f_d = \frac{v f_c}{c} \cdot \cos\theta_1, \tag{9}$$

$$h_a = \frac{a f_c}{c} \cdot \cos\theta_2, \tag{10}$$

where f_c represents the carrier frequency, v represents the relative motion speed between the satellite and the mobile terminal, a represents the acceleration between the satellite and the mobile terminal, θ_1 refers to the angle of the relative motion direction and the signal propagation direction, θ_2 represents the angle of the relative acceleration direction and the signal propagation direction, and c is the electromagnetic wave propagation velocity.

Specially, the codebook match algorithm based on the fast Fourier transform (FFT) is proposed to estimate the transmitted index sequence $\mathbf{b}_1^{(l)}$ and modulation sequence $\mathbf{b}_2^{(l)}$. The structure of the demodulation is shown in Fig. 4.

The peak value of the FFT in each time slot is passed to the peak comparison, which can select the maximum value from the rising chirp signal and the falling chirp signal. The result of the peak comparison can be expressed as

$$\widehat{s}_m^{(l)} = \begin{cases} p_1 & p_2 < p_1 \\ -p_2 & p_1 < p_2 \end{cases} \tag{11}$$

where p_1 and p_2 represent the peak value of the FFT for the rising chirp signal and falling chirp signal respectively.

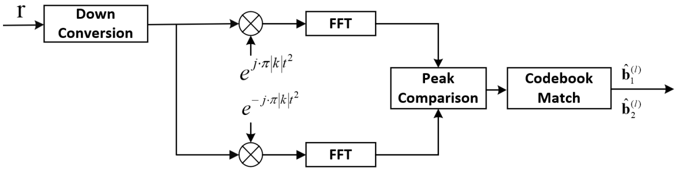


Fig. 4. The structure of the joint demodulator.

With the aid of the FFT and peak comparison, the peak value of each chirp signal in the lth subframe can be written as

$$\widehat{\mathbf{s}}^{(l)} = \begin{bmatrix} \hat{s}_1^{(l)} & \hat{s}_2^{(l)} & \dots & \hat{s}_M^{(l)} \end{bmatrix}. \qquad (12)$$

By means of the codebook match, the search process can be expressed as

$$(\hat{\mathbf{b}}_1^{(l)}, \hat{\mathbf{b}}_2^{(l)}) = \underset{(\mathbf{b}_1^{(l)}, \mathbf{b}_2^{(l)})}{\arg\max} \left| \widehat{\mathbf{s}}^{(l)} \cdot \mathbf{s}^{(l)} \Big|_{(\mathbf{b}_1^{(l)}, \mathbf{b}_2^{(l)})} \right|, \qquad (13)$$

where $\mathbf{s}^{(l)}\big|_{(\mathbf{b}_1^{(l)}, \mathbf{b}_2^{(l)})}$ represents possible combinations of index bits and modulation bits in the codebook. Basically, received information bits among all legitimate sequences in the preset codebook are detected by exhaustive search. In this case, the result given in (13) is taken as the detected sequence that consists of the index sequence and the modulation sequence. Specially, based on the preset codebook, the proposed system is capable of achieving the attainable coding gain, hence yielding a significant BER performance improvement.

IV. SIMULATION RESULTS

In this section, simulation results based on MATLAB are provided to evaluate the performance of SOTF modulation. The proposed system is a general framework, not limited to specific parameters. In this simulation, we assume that the angle of sight is 18° at least, the maximal velocity of the mobile terminal is 17 mach ($5780m/s$), and the maximal acceleration is about $300m/s^2$. In such a case, the maximum carrier frequency offset (CFO) can be up to $55kHz$ when the carrier frequency $f_c = 3GHz$. Therefore, the maximum CFO is $55kHz$ in this simulation. In addition, some essential parameters are shown in Table I.

TABLE I: Essential Parameters

Notation	Parameters
Channel Model	AWGN
Carrier Frequency	$f_c = 3GHz$
Center Frequency	$f_0 = 1MHz$
Signal Time Duration	$T_s = 400us$
Chirp Rate	$k = \pm 1.28GHz$
Maximal velocity	$v_{\max} = 17mach$
Maximal acceleration	$a_{\max} = 300m/s^2$
Sample Rate	$f_s = 4MHz$
Frame Length	$N = 256\ symbol$

A. Low SNR Performance

Fig. 5 shows the BER performance of the proposed modulation method with different values of (K, M, Q). Specially, the BER performance of the BPSK and LFM is shown as a reference. We can observe that the BER performance of the proposed modulation method is better than the classical BPSK modulation and LFM. When the bit error ratio $P_e = 10^{-5}$, the BER performance of the proposed method is about 2.6dB and 3.4dB higher than the BPSK with parameters ($K = 1$, $M = 8$, $Q = 2$) and ($K = 1$, $M = 16$, $Q = 2$) respectively. Because the minimum distance for the codebook of ($K = 1$, $M = 16$, $Q = 2$) is larger than the the codebook of ($K = 1$, $M = 8$, $Q = 2$). However, the bit rate is also reduced with the increase of the high minimum distance for the codebook, i.e., the bit rate of ($K = 1$, $M = 16$, $Q = 2$) is lower than the bit rate of ($K = 1$, $M = 8$, $Q = 2$). Compared with parameters ($K = 1$, $M = 8$, $Q = 2$), the bit rate of SOTF reduces 37.5% when ($K = 1$, $M = 16$, $Q = 2$). Generally, the modulation gain of the proposed algorithm increases with the decrease of the bit rate. Overall, compared with traditional modulation methods, the proposed modulation method is capable of achieving better low-rate performance, which can reduce the demodulation threshold effectively.

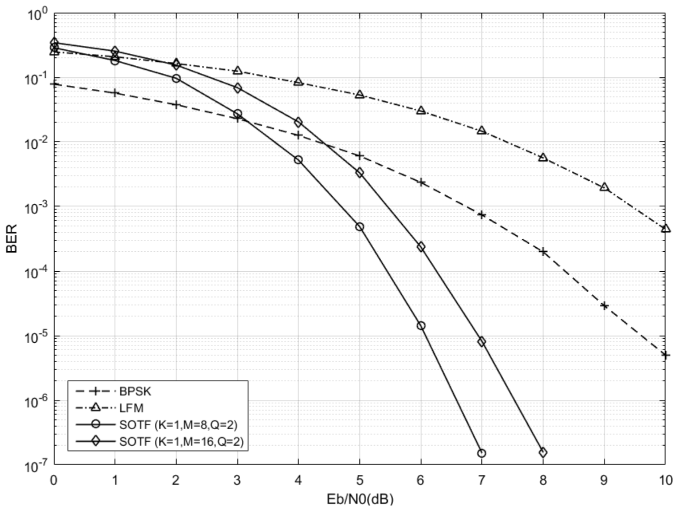


Fig. 5. BER performance of the proposed method.

B. High-Mobility Performance

Fig. 6 presents the BER performance of the proposed modulation method with different values of Doppler frequency offset and Doppler rate, and the BPSK modulation is also as a reference. Compared with conventional PSK modulation, the proposed method is insensitive to Doppler frequency offset and Doppler rate. It is shown in Fig. 6 that the BER performance of BPSK modulation degrades seriously when Doppler frequency offset and Doppler rate are relatively high. Specially, the BER performance of the proposed modulation method with high Doppler frequency offset and Doppler rate is better than the ideal BER performance of BPSK modulation without Doppler frequency offset and Doppler rate, where the performance gaps of about 2.55dB and 3.35dB are recorded for ($K = 1$, $M = 8$, $Q = 2$) and ($K = 1$, $M = 16$, $Q = 2$), respectively.

On the one hand, the influence of Doppler rate is negligible in SOTF modulation, since the Doppler rate caused by the variation of the motion speed is lower than the chirp rate, which has little effect on the BER performance. On the other hand, the BER performance of the proposed method degrades about 0.05dB when the Doppler frequency offset $f_d = 55kHz$ and the Doppler rate $\mathrm{h}_a = 1kHz/s^2$, which demonstrates that SOTF modulation is insensitive to Doppler frequency offset and Doppler rate. In addition, compared with the PSK modulation, the proposed method is robust, since the relatively ideal BER performance can be achieved in large range of the Doppler frequency offset.

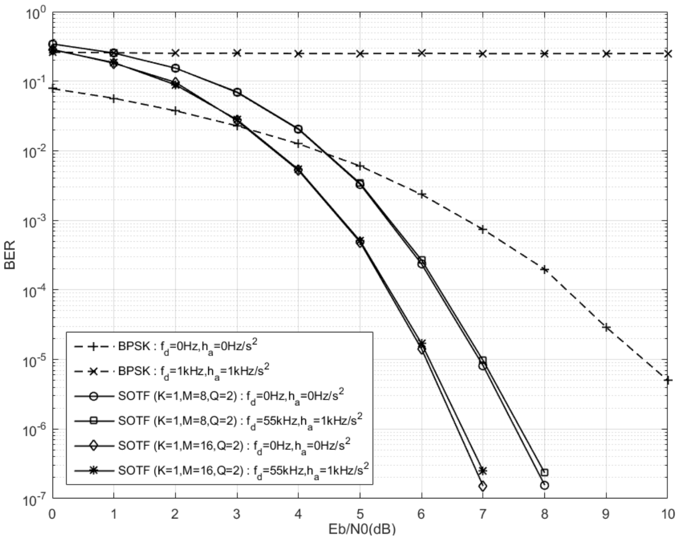


Fig. 6. BER performance of the proposed method in high-mobility environments.

C. Complexity Analysis

The computational complexity of the proposed method mainly depends on the demodulation method based on the codebook match. The computational complexity of the exhaustive search in (13) is specified by the parameters of K, M and Q, i.e., $O(Q^K \cdot \left\lfloor \log_2 \begin{pmatrix} M \\ K \end{pmatrix} \right\rfloor)$. While for the FFT, the time complexity of the FFT is $O(W \cdot \log_2 W)$ for the chirp signal, where the number of samples in a time slot is W. Overall, the computational complexity is not significantly high when the size of (M, K, Q) is moderate.

Finally, some comments on the proposed algorithm are summarized in order. Firstly, the proposed method has strong robustness, which can achieve well performance in a large range of Doppler frequency offset and Doppler rate. Secondly, compared with traditional modulation methods, the proposed algorithm has better BER performance to cope with challenges of the high Doppler frequency offset and high Doppler rate in low SNR circumstances, which can be well applied in satellite high-mobility communication systems. Thirdly, the complexity of the joint demodulation algorithm is moderate. Fourthly, the proposed method is expected to reduce the cost of the pilot sequence in satellite communication systems, which can save spectrum resources effectively.

V. Conclusion

In this paper, we propose a novel modulation method to cope with the challenges in satellite high-mobility communication systems under the low SNR condition. On the one hand, in the transmitter, information bits to be transmitted are divided into index bits and modulation bits, which is capable of achieving the attainable coding gain with aid of the preset codebook. On the other hand, in the receiver, the joint demodulation algorithm can extract transmitted bits by means of the exhaustive search according to the codebook specified by preset parameters. Based on different codebooks, a beneficial trade-off between bit error ratio and bit rate can be adjusted flexibly. Simulation results demonstrate that the proposed modulation method is capable of achieving better performance than traditional modulation methods with moderate complexity, which can be well applied in satellite high-mobility communication systems for its good performance.

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