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Design of satellite mobile synchronization system based on OFDM code

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Abstract. In the 5G era, satellite communication has been widely applied in more scenarios. Orthogonal Frequency Division Multiplexing (OFDM) has been adopted to the 3GPP standard and is the primary sync encoding method for satellite communication. However, the OFDM-based system is extremely susceptible to carrier frequency offset (CFO), and Doppler shift make a major impact on the CFO. Therefore, the traditional methods of synchronization based on OFDM cannot meet the requirement of satellite communication with large frequency offset and delay. There are many studies focus on improving the methods of CFO estimation and compensation to adapt the technologies of synchronization based on OFDM to the satellite communication system. In this paper, ZC based and matrix-vector multiplication method, multi-symbol merging method and preamble and PSS symbols based and filter frequency locked loop-based method of synchronization of OFDM-based satellite communication will be introduced. The accuracy and complexity of these methods both meet the requirement of 5G satellite communication system. Future researchers may focus on reducing complexity and expanding application scenarios.

Keywords: satellite communication, synchronization system, carrier frequency offset estimation, OFDM-Based system.

1. Introduction

Satellite communication has the advantages of full coverage, large bandwidth, low latency, and low cost [1]. So, it can be applied in wide-range and high-speed communications. OFDM, which is Orthogonal Frequency Division Multiplexing in full , is applied in satellite communication because of its property of anti multi-path fading, high spectrum efficiency and large-capacity information transmission [2]. The combination of satellite communication and ground-based cell communication has been widely used throughout the world, which is a hot topic. And OFDM-based synchronization technologies have emerged and developed to improve the property of synchronization between satellite and ground cellular network. However, oscillator mismatches in the transmitter and receiver and timing shift errors due to the unknown arrival time of the OFDM symbol generate high sensitivity for the CFOs (carrier-frequency offsets), which makes much effect on synchronization accuracy [3]. Previous researches show the methods to solve the problem of time and frequency synchronization caused by high sensitivity to CFOs of OFDM. Blind estimators are commonly used on this issue, such as Gini-Giannakis estimator for single-carrier systems and maximum likelihood estimator [4,5]. Dataaided schemes based on training symbol are the other way to solve the problem, and two training symbols have been reduced to one in the research [6]. And algorithm with more identical parts in training symbol was presented to lower the BER [2].

Satellite communication has been a hot field in past few years. Due to relative motion between satellites and user terminals, between satellites and base stations, and between satellites and satellites, there is large Doppler shift. Estimating the frequency offset is the key point in solving the problem of synchronization of satellite communication. Therefore, there are many studies dedicated to the problem of synchronization of satellite communication and new technologies of CFO estimation are constantly emerging. Combined with blind timing algorithm that have been applied all along, multi-symbol merging method is presented by J. Tong et al. substituted single symbol to improve the accuracy [7]. Methods based on cross-correlation operation have always used and Y. Liu et al. present a new cross-correlation based method [8]. For single fading channel and multi-path fading channel, ZC sequence-based method and matrix-vector multiplication-based method were proposed by M. Huang et al. [9]. And the CFO estimation issue is turned into the issue of estimating the frequency with their method [9]. Another method of recasting the timing and frequency offset estimation into the problem of one-dimensional peak searching is presented by W. Wang et al. [10]. For inter-satellite links, R. V. Şenyuva and G. K. Kurt use 2-D Esprit to solve the problem of estimation of CFO and frame misalignment [11]. Besides, D. Castelain solves the problem of time synchronization in the uplink of satellite communication [12]. These new methods fixed the adaptation problem with terrestrial 5G, and contribute to the convergence of satellite-ground communication.

The technology of synchronization for satellite communication has broad application prospects in the future. In the further 5G era, large area coverage and high stability of satellite communication will be important needs and challenges to satisfy all of the user requests and provide the desired Quality of Service in complex condition [13]. To reach large-capacity coverage, the integration of terrestrial systems with Geostationary Earth Orbit (GEO) satellites would be a good scheme, however, large delays and Doppler shifts make effects on the system [14]. To estimate and compensate the large delays and Doppler shifts may be the key issues. Looking ahead to the 6G era, to realize the ubiquitous wireless intelligent network, three-dimensional coverage and ubiquitous connection [15], the matching synchronization technology is necessary.

In this paper, three important contributions [7-9] of synchronization of OFDM-based satellite communication will be introduced in section III. And the basic theory of satellite communication, OFDM based signal, and Doppler shift will be discussed in section II. The author will analyse and compare the features of the new methods proposed. And the innovative points of optimizing the estimation accuracy and reducing the calculation complexity will be detailed introduced.

2. Principle

2.1. Satellite communication model

The satellite communication consists of two segments. There are geostationary earth orbit (GEO) and low earth orbit (LEO) satellites in the space segment. And in the terrestrial segment there are various kinds of gateways and data networks. The satellite-to-earth communication gateway are linked to the next-generation core (NGC) and the public data network (PDN). Furthermore, there is direct communication between earth-to-space links and satellites or via ground relay nodes [8]. The movement of satellites and long distance of communication both affect the accuracy of synchronization [7].

2.2. OFDM based signal model

Three important researches to be discussed next all consider the OFDM symbols-based satellite communication system. The primary synchronization signal (PSS) is encoded through OFDM. The signal form of PSS after IFFT can be obtained by the following formula.

$$s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S(k) e^{j2\pi kn/N} \quad n = 0,1,\ldots N-1 \tag{1}$$

Where S(k) is the frequency domain PSS, k is the moment of sampling and N is the subcarrier number.

The channel linked between the satellite in space orbit and the user equipment (UE) is modelled by multipath fading [9]. The unit impulse response of the channel can be expressed as follow

$$h(n) = \sum_{d=0}^{D-1} h_d \delta(n-d) \tag{2}$$

Where D denotes to the maximum number of the path.

Next, the receive-side signal can be obtained by convolution operation as the following form.

$$r(n) = e^{j2\pi\varepsilon(n+N_{cp})/N} \sum_{d=0}^{D-1} h(n-d)s(n-d) + w(n) \tag{3}$$

Where ε is the CFO normalized by the subcarrier spacing, N_{cp} is the length of cycle prefix (CP) and $w(n)$ is the additive white Gaussian noise (AWGN) with variance of σ^2. The CP can also be expressed as a part of PSS function equivalently.

2.3. Frequency offset

Systems built on OFDM are extremely susceptible to carrier frequency offset (CFO) which originates from Doppler shift or frequency deviation between the local oscillators of the transmitter and receiver. And, the primary cause of timing and frequency errors is CFO, which will be discussed below.

In satellite communication system the Doppler shift generated by the consumer has a major impact on synchronization. Only during a short portion period, known as the visibility window, can a LEO satellite effectively communicate with a UE because a LEO satellite's coverage depends on its elevation angle. [10]. The Doppler Shift depends on relative tangential velocity related to elevation angle and it can be expressed as follow

$$f_d = \frac{v_T}{\lambda} cos\varphi = f_c \frac{v_T}{c} cos\varphi = f_m cos\varphi \tag{4}$$

re v_T is the relative velocity between satellite in space orbit and UE on the earth, φ is the elevation angle, f_c denotes to the carrier frequency, c is the light velocity and f_m denotes to the maximum Doppler frequency shift.

3. Introduction of important contribution

3.1. ZC based & matrix-vector multiplication method

Miaona Huang et al. proposed two satellite communication synchronization methods in their paper, whose focal point is to transform the CFO estimation issue into the carrier frequency offset estimation. There are less complexity because of transforming the problems. Their methods are characterized by the rational use of the features of the signal and channel of satellite communication transform the problem of CFO estimation.

3.1.1. single-path fading channel. Single-path fading channel of satellite communication is suitable for cleared ground condition. The proposed synchronization method is based on the characteristic of ZC(Zadoff-Chu) sequence, which is used to generate PSS in the 3GPP standard.

The Method of CFO estim ation of single-path fading channel process is as follows：

1. Estimate and compensate FFO
2. Determine the unknown parameters of IFO estimation through autocorrelation function of signal
3. Remove the CP and do FFT operation

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4. Do autocorrelation operation and define the summation of the autocorrelation S()

5. Estimate the IFO

The autocorrelation operation is realised by considering the asymmetry of time domain ZC sequence. And, IFO is estimated by considering the constant envelop of ZC sequence. In the CFO range of [0, 20], the RMSE can reach the CRLB In result of simulation is shown in the Figure 1. The precision and the range of CFO estimation are higher than the requirement of satellite communication.

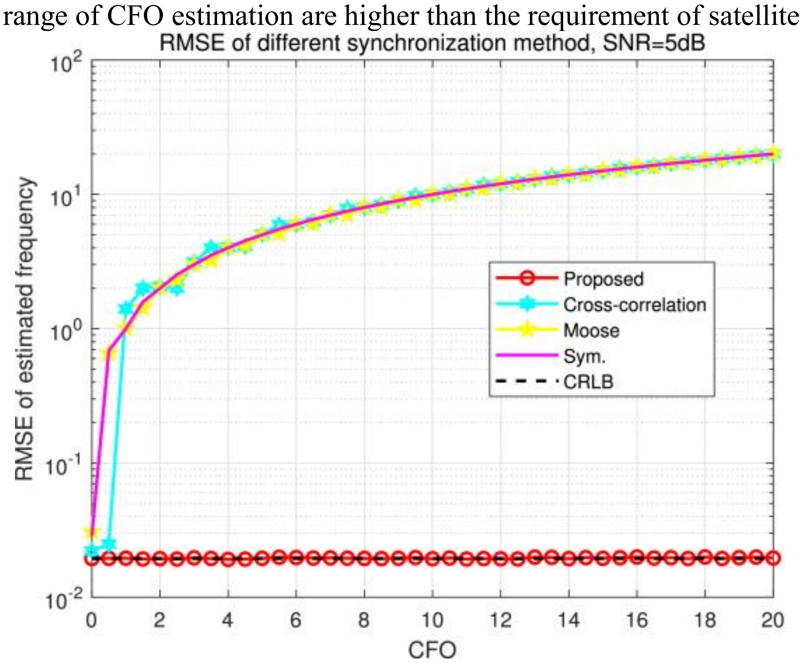

Figure 1. Estimated CFO RMSE vs CFO (Considered single path channel) (SNR=5dB).

Considered fixed CFO and different SNR the RMSE can also reach the CRLB. In the comparison shown in the Figure 2-3, it is obviously seen that the previous methods' problem of imprecise CFO estimation of higher range is solved in the proposed method.

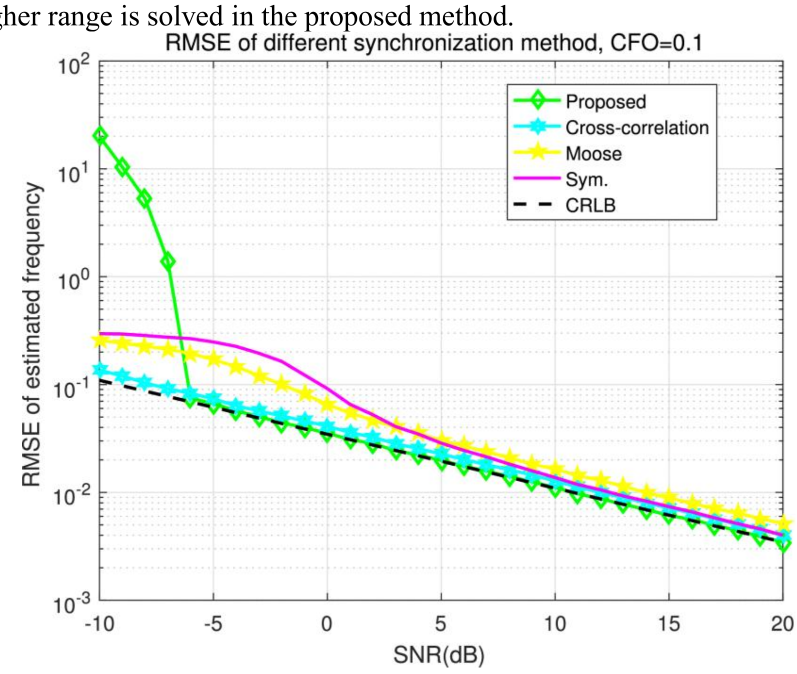

Figure 2. Estimated CFO RMSE vs SNR (Considered single path channel) (ε=0.1).

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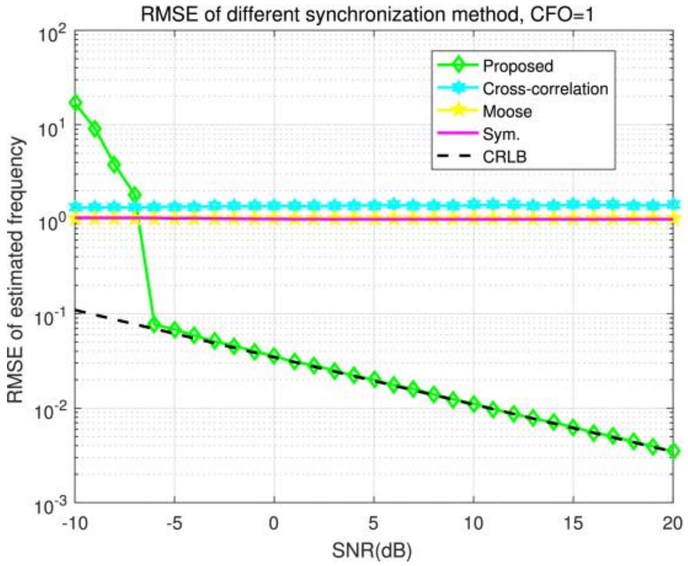

Figure 3. Estimated CFO RMSE vs SNR (Considered single path channel) (ε=1.0).

*3.1.2. Multi-path fading channel.*Multi-path fading channel of satellite communication is suitable for environment with obstacles. The signal and channel can be defined in matrix form in substitution. The matrix multiplication and the feature of the satellite channel are applied on the proposed method. The method of timing synchronization process is shown as follows.

l. Define the receiver signal in matrix form.
2. Introduce the regularization to stabilize the solution
3. Estimate the matrix-form channel by iteratively reweighted least squares (IRLS)
4. Obtain the estimated CFO.

The proposed method of multi-path fading channel focus on improving precision and reducing complexity. The feature of channel of satellite communication is used to reduce the complexity. In result of simulation is shown in the Figure 4, considered fixed CFO and different SNR the RMSE of proposed method can also reach the CRLB. And, the lowest SNR to attain the CRLB is lower than the link budget. There is better performance of CFO estimation than the other methods.

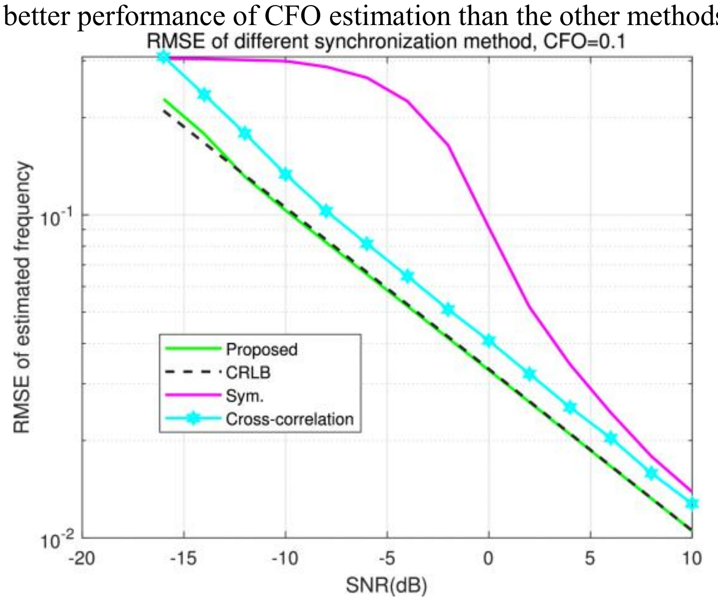

Figure 4. Estimated CFO RMSE vs SNR (Considered multiple path channel) (ε=0.1, p=1/2).

To sum up, the two newly proposed methods both meet the requirement of satellite communication and reduce the complexity. The proposed methods be separately applied for channels with single-path fading and multi-path fading, so they have wide range of application scenarios for satellite-ground communication convergence.

*3.2. Multi-symbol merging method.*Jianfei Tong et al. propose a multi-symbol merging method of 5G satellite communication synchronization based on CP-based blind timing synchronization algorithm. The proposed method focuses on solving the problem of degraded performance of existing cross-correlation based synchronization methods under large CFO and large distance conditions in satellite-to-ground wireless communication scenarios. Their innovative breakthrough is substituting the multi-symbol merging for single-symbol way. The method consists of coarse timing synchronization and fine timing synchronization. This optimization of the algorithm improves performance of CFO estimation. And the results of the coarse timing synchronization are the foundation of the fine timing synchronization as the initialization state. The Method of Coarse timing synchronization process is shown as follows:

1. Define the multi-symbol merging function by the correlation operation.
2. Do coarse timing synchronization:
3. Introduce new parameter for multipath channels
4. Define the multi-symbol as coarse synchronization
5. Initialize the multi-symbol merging function based on the results of coarse timing synchronization
6. Do fine timing synchronization through iteration

The precision of coarse timing synchronization is affected since the length of CP is short and CP does not have ideal auto-correlation characteristics. The multi-symbol merging function is introduced to solve this problem. The simulation results shown in Figure 5-6 prove that the proposed multi-symbol timing estimation performs better under the condition of lower signal-to-noise ratio of satellite-to-ground conditions than the single-symbol based methods.

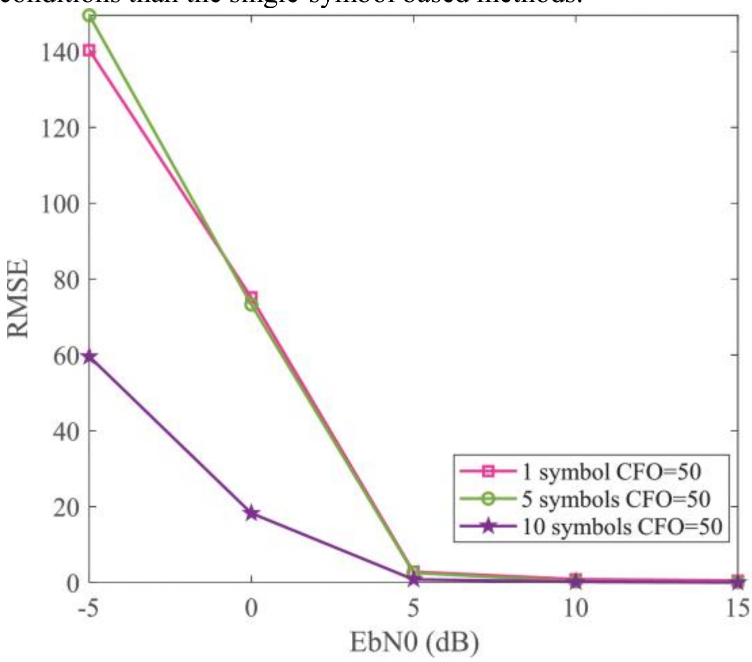

Figure 5. Performance of Timing Estimation with CFO=50 under multipath channel (L=7).

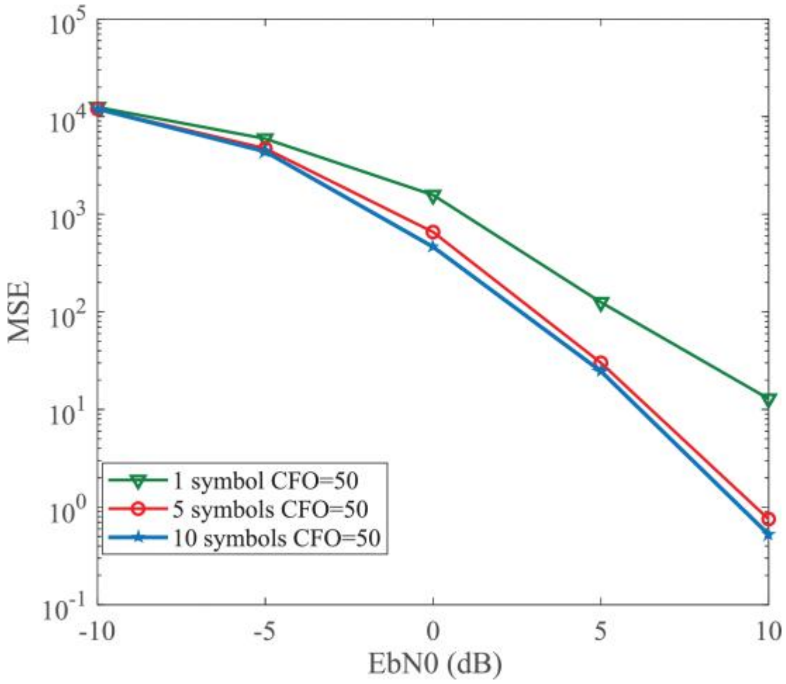

Figure 6. Performance of Frequency Estimation with CFO=50 under multipath channel (L=7).

The simulation results of the integrated link-level BER performance in the satellite scenario is shown in Figure 7. The performance of the proposed multi-symbol merging timing method is verified to precisely enough to be applied under the complex environment of the satellite channels. The curves considered time and frequency offset are closed to the curves without time and frequency offset. Therefore, the time and frequency offset are well corrected and compensated. The problem of degraded performance under large CFO and large distance conditions is well solved. Since the complex situation of satellite communication channel is considered, the results proves that the multi-symbol merging method is suitable for satellite communication.

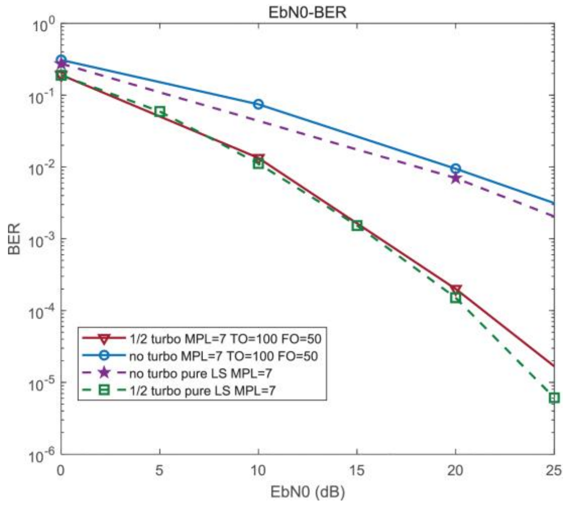

Figure 7. Performance of BER with CFO=50 and TO =100 under multipath channel (L=7).

To sum up, the precision of timing synchronization is improved through the innovation by introducing multi-symbol merging function. The proposed method has made important contributions to the realization of high-speed dynamic synchronization of satellite-ground communication. It has a wide range of application prospects under the trend of high-speed and full coverage of satellite communication.

*3.3. Method based on preamble symbol & PSS symbols& filter frequency locked loop.*Yun Liu et al. provide time-frequency synchronization methods for OFDM-based wireless communication on the large Doppler frequency shift NTN system in their paper. The synchronization is divided into three steps: coarse symbol timing and frequency estimation, fine symbol timing and frequency estimation and residual frequency offset estimation. The proposed method has high precision in the satellite communication condition of wide estimation range of frequency offset and low Signal to Noise Ratio (SNR). The method has low complexity with no matrix arithmetic required, so that it has considerable engineering application performance. The coarse synchronization is based on the feature of preamble. Then the correlation between the PSS symbols is operated for fine synchronization. Based on the first-order filter frequency locked loop, the residual frequency offset is estimated and tracked. The process of the method is shown in Table 1 as follows.

Table 1. Method of timing and frequency synchronization.

A. Coarse Synchronization	B. Fine Synchronization	C. Residual Frequency Offset Estimation and Tracking
• Operate the sliding cross-correlation. • Detect the correlation peak • Estimate the large Doppler frequency offset (FFO&FO) through preamble symbol • 4.Perform initial frequency offset compensation and correction.	• Find the maximum correlation time offset from cross-correlation operation between the PSS symbols • Perform FFT operation	• Compensate the residual frequency offset for the current data symbol • Estimate residual frequency offset by the frequency-domain pilot of the i-th received data symbol and the local data symbol • Estimate the next data symbol's residual frequency offset by using the frequency locked loop

In the condition of different channels, the proposed high precision of CFO. The simulation results presented in Figure 8-9 separately considered AGWN channel and Rician channel proves is good performance. The CFO has small effect on the RMSE. Therefore, the CFO is Well compensated and corrected.

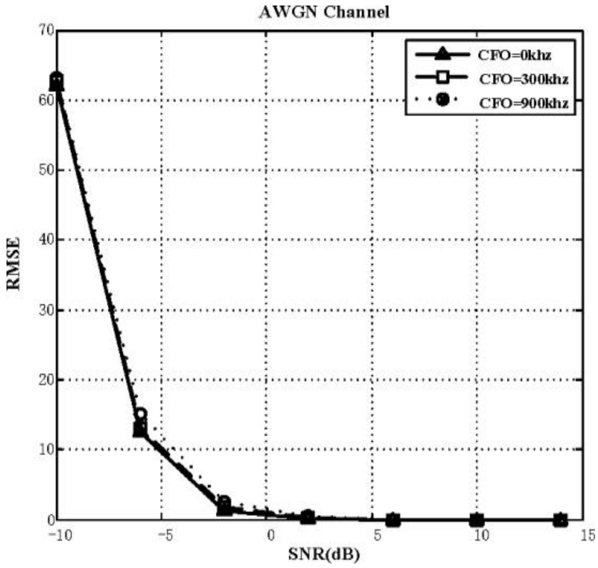

Figure 8. RMSE vs SNR with different CFO (Considered AWGN channel).

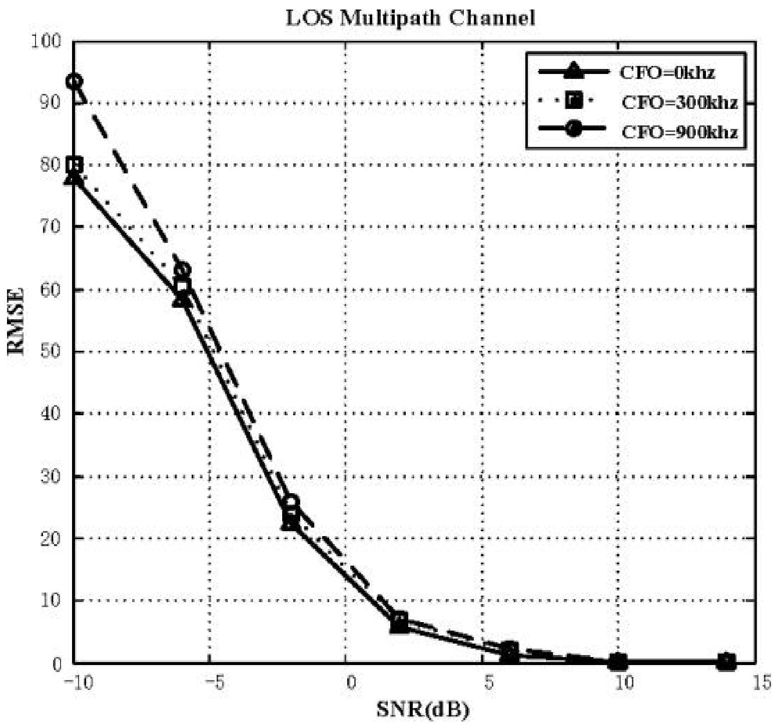

Figure 9. RMSE vs SNR with different CFO (Considered Rician channel).

The proposed method of timing and frequency synchronization has better performance on binary error rate in the case of high SNR satellite communication environment with high Doppler frequency shift. The performance can be obviously seen in the simulation results shown in Figure 10. There is small deviation he two curves, so that this synchronization can be applied in different environment.

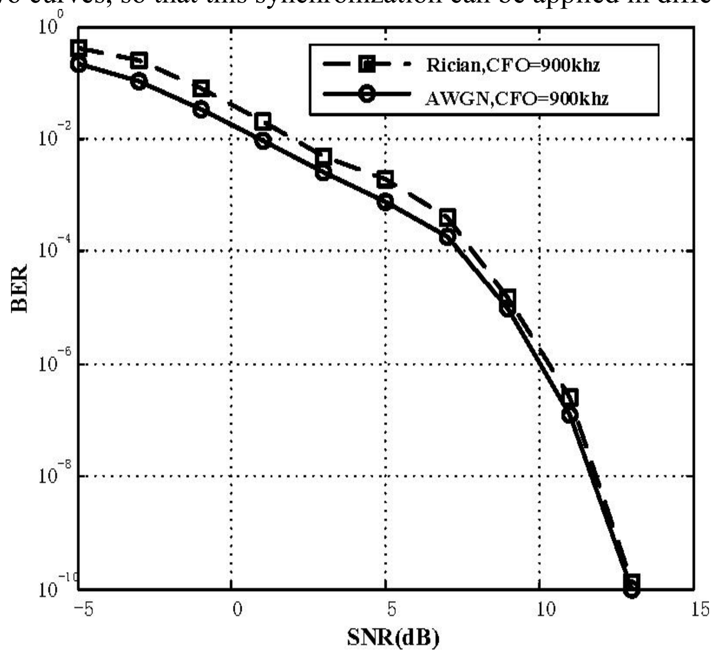

Figure 10. BER vs SNR under Rician channel and AWGN channel.

To sum up, the proposed method well meets the requirement of satellite communication in condition of large CFO and high SNR, and the estimation has high precision. The new method of compensating and tracking residual frequency offset well improve the performance. It can provide additional technical support for dynamic synchronization of 5G satellite-earth communication and contribute to the convergence of satellite-to-ground communications going forward.

3.4. Comparison and discussion

Table 2. Comparison of the methods.

	3.1	3.2	3.3
Channel model	Single path fading channel& multi-path fading channel	Multi-path fading channel	Awgn& rician channel
Features	Converting the CFO estimation to frequency estimation	Introducing multi-symbol merging	The feature of preamble symbol taken in account & frequency locked loop applied
Algorithm Foundation	FFT based Estimation algorithm& iteratively reweighted least squares	Blind timing Algorithm based on the cyclic prefix	Algorithm based on cross- correlation operation

Those three important research contributions all focus on solving the problem of frequency offset estimation in synchronization. The methods are aimed at reducing the computational complexity and improving the estimation accuracy. The methods mentioned in 3.1 simplify the estimation problem mainly through transforming the object to be estimated and the methods in 3.2 and 3.3 focus on optimizing the algorithm. To improve the estimation accuracy, the method mentioned in 3.2 introduces multi-symbol merging way and the method mentioned in 3.3 estimates and tracks the residual frequency by the first-order filter frequency locked loop. All of the methods consider the complex channel of satellite communication and the methods are well adapted to the requirements of satellite communications. Table 2 sums up all the methods proposed in those three important research contributions have good performance and realisability.

4. Conclusion

In this paper, ZC based and matrix-vector multiplication method, multi-symbol merging method and preamble and PSS symbols based and filter frequency locked loop Based method of synchronization of OFDM-based satellite communication proposed in those three important contributions were introduced and analysed. Those methods are representative and have better performance than the methods presented in previous studies. In summary, the current development of synchronization for satellite communication based on OFDM code is relatively mature. The new methods solve the problem of insufficient range of CFO and make the long-studied OFDM-based synchronization algorithms be adapted to the application scenarios of satellite communications. The accuracy and complexity both meet the requirement of 5G satellite communication system. The future trend is to further optimize algorithms to reduce complexity and expand application scenarios such as high-speed transportation, extensive coverage and intelligent network. Due to the increasing demand for satellite communication broadening range of applications, technology of synchronization for satellite communication will always be a big focus.

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