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RESEARCH ARTICLE

A Fast and High-Precision Satellite-Ground Synchronization Technology in Satellite Beam Hopping Communication

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A key requirement for future multibeam broadband satellite communication systems is the ability to flexibly adjust beam capacity according to changes in business distribution, in order to meet time-varying business requirements. Beam hopping technology provides an efficient solution to achieve the efficient use of frequency resources and power resources. At the same time, the use of beam hopping makes the beam hopping of satellite payload need to match the business signals of ground signal stations, bringing about the need for synchronization of beam hopping between satellite and ground. On the basis of analyzing the basic principles and key technologies of hopping beam, the paper analyzes the synchronization problem of satellite to ground hopping beam, proposes a signaling-assisted fast synchronization method of hopping beam for satellite to ground synchronization, and conducts simulation analysis of synchronization performance.

Introduction

With the advancement of Internet applications, the global demand for broadband satellite communication services is incessantly escalating. Furthermore, there exists an exponential surge in the requisition for the capacity of satellite communication systems. In response to this evolving demand, the domain of satellite communication technology is progressively evolving toward the realm of high-throughput satellite communication systems. Figure 1 compares conventional and high-throughput satellites.

The typical technical characteristics of "High Throughput Satellite (HTS)" are: (a) the satellite adopts multibeam technology for beam overlapping coverage of the service area, which improves the quality of the wireless link while realizing the spatial dimension segmentation; (b) based on this, the system adopts multiple frequency multiplexing to improve the communication capacity of a single satellite; (c) the gateway station is tightly coupled with the user beam clusters are tightly coupled to complete 2-hop communication, which makes multiple gateway stations share the communication resources of the same satellite, forming a spatial isolation of the gateway stations, and once again realizing the frequency multiplexing of the gateway station links [1,2].

Currently, the problems faced in the development of HTS satellite communication system mainly focus on 2 aspects, firstly, how to further increase the system capacity to provide more communication resources; secondly, how to improve the system flexibility to meet the various application scenarios and the possible needs of various communication applications. In 2010, the European Space Agency supported the Autonomous University of Barcelona and the German Aerospace Centre to carry out relevant research work, which proposed the concept of beam-hopping technology and theoretically proved the feasibility of increasing the capacity of the system, and since then, beam-hopping has been the focus of attention of a wide range of related research institutions [3,4]. The HTS beam-hopping communication system is shown in Fig. 2. In recent years, scholars at home and abroad have focused their research efforts on the design of high-throughput satellite systems based on hopping-beam technology, key technologies affecting the performance of high-throughput satellite systems, and the optimization of efficient resource use for high-throughput satellite systems. In addition, with the construction of low-orbit large-scale communication constellations represented by star chains, hopping-beam communication for low-orbit satellites has also become a hot spot in the industry [5–7].

This paper firstly introduces the basic principle of high-throughput satellite hopping beam communication and analyzes the key technologies involved in the satellite hopping beam communication system. Secondly, it investigates the forward hopping beam star-Earth synchronization method for high-throughput satellites, proposes a forward hopping beam synchronization method based on independent signaling carrier assistance, and analyzes its performance. Lastly, it proposes a high-precision synchronization method based on guide

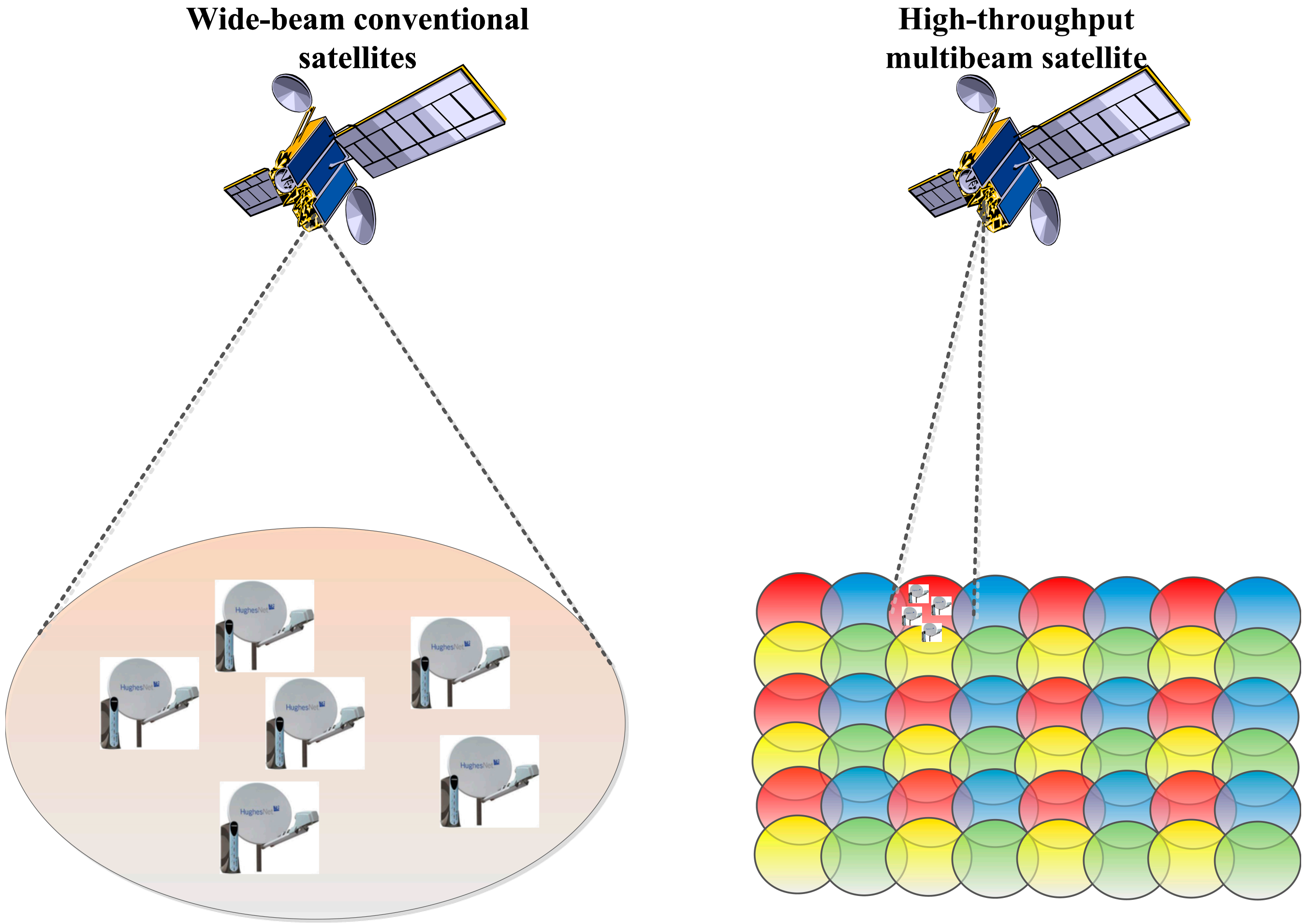

Fig. 1. Schematic comparison of conventional and high-throughput satellites.

frequency assistance for high-throughput satellite forward hopping beam star-Earth synchronization. The paper concludes with a discussion on the demand for high-precision synchronization in this context, presenting a high-precision synchronization method based on guide frequency assistance and analyzing its performance through simulation.

Methods

Key technologies for high-throughput satellite hopping-beam communications

Fundamentals of high-throughput satellite hopping beam communications

Beam hopping in HTS system is a special way of load design, the on-satellite antenna is a full-coverage multibeam antenna, but the transponder resources are shared among multiple beams in time-sharing, which is essentially a signal hopping between different beams in time sharing on demand, and it is a beam-hopping system from the point of view of the user's use, and Fig. 3 gives a schematic diagram of the working principle of the hopping load of a typical forward link of HTS satellites.

The typical features of high-throughput satellite hopping beam system are summarized as follows:

1. Breaking the frequency multiplexing of traditional HTS system (generally dual-frequency dual-polarization 4-color multiplexing), and frequency and power resources are shared within a cluster of beams by way of time division.

2. Able to dynamically adjust the service capacity of different beams at different times, which improves the overall use efficiency of the transponder.

3. The C/I of the system is optimized through efficient resource management, which further improves the communication capacity of the system.

4. The number of traveling-wave tube amplifier in the transponders decreases significantly, which reduces the complexity of the transponder design.

Although the hopping beam system can effectively improve the communication capacity and resource flexibility of the high-throughput satellite system, it also introduces new problems in system synchronization, signal processing and resource management, etc. The following 3 aspects are analyzed for the key technologies of hopping beam communication in the high-throughput satellite system.

Beam-hopping high-precision satellite-ground synchronization technology

Since beam-hopping is essentially a time-division system, if the service signal sent by the gateway station and the satellite beam-hopping load time are not synchronized, resulting in the mismatch between the satellite beam switching time and the forward service signal, it will directly affect the normal

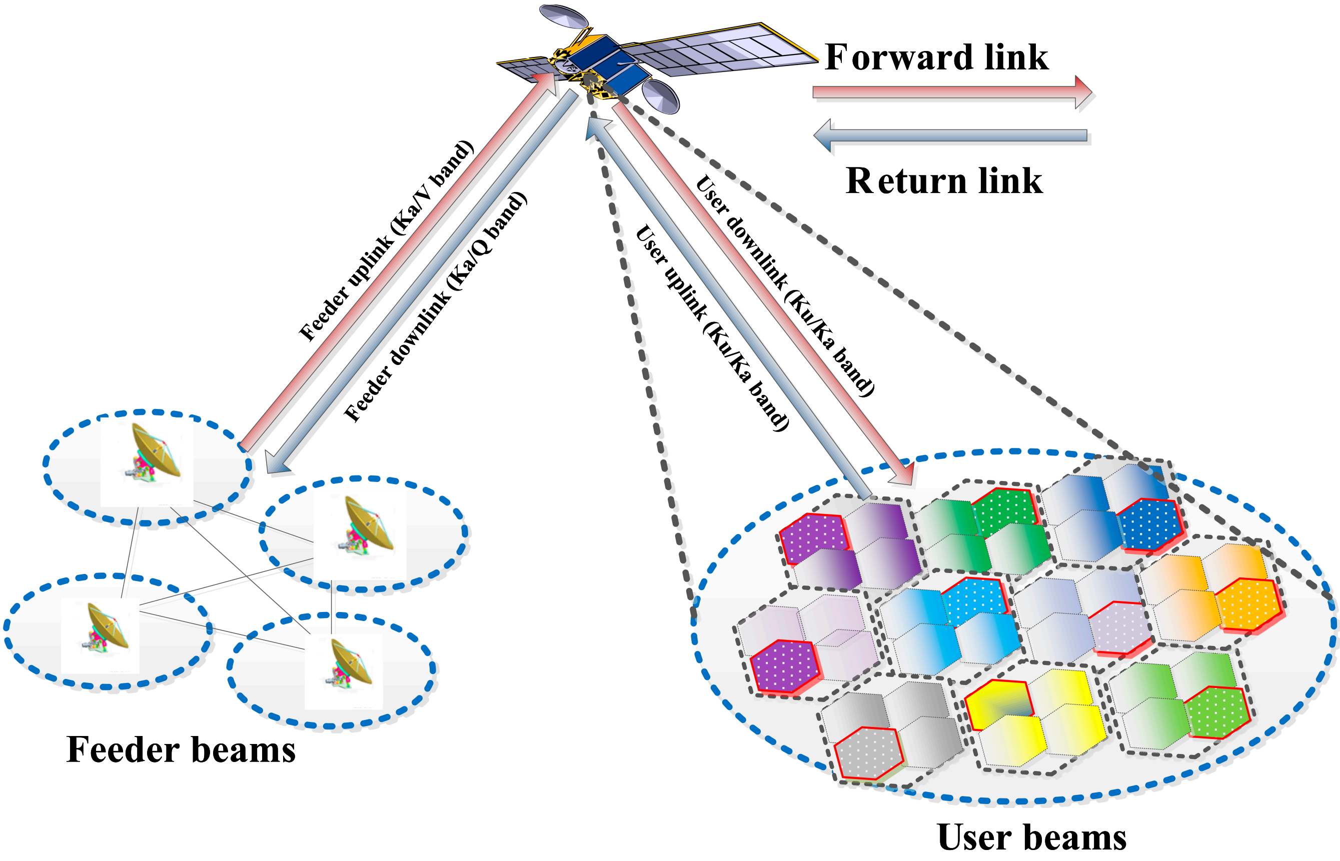

Fig. 2. Schematic diagram of the HTS beam-hopping communication system.

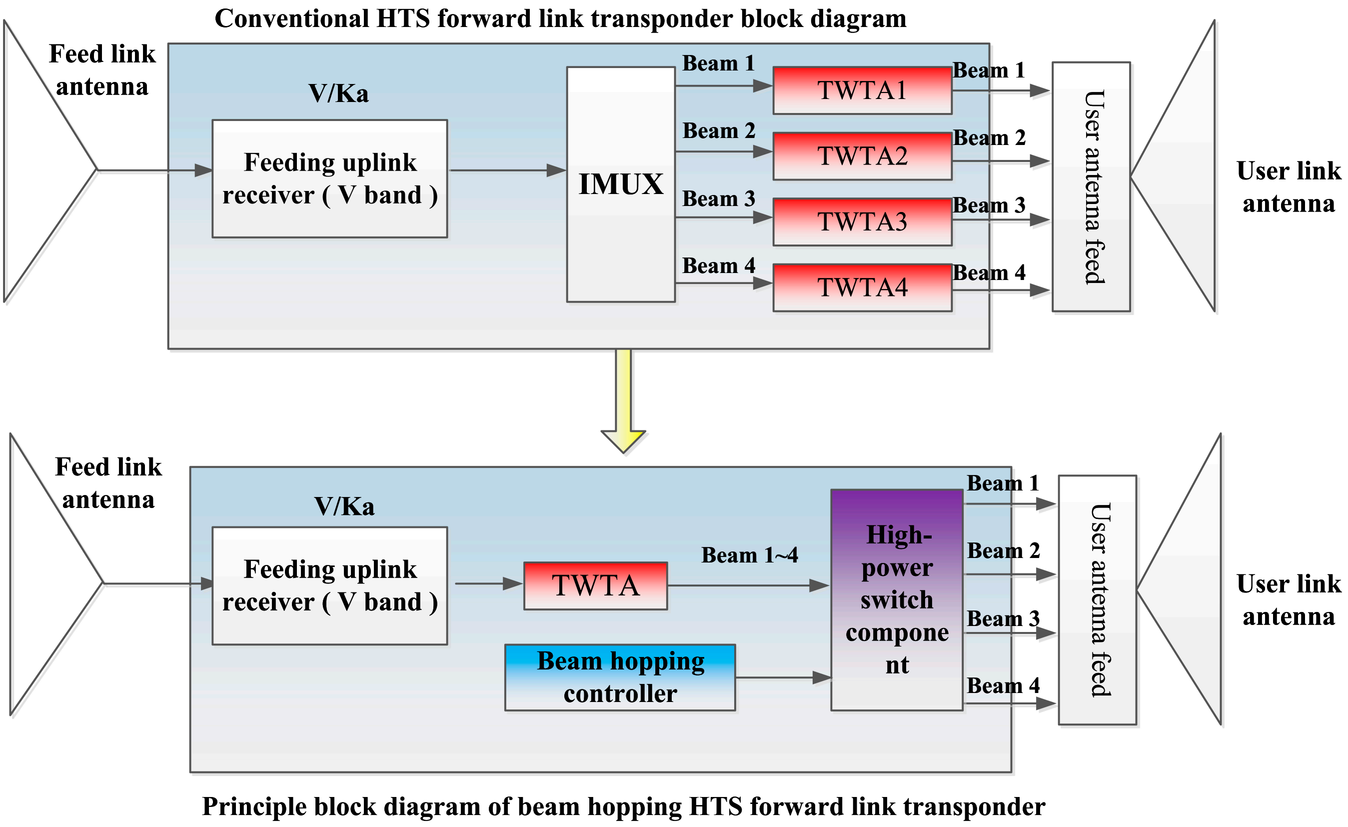

Fig. 3. Block diagram of a typical forward hopping beam loading principle.

reception of the user terminal. If the satellite beam switching time falls within the protection time of the service signal, the service signal sent by the gateway station and the satellite beam hopping can be strictly time synchronized, which ensures that the service signal is correctly forwarded to the user by the satellite [8,9].

Figure 4 illustrates the misalignment of signals between user beams caused by the out-of-step satellite-ground hopping beams in the hopping beam system. To avoid misalignment between forward service signals among user beams, it is essential to ensure strict synchronization between the forward signals sent by the gateway station and the time of satellite load beam switching. The accuracy of time synchronization depends on the switching time of the high-power switch on the satellite, with a general requirement that the synchronization accuracy is better than 1 μs.

Low signal-to-noise demodulation of high-speed burst signals

In the beam-hopping communication system, beam-hopping causes the continuous time-division multiplexing (TDM) signal of the traditional forward link to become a burst TDM signal. As a result, the ground receiver needs to adapt to demodulation in burst mode, which necessitates fast synchronization of the ground demodulator. Additionally, existing forward service communication systems mainly utilize standard systems such as Digital Video Broadcast-Satellite 2/Satellite 2X (DVB-S2/S2X), which typically employ high-performance error correction codes such as Low Density Parity Check Code for channel coding. The use of high-performance Low Density Parity Check Code codes further reduces the working threshold of communication demodulation. Consequently, demodulating low signal-to-noise-ratio bursty signals becomes crucial for processing beam-hopping service communication [10]. Figure 5 gives a schematic diagram of a downlink burst received by a user in a beam-hopping system.

Efficient resource management techniques for beam-hopping systems

The significant advantage of the hopping beam technology is that it can dynamically allocate resources according to the service volume of different wave positions, which makes the resource use efficiency of the whole system optimal. In order to give full play to the advantages of the hopping beam system, it is necessary to study the highly efficient resource allocation technology used in the hopping beam. Figure 6 gives the example of service statistics for different wave positions in a hopping-beam system. Numerous literatures show that the hopping beam satellite system has better performance in resource allocation compared with nonhopping beam satellite system, and a large number of scholars have researched and analyzed the optimal resource allocation method of hopping beam system from different perspectives, and researched and analyzed the resource usage modeling and allocation algorithm of hopping beam system from various perspectives such as optimal matching of service demand, delay fairness, etc. [11–15].

Among the above key technologies, the hopping beam satellite-ground synchronization is the most important technology, which is the key to the successful operation of the system, and the following focuses on the hopping beam synchronization technology to carry out research and analysis and simulation work.

Research on forward hopping beam satellite-ground synchronization methods

Forward hopping beam synchronization model

Different from the traditional HTS system, beam-hopping technology adopts a time-division communication system, which adjusts the beam pointing according to rules in the satellite coverage area. Since beam hopping is essentially a time-division system, if the service signals sent by the gateway station and the satellite beam hopping load time are not synchronized, resulting in the mismatch between the satellite

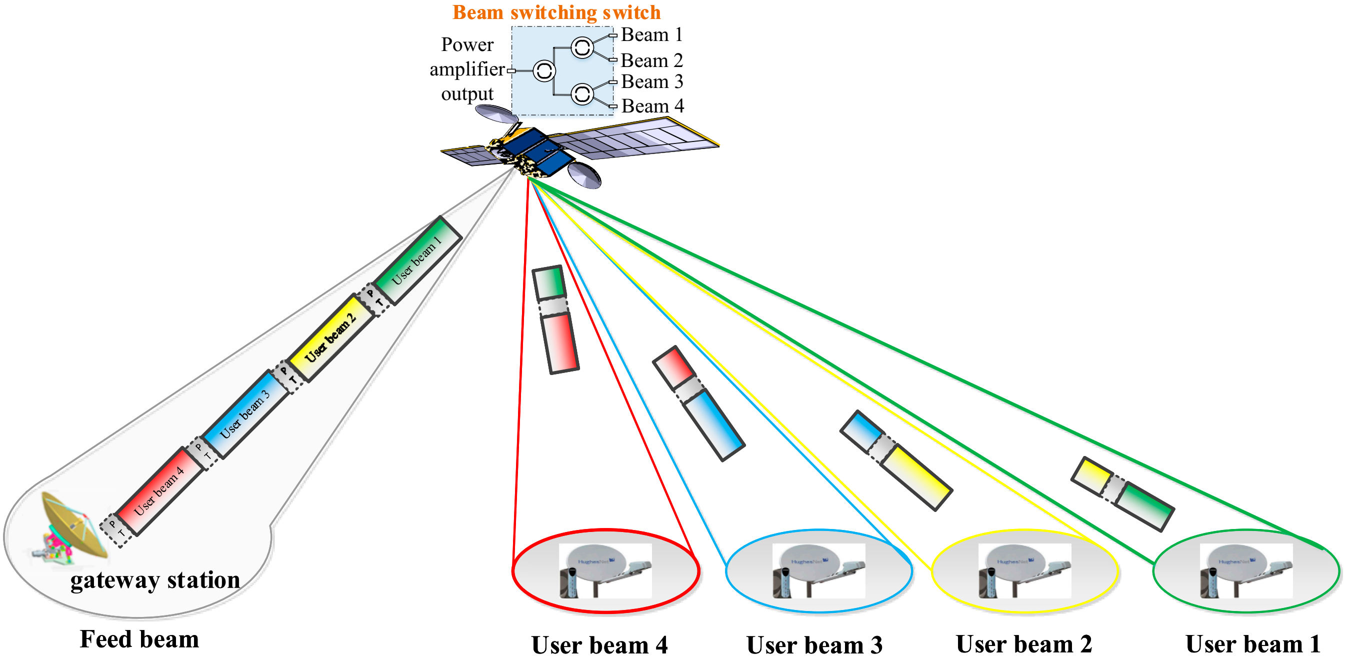

Fig. 4. Schematic diagram of satellite-ground synchronization of a hopping beam system (out-of-step condition).

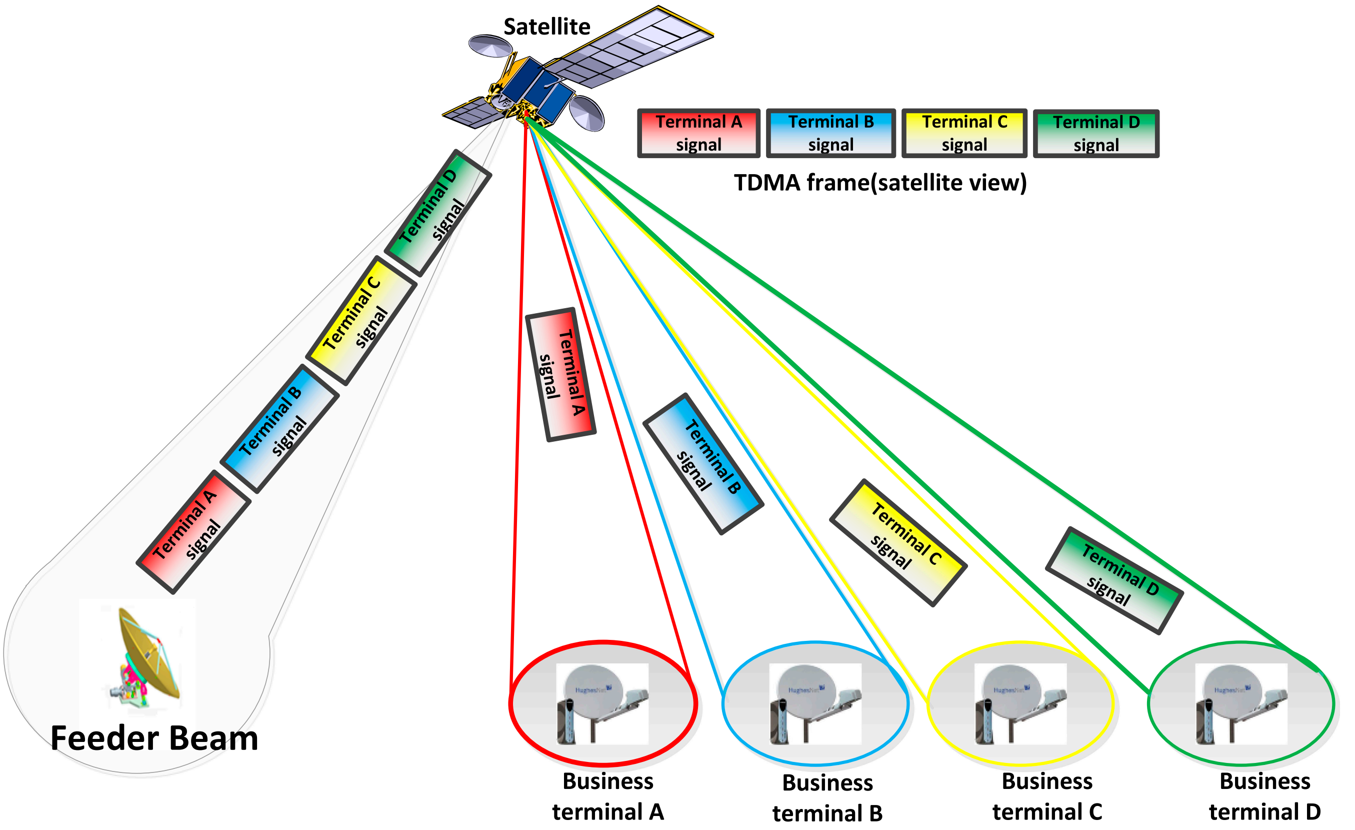

Fig. 5. Schematic diagram of a downlink burst received by a user in a beam-hopping system.

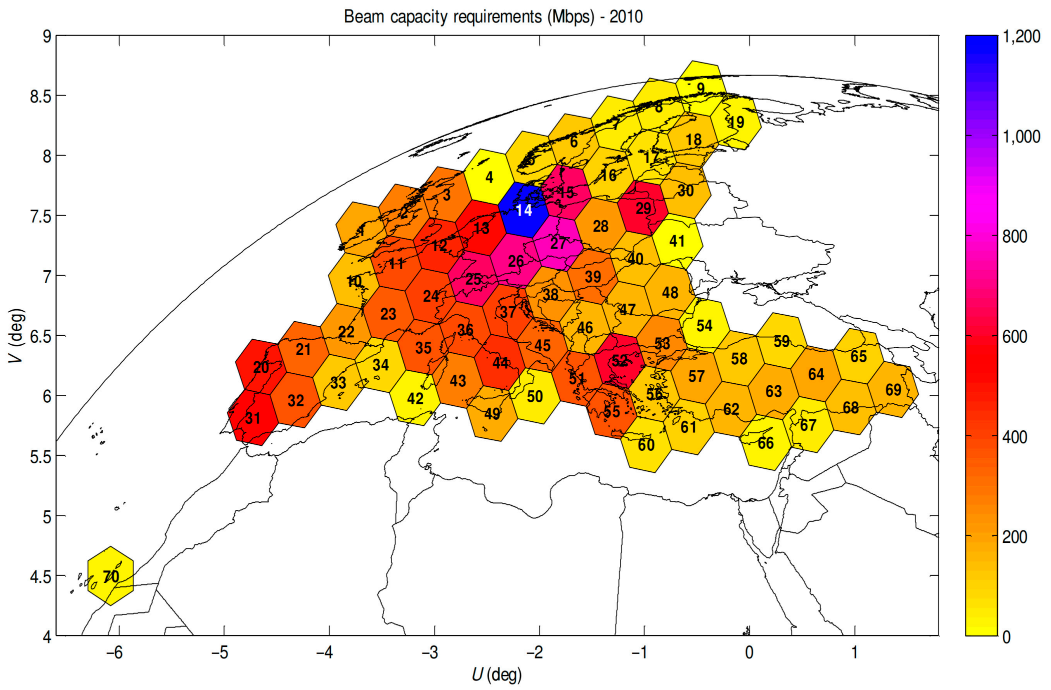

Fig. 6. Example of service statistics for different wave positions in a hopping-beam system [15].

beam switching time and the forward service signals, it will directly affect the normal reception of the user terminals; the satellite beam switching time falls within the switching protection time position of the service signals, and the time between the service signals sent by the gateway station and the satellite beam hopping can be strictly time synchronized, at

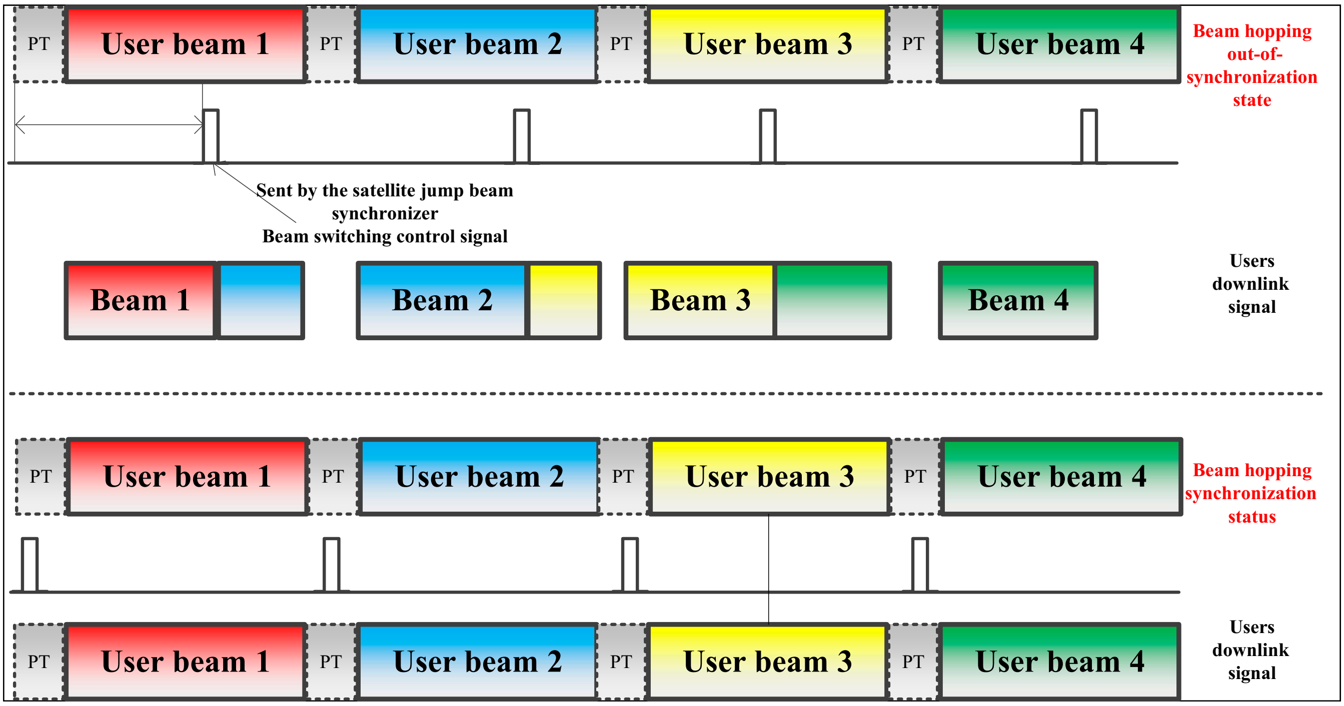

Fig. 7. Schematic diagram of hopping beam synchronization.

which time it can be ensured that the service signals will be received by the satellite. When the time of satellite beam switching falls within the protection time of the service signal, the service signal sent by the gateway station and the satellite beam hopping can be strictly time-synchronized, which ensures that the service signal is correctly forwarded to the user by the satellite. The synchronization between the forward service signal sent by the gateway station and the satellite beam hopping is shown in Fig. 7.

In the actual system, the satellite needs to be configured with hopping beam synchronization equipment to achieve accurate time-sharing of the actual service signals under different beams, so it is necessary to ensure fast and high-precision synchronization between the service signals sent by the gateway station and the beam switching on the satellite.

Comparison of 2 hopping beam synchronization methods

The first international research and application of beam-hopping synchronization technology was carried out in the 1990s as part of the Advanced Communication Technology Satellite satellite system, which utilized satellite switched time division multiple access (SS-TDMA) technology. This technology facilitated the synchronization of all beams through a lightweight on-satellite switching matrix, enabling time-division interconnection of all beams. To achieve synchronization in the entire beam-hopping TDMA system, 3 common signaling and synchronization channel time slots were designed to support various synchronization functions. These include outward synchronization from the ground reference station to the service station, self-synchronization at the service station, and inward synchronization from the service station to the reference station. In satellite-Earth synchronization, the predominant method involves ground synchronization with the satellite, which typically requires longer synchronization times and results in relatively static beam hopping [16].

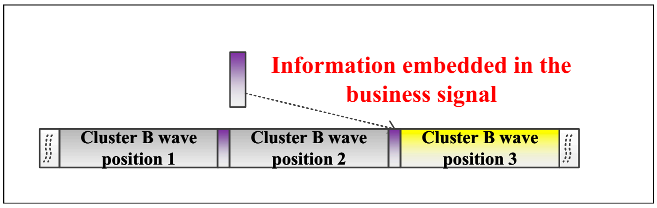

Fig. 8. Schematic of control information multiplexed with service carrier time.

In order to complete high-precision forward hopping beam synchronization, simplify the complexity of hopping beam synchronization and enhance the flexibility of hopping beam application, the paper proposes a satellite-Earth hopping beam synchronization method with on-satellite synchronization to the ground gateway station, the basic principle of this method is to send an auxiliary hopping beam synchronization signal in one direction through the ground gateway station, and the on-board hopping beam controller will synchronize the hopping beam synchronization signal and then drive and control the switching of the hopping beam switch to achieve the star-ground synchronization.

Based on the relationship between the auxiliary hopping beam synchronization signal and the service signal, the synchronization scheme can be categorized into 2 types: time multiplexing-based hopping beam synchronization scheme and independent synchronization carrier-based hopping beam synchronization scheme, which are introduced below.

- Satellite-ground hopping beam synchronization scheme based on time multiplexing. Based on time multiplexing with the service carrier, the basic principle of the

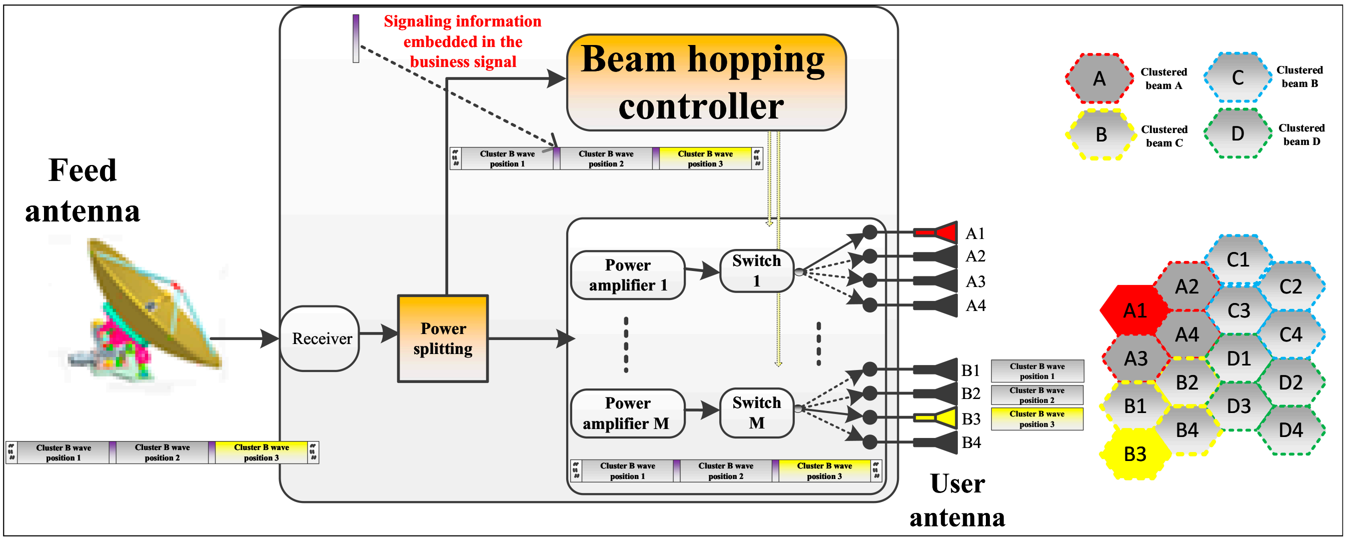

Fig. 9. Time-multiplexing based hopping beam synchronization on-satellite process.

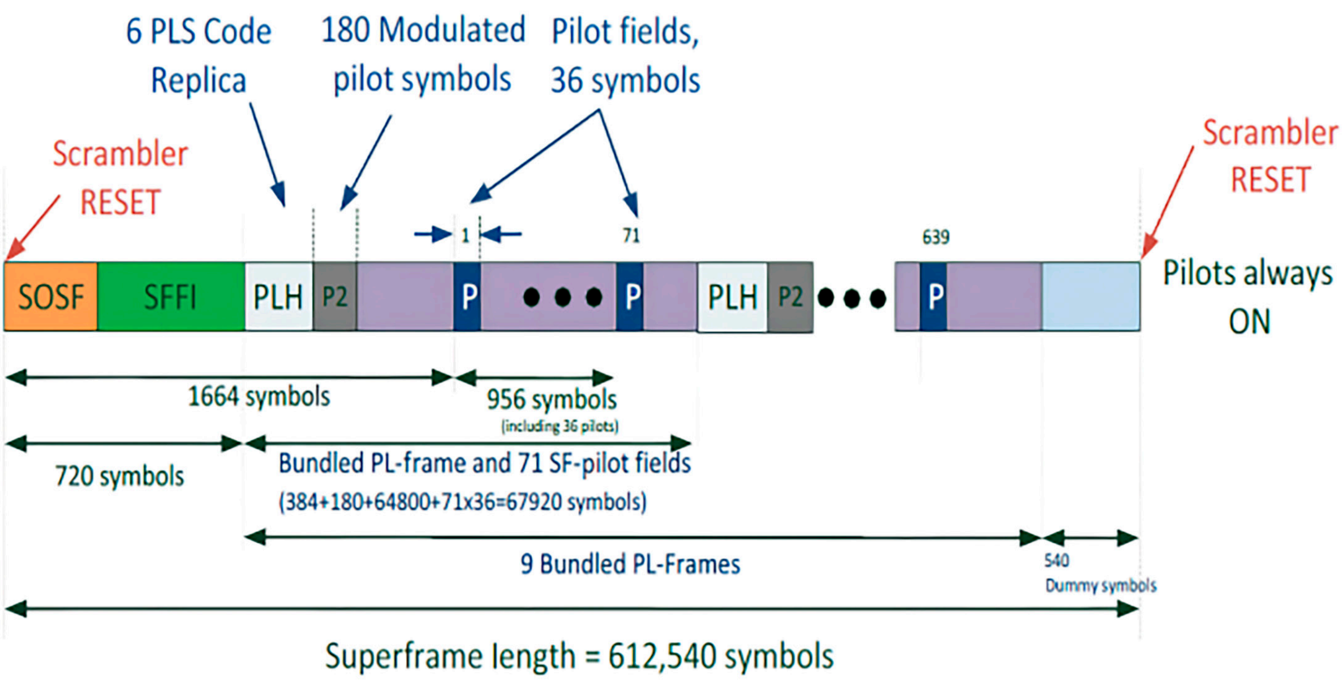

Fig. 10. Example of DVB-S2X physical layer superframe format [17].

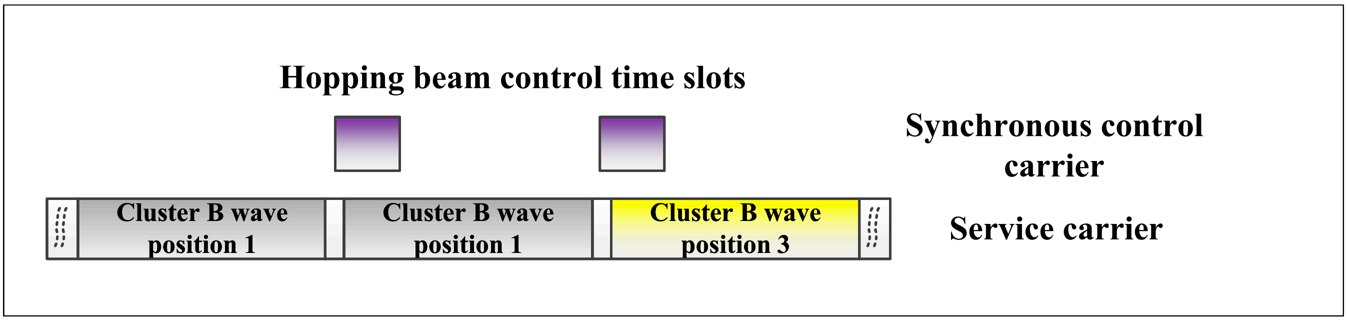

Fig. 11. Relationship between carrier and service signals for independent synchronization control.

satellite-ground hopping beam synchronization scheme is to embed the synchronization control time period in the service carrier, which carries the hopping beam control information and also serves as the protection time for inter-beam switching, and its signal format is shown in Fig. 8.

The synchronization process of the satellite-ground hopping beam synchronization scheme based on time multiplexing is as follows.

Step 1: When the gateway station transmits the service signals, it embeds the control information of the next set of signals to be hopped after each moment when beam hopping is required, and the carrier bandwidth and modulation mode of the control signals are generally the same as those of the service signals, and the length of the control signals needs to be determined by the satellite retransmission time delay, the control signal processing delay, etc.;

Step 2: The on-satellite forward link transponder divides the service signal into 2 groups; one group enters the service forward forwarding channel, and one group enters the beam hopping controller for processing, extracting the beam hopping time reference and the beam hopping switch control information;

Step 3: The beam hopping control processor realizes switching of the beam control switch according to the beam hopping control information at the extracted beam hopping time reference moment.

Based on this, the satellite hopping beam controller needs to process the synchronous time slots in the service carrier, and the bandwidth and modulation method of processing are matched with the service carrier, and the satellite hopping beam forwarding schematic diagram for this scheme is shown in Fig. 9. With the development of high-throughput satellite technology, the DVB-S2X standard has become one of the main standards used in the forward link of the current HTS satellite system. In the DVB-S2X standard, the application of beam hopping is considered, and the frame format is designed to support the use of TDM based beam hopping. Figure 10 gives the transmission frame format that supports beam hopping in DVB-S2X [17], with 36 symbols as well as 540 symbols reserved for beam switching, respectively.

- Satellite-ground hopping beam synchronization scheme based on independent synchronous carriers. Based on the independent synchronous carrier satellite-ground hopping beam synchronization scheme in the design of the synchronous control information and business information separately, occupying different frequencies, not only flexible adaptation to the use of business communication signals, and at the same time with the transmission bandwidth of business signals and modulation decoupled, the relationship between the independent synchronous carrier and the business carrier is shown in Fig. 11.

The synchronization process of the satellite-ground hopping beam synchronization scheme based on independent synchronized carriers is as follows.

Table. Comparison of 2 synchronization methods

Number	Parametric	Time Division Multiplexing control	Independent carrier control
1	Coupling to business signals	Tightly coupled	Unrelated
2	System flexibility	Weak	High
3	Processing complexity	Higher	Low
4	Frequency usage efficiency	No independent carrier required	Independent carrier required

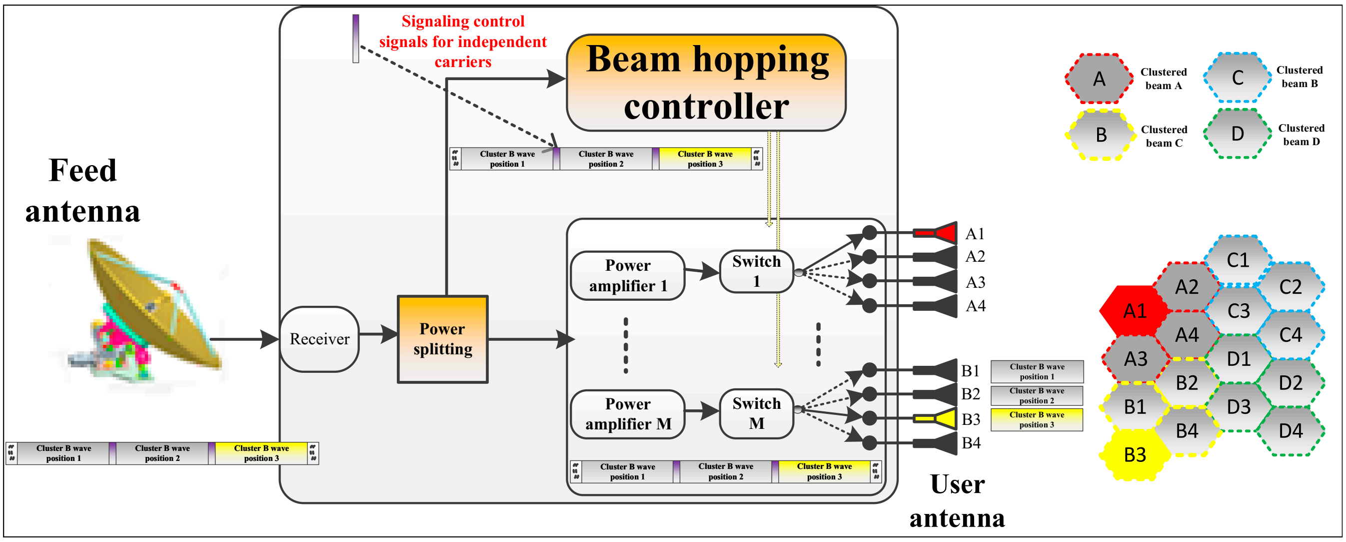

Fig. 12. Hopping-beam synchronous on-satellite process based on independent synchronous carriers.

Step 1: The gateway station, when transmitting a service signal, generates a beam-hopping control signal synchronously at each moment when beam-hopping is required, and the beam-hopping control signal generally overruns the service signal by a fixed time, which is mainly dependent on the processing delay of the on-satellite beam-hopping controller and the switching delay of the switch;

Step 2: The on-satellite forward link transponder sends the beam-hopping control signal carrier to the beam-hopping control processor, the on-satellite beam hopping control processor detects the beam hopping control signal and extracts the beam hopping time reference and the beam hopping switch control information;

Step 3: The beam-hopping control processor realizes switching of the beam control switch according to the beam-hopping control information at the extracted beam-hopping time reference moment.

Based on this, the on-satellite hopping beam controller only needs to process the synchronous carrier, simplifying the processing complexity of the hopping beam controller, and the on-satellite hopping beam forwarding schematic for this scheme is shown in Fig. 12.

According to the above analysis, the hopping beam method based on independent carrier synchronization is more flexible in application, and its comparison with the synchronization method based on TDM is shown in the following Table.

Hopping beam synchronization method based on independent signaling carrier assistance

- Efficient synchronization control signal design. In the hopping beam synchronization method of the on-satellite synchronous signaling gateway station, the design of the beam-hopping synchronization signaling signal is the key to the whole system, which not only ensures a high synchronization probability on-satellite but also simplifies the complexity of the on-satellite realization, and the following are a few principles of the design of the hopping wave signaling signal:

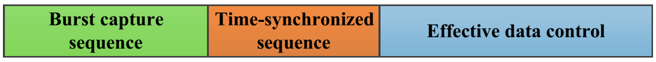

Fig. 13. Schematic diagram of beam-hopping synchronization control signal.

1. The signaling signal should be as short as possible to reduce the average power consumption of the ground station and the probability of being interfered;

2. The signaling signal is designed to ensure that it can be received by the satellite with high probability, thus improving the reliability of communication;

3. The design of the signaling signal should be able to effectively support the synchronization accuracy on the satellite, thus reducing the protection interval of the service signal and the synchronization overhead;

4. The design of the signaling signal should be able to simplify the implementation complexity of the on-satellite hopping beam synchronizer.

According to the above principles, the whole signaling signal adopts burst transmission mode, and Fig. 13 gives the structure of the hop-beam follower signaling signal.

In order to improve the capture probability of the beam-hopping synchronization control signal on the satellite, reduce the probability of missed capture and mis-capture, and at the same time improve the data correctness of the beam-hopping switching control signal, the whole beam-hopping synchronization control signal consists of 2 parts; the first part is the fixed Pseudo-Random (PN) capture sequence with long length, and the second part is the control information.

1. Fixed-length PN sequence is used for satellite control signal burst detection, which requires good correlation, the selection of specific PN code length reading can be based on the actual control information to reach the hopping beam controller signal-to-noise ratio; in order to improve the probability of capture and reduce the probability of mis-capture, it is recommended that the length of the PN sequence is more than 128 bit.

2. Time synchronization sequence for assisting to achieve high precision time deviation estimation.

3. The control information is recommended to be encoded by RM(7,64) in the DVB-S2X standard, which is characterized by a BER still better than $10e^{-9}$ at Es/N0=0dB.

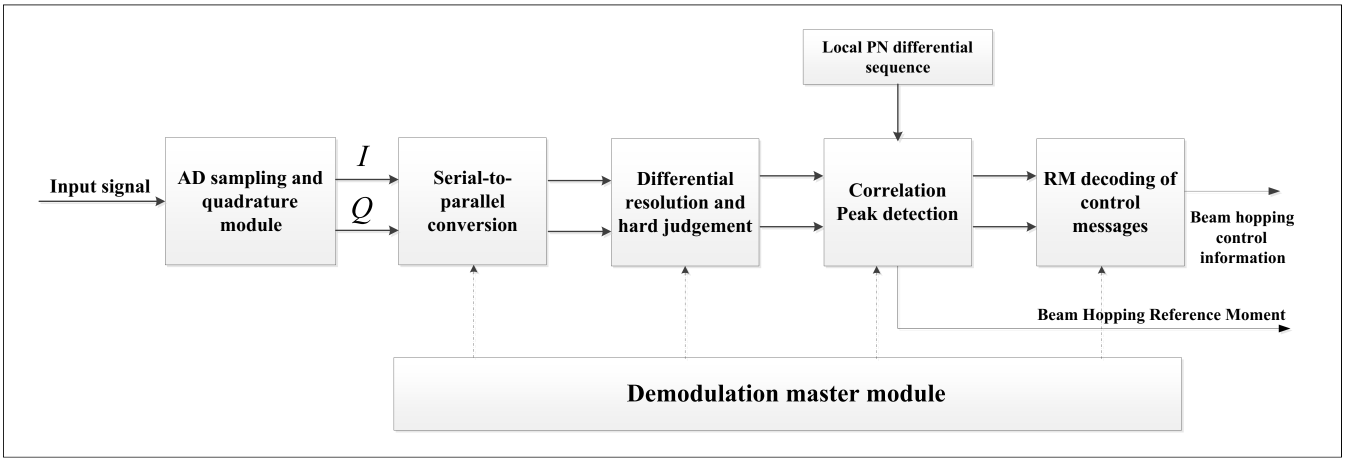

Fig. 14. Beam hopping synchronization control signal on-satellite demodulation process.

4. The beam-hopping synchronization control signal adopts DBPSK, which facilitates the adoption of a simplified demodulation scheme on the satellite.

- On-satellite processing flow of synchronization control signal. Since the beam-hopping synchronization control signal adopts a short-burst signal structure, combined with the structure of the synchronization control signal given in Fig. 3, the block diagram of the on-satellite processing flow is given in Fig. 14. The advantage of this method is that it does not need the carrier synchronization and bit synchronization process required by the traditional demodulator, which greatly simplifies the on-satellite processing complexity, and the specific demodulation process is described as follows:

Step 1: Perform AD sampling and quadrature frequency conversion on the input signal to ensure 8 sampling points per symbol;

Step 2: Perform serial-to-parallel conversion on the frequency-converted I/Q data to generate 8-channel parallel data;

Step 3: Under the control of the demodulation master control module, the 8-channel parallel data are time-differentiated and then hard-judged;

Step 4: correlating the 8-channel data sequence after the hard judgement of the dedifferencing with the local differential PN sequence in time, performing the detection of the correlation peak, comparing the size of the correlation value with the threshold value, and when the correlation value is larger than the threshold value, taking the point with the largest correlation peak among the adjacent 8 positions as the time reference point;

Step 5: The data with the largest correlation peak all the way goes to the control information Reed-Muller (RM) decoding, and the beam control information is extracted.

The implementation of the modules in the whole processing flow is simple, there is no complex algorithm, only simple multiplication, addition and logic operations, do not need RAM and ROM and other storage resources, the implementation of the entire demodulator hardware resource overhead is small, and is suitable for the implementation of the satellite payload engineering.

- Analysis of capture probability and synchronization accuracy. If the 128 bits inside the leading header are used for correlation, the correlation value of each symbol is only taken as 1 (correlation) and -1 (not correlation), and the threshold value is set to 128 symbols inside k (assuming 108) is considered to be the same as the capture on, the false capture probability can be calculated:

$$P_{\text{imag}} = \sum_{k=108}^{128} \left(\frac{1}{2}\right)^{k} \left(\frac{1}{2}\right)^{128-k} C_{128}^{k} = 4.29 \times 10^{-16} \tag{1}$$

At Eb/N0=6dB, the error bit rate of DQPSK differential demodulation is 0.01724, then the missed capture probability is:

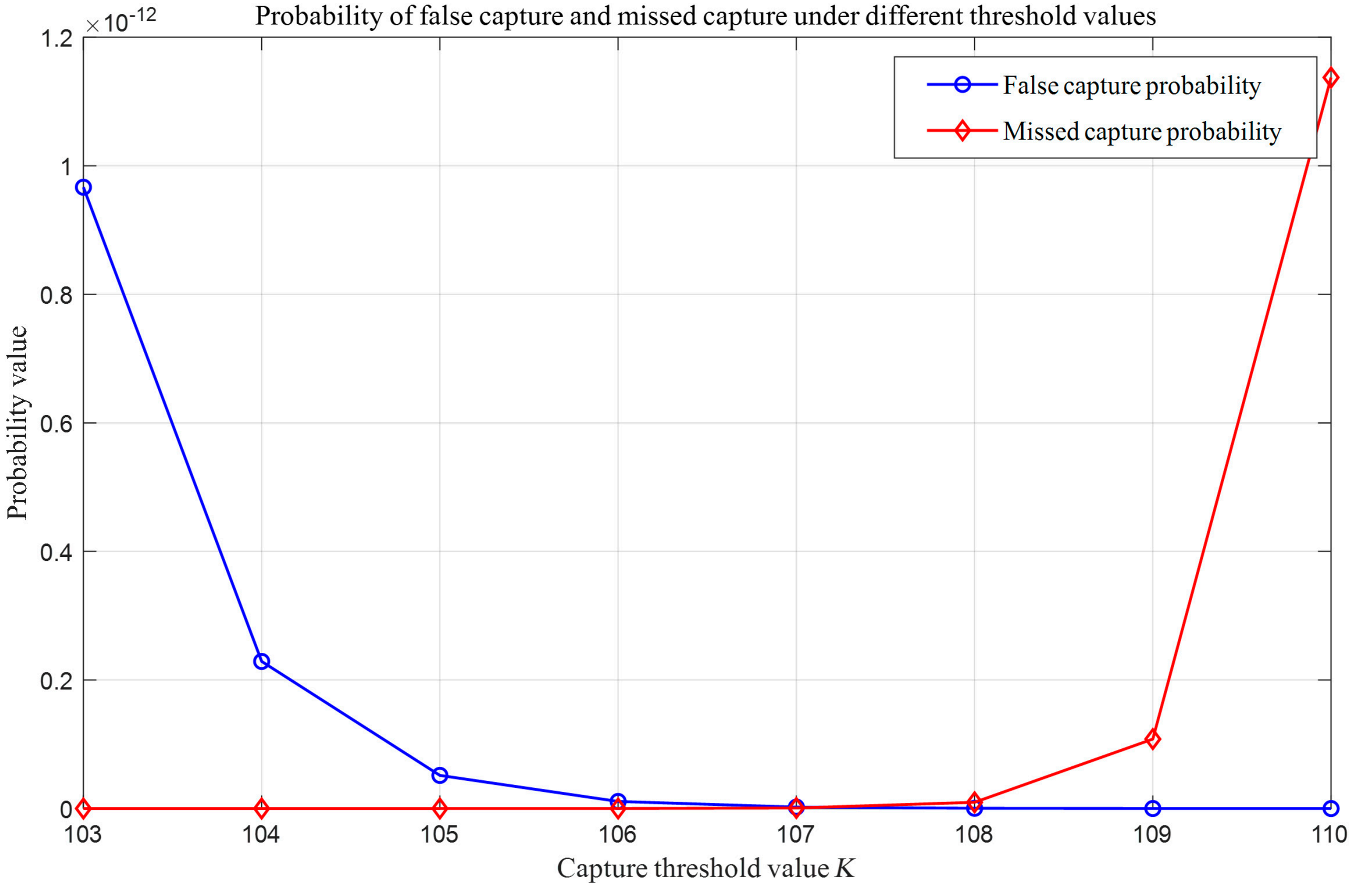

Fig. 15. False capture probability and missed capture probability at different K values.

$$
\begin{aligned}
P_{\text{missed}} &= \sum_{k=21}^{128} \left(1.724\times10^{-2}\right)^{k}\left(1-1.724\times10^{-2}\right)^{128-k} C_{128}^{k} \\
&= 9.70\times10^{-15}
\end{aligned}
\quad (2)
$$

By changing the value of k appropriately, the false capture and missed capture probabilities can be changed. In the above equation, the false capture probability is closely related to the value of k. The larger k is, the smaller the false capture probability is, while the value of K affects the leakage capture probability, the larger k is, the larger the leakage capture probability is, and the value of k has to take into account the false capture probability and the leakage capture probability, and has to be chosen as a compromise in the practical engineering application. Figure 15 gives the effect of different values of k on the probability of false capture and the probability of leakage capture.

High-precision synchronization method based on guide frequency assistance

According to the principle of forward hopping beam synchronization, the transmission delay jitter of the hopping beam controller is mainly solved by system design and algorithm design, theoretically, the higher the transmission symbol rate of signaling, the lower the output delay jitter of the hopping beam controller, but the high transmission symbol rate will bring about the increase of the system bandwidth overhead and the waste of the power of the terrestrial gateway station, and at the same time, it brings about the increase of the complexity of the implementation of the hopping beam synchronizer. Therefore, a high-precision time deviation estimation algorithm is needed to eliminate the delay jitter and improve the synchronization accuracy at a lower transmission symbol rate.

Two structures for timing bias estimation and correction

Timing deviation estimation is mainly used to realize the symbol synchronization at the receiver side, and the interpolation filtering-based symbol synchronization method [18,19] is widely used, which mainly consists of 2 parts: timing deviation estimation and timing error correction. According to whether its topology constitutes a closed loop or not, it can be categorized into 2 forms: feedback structure and feed-forward structure.

The structure of feedback symbol synchronization is shown in Fig. 16. where $r(t)$ is the received analogue input signal, $r(kT_s)$ is the digitised sampled signal with T_s as the sampling period for the analogue input signal $r(t)$, $X(kT_s)$ is the matched filtered signal for $r(kT_s)$, m_k is the integer multiples of the sampling period error signal, μ_k is the fractional multiples of the sampling period error signal, and $y[(m_k + \mu_k)T_s]$ is the interpolated adjusted sampled signal. A typical feedback symbol synchronization method is the Gardner algorithm [20]. The algorithm uses error detection to obtain an estimate of the timing error, uses loop filtering to suppress the effect of noise, and then feedback controls the interpolation filter to achieve the

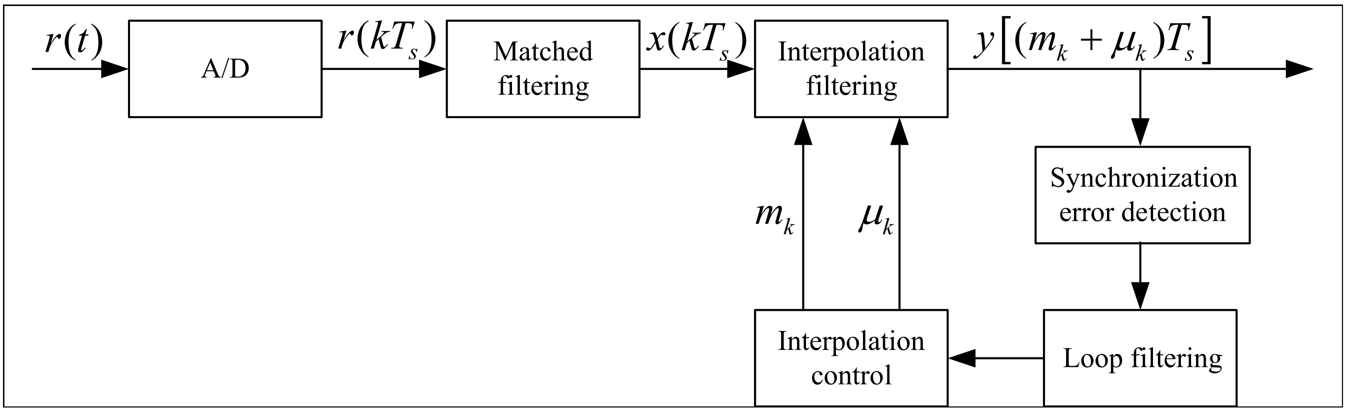

Fig. 16. Feedback synchronization structure.

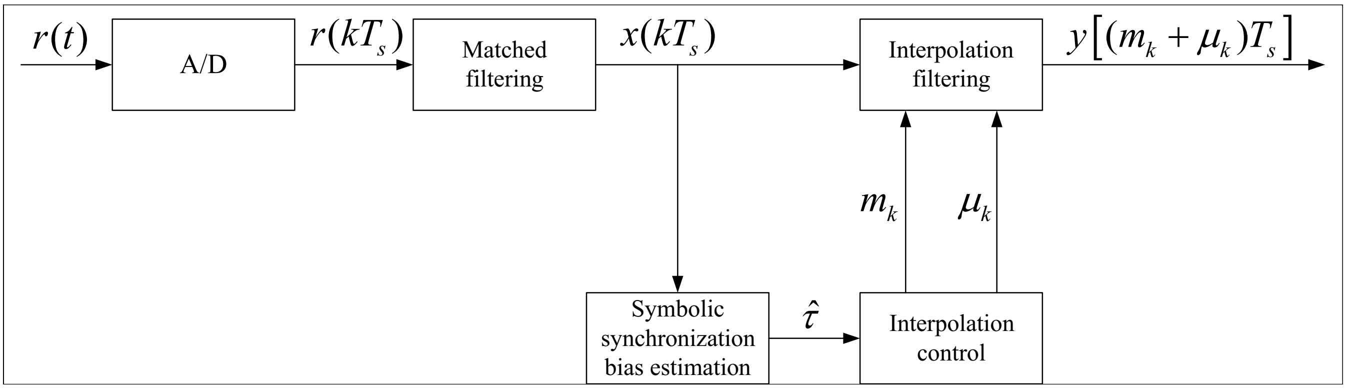

Fig. 17. Feed-forward synchronous structure.

realization of the error correction to achieve the purpose of symbol synchronization. Gardner's algorithm has better performance in most application scenarios. The signal in the feed-forward structure flows in one direction and does not form a feedback logic. The algorithm in this structure estimates the timing deviation directly from the received signal, and then interpolates the optimal sampling point based on the estimation result. Its synchronization structure is shown in Fig. 17.

As the feedback structure adopts the closed-loop mechanism of error feedback and timely correction, it determines that its tracking performance is better, especially when there is a large sampling frequency deviation, the algorithm can still work properly, but also due to the existence of the feedback mechanism of the processing delay, resulting in a longer capture time; feed-forward structure of the symbol synchronization of the response is fast, and thus is mostly used in the burst signal reception, but the open-loop form of the structure leads to the estimation of its error is only dependent on a finite number of input signals, which directly determines that the final phase jitter is larger.

A high-precision time bias estimation method

Accurate timing deviation estimation is the key to the time synchronization of the hopping beam system, which affects the performance of the whole system, based on this, a variety of commonly used estimation algorithms are studied and compared in the paper. In the feed-forward timing synchronization method, the most commonly used algorithm for timing deviation estimation is the digital squared filter method given in literature [21], which has high estimation accuracy and does not require data assistance, but its performance decreases rapidly with the reduction of the signal-to-noise ratio; a timing deviation estimation algorithm based on CAZAC sequences is given in literature [22], which works under 2 sampling points per symbol, with low implementation complexity, but its estimation accuracy is limited; literature [22] gives an estimation algorithm based on the CAZAC sequence, which operates at 2 sampling points per symbol, with low estimation accuracy. low, but its estimation accuracy is limited; the algorithm given in [23] also works at 2 sampling points per symbol and does not require auxiliary sequences, but the algorithm has a high implementation complexity; literature [24] gives a timing deviation estimation algorithm based on energy comparisons, this algorithm operates at a high number of sampling points, and the synchronization accuracy is dependent on the relative sampling rate, and is insensitive to the carrier frequency deviation, but its complexity is high. The common technical characteristics of timing error estimation algorithms are obtained after careful study and comparison of the above algorithms:

1. The technical way to effectively improve the timing deviation estimation accuracy is to increase the over-zero point information of the signal being estimated. Under the premise of limiting the length of the sequence, the richer the over-zero

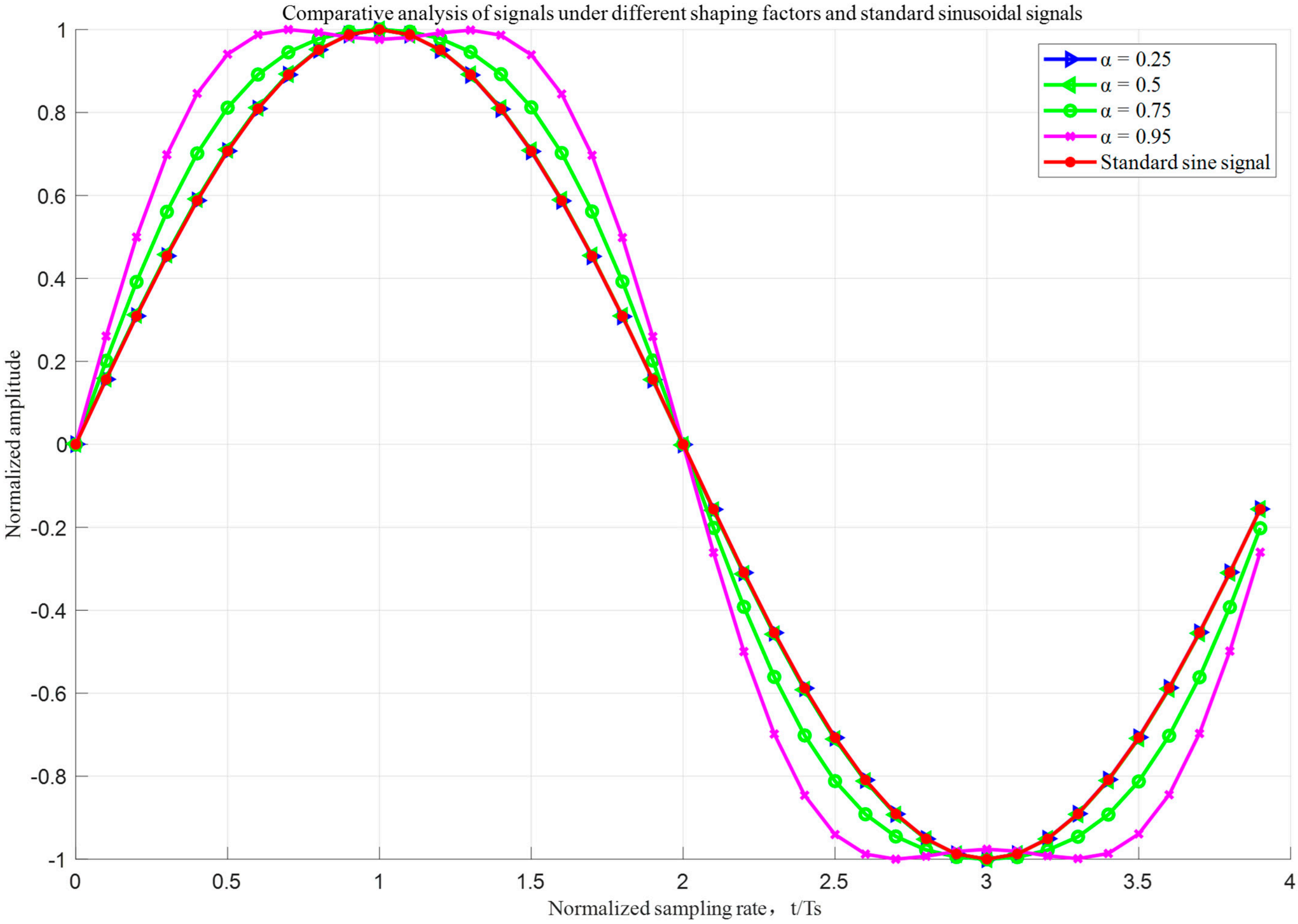

Fig. 18. Comparison of auxiliary sequences with standard sinusoidal signals at different shaping factors.

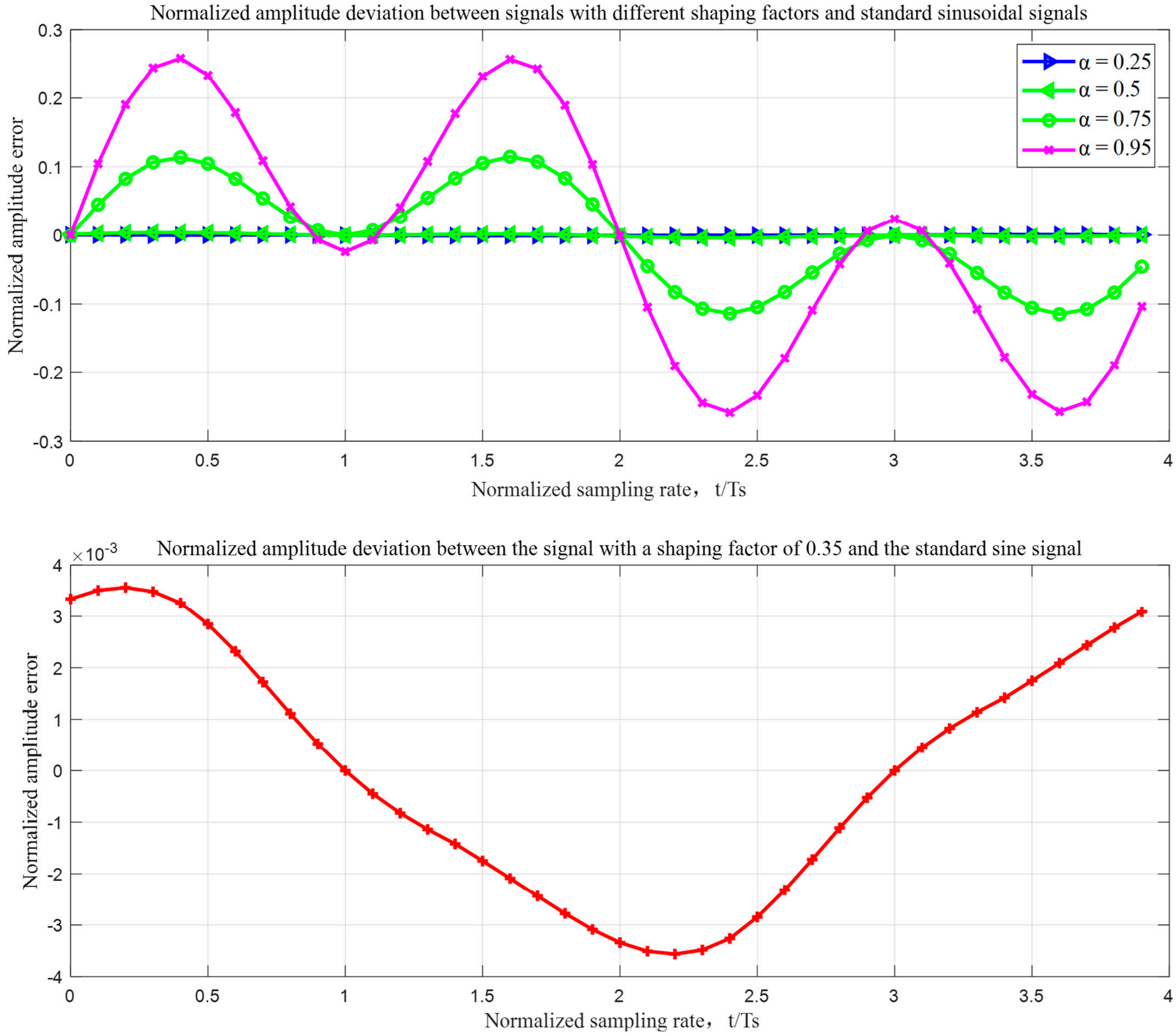

Fig. 19. Errors of auxiliary sequences with standard sinusoidal signals at different forming factors.

information is, the more samples of timing deviation data can be provided, which will help to improve the accuracy of timing deviation estimation;

2. The technical way to improve the accuracy of the algorithm is to ensure that the detection performance curve of the timing deviation estimation algorithm maintains a good linearity and possesses a large slope at the over-zero point.

In addition, since the satellite-carried hopping beam synchronizer needs to simultaneously process the follow-the-road synchronization signaling signals from multiple gateway stations, the timing deviation estimation algorithm needs to be low-complexity and be able to support a lightweight engineering implementation.

In view of the above specific characteristics and engineering realizability requirements, this paper adopts a lightweight high-precision timing deviation estimation method, which uses alternation as an auxiliary sequence to achieve high-precision timing deviation estimation while reducing complexity. The sequence is modulated by BPSK, and presents sinusoidal signal characteristics after root-raised cosine pulse shaping at the sender end and matched filtering at the receiver end, and the comparison of its waveform with the standard sinusoidal signal and the calculation of the error under different shaping factors are given in Figs. 18 and 19. It can be seen that the value of the shaping factor directly affects its characteristics, and the smaller α is, the more similar the corresponding waveform is to a sinusoidal signal. However, for the on-board receiver processing system, the lowering of the forming factor α will lead to the lowering of the filter performance and the increase of the complexity while bringing the increase of the frequency band utilization. Therefore, considering the transmission performance, the commonly used shaping factor parameter $\alpha = 0.35$ can be selected, in which the normalized error between the shaped sequence waveform and the sinusoidal signal is less than $5e^{-3}$.

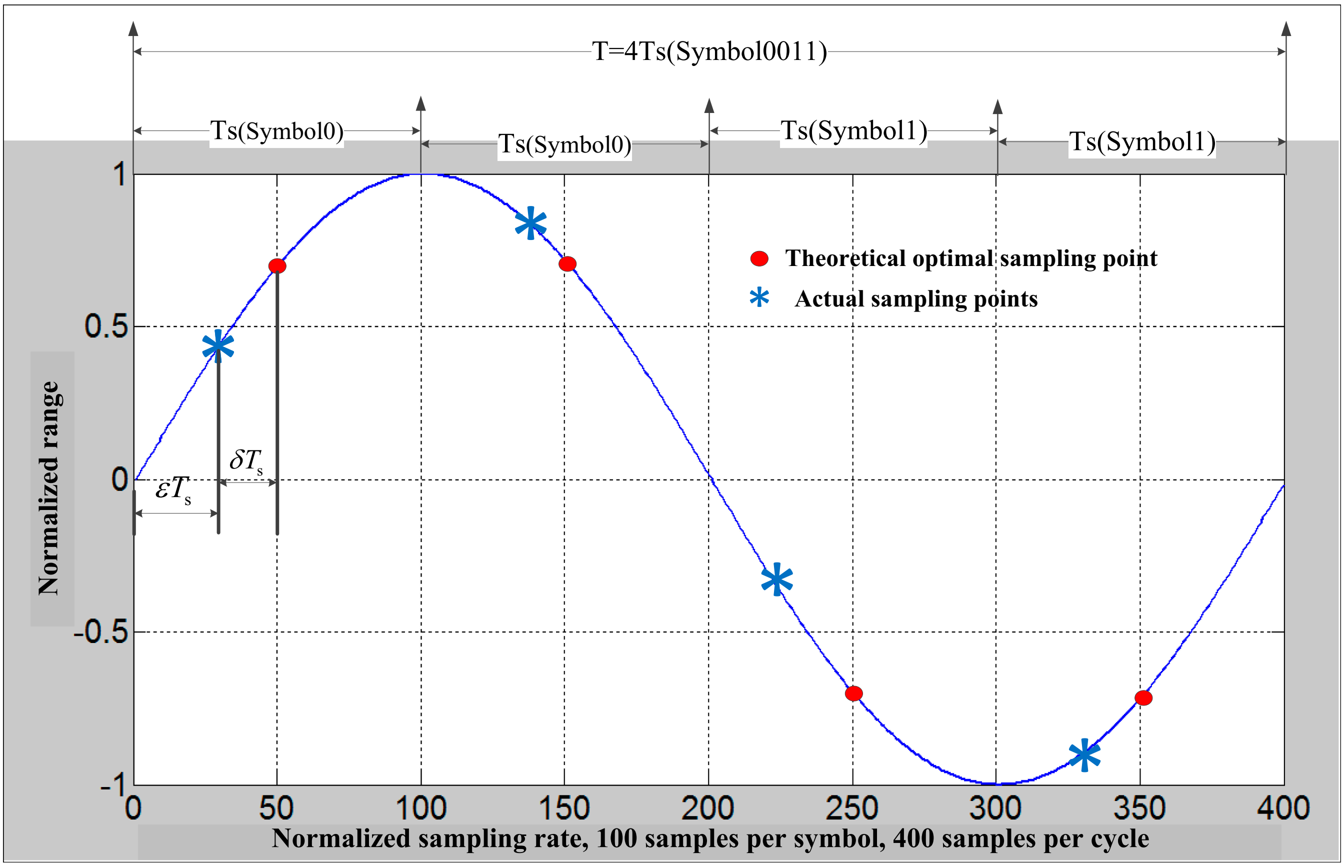

Fig. 20. Schematic representation of time bias based on auxiliary series.

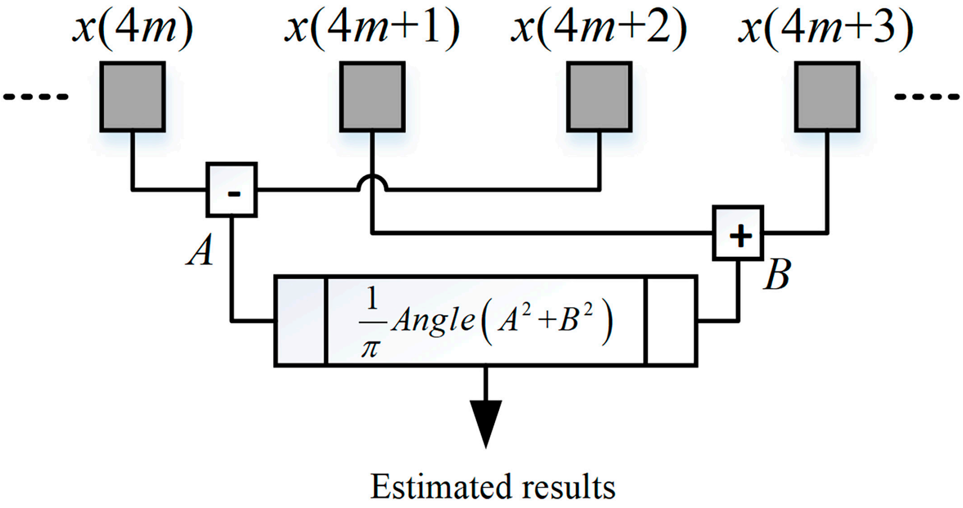

Fig. 21. Block diagram of time bias estimation based on auxiliary series.

Based on the sinusoidal characteristics presented by the shaping of the 0011 sequence, we transform the time bias estimation into the estimation of the phase bias, which makes the complexity of the algorithm implementation greatly optimized. As shown in Fig. 20, the period of the signal 0011 repetition is T, the single-symbol period is T_s, the sampling moment at the receiving end is εT_s, and the sampling time deviation is δT_s. Define $\delta = \varepsilon - 0.5$

A clock deviation 4-sample point estimation algorithm is given for a signal design as above.

The continuous signal can be expressed as:

$$x(t) = \sin(2\pi t / \mathrm{T}) e^{j(\Delta\omega t + \varphi_0)} \tag{3}$$

Sampling them can be obtained:

$$x(n)=\sin((n+\varepsilon)\pi/2)e^{j(\Delta\omega Tn/4+\Delta\omega T\varepsilon/4+\varphi_0)} \tag{4}$$

$$t(n)=(n+\varepsilon)T/4, n=4m+l(l=0,1,2,3) \tag{5}$$

$$\begin{gathered}x(n)=\sin((l+\varepsilon)\pi/2)^{*}\\ e^{j\Delta\omega T(4m+l)/4}e^{j(\Delta\omega T\varepsilon/4+\varphi_0)}\end{gathered} \tag{6}$$

Let $\Delta\omega' = \Delta\omega T/4$, then:

$$\begin{gathered}x(n)=\sin\left((l+\varepsilon)^{*}\pi/2\right)^{*}\\ e^{jl\Delta\omega'}{*}e^{j\left(4m\Delta\omega'+\varepsilon\Delta\omega'+\varphi_0\right)}\end{gathered} \tag{7}$$

So, each of the 4 consecutive sampling points can be represented as:

$$\begin{gathered}x(4m)=\sin(\varepsilon\pi/2)^{*}\\ e^{j\left(4m\Delta\omega'+\varepsilon\Delta\omega'+\varphi_0\right)}\end{gathered} \tag{8}$$

$$\begin{gathered}x(4m+1)=\cos(\varepsilon\pi/2)^{*}\\ e^{j\Delta\omega'}{*}e^{j\left(4m\Delta\omega'+\varepsilon\Delta\omega'+\varphi_0\right)}\end{gathered} \tag{9}$$

$$\begin{gathered}x(4m+2)=-\sin(\varepsilon\pi/2)^{*}\\ e^{j2\Delta\omega'}{*}e^{j\left(4m\Delta\omega'+\varepsilon\Delta\omega'+\varphi_0\right)}\end{gathered} \tag{10}$$

$$\begin{gathered}x(4m+3)=-\cos(\varepsilon\pi/2)^{*}\\ e^{j3\Delta\omega'}{*}e^{j\left(4m\Delta\omega'+\varepsilon\Delta\omega'+\varphi_0\right)}\end{gathered} \tag{11}$$

A 4-point DFT transform is applied to it:

$$\begin{aligned}X(k)=DFT[x(n)] &= \sum_{n=0}^{3} x(n)W_N^{nk}\\ &= \sum_{n=0}^{3} x(n)e^{-j\frac{2\pi nk}{4}}, k=0,1,2,3\end{aligned} \tag{12}$$

Then:

$$\begin{aligned}X(1)= {} & x(4m)+x(4m+1)e^{-j\pi/2}\\ & +x(4m+2)e^{-j\pi}+x(4m+3)e^{-j3\pi/2}\\ = {} & \left(\sin(\varepsilon\pi/2)-j\cos(\varepsilon\pi/2)e^{j\Delta\omega'}\right)\\ & *\left(1+e^{j2\Delta\omega'}\right)*e^{j\left(4m\Delta\omega'+\varepsilon\Delta\omega'+\varphi_0\right)}\end{aligned} \tag{13}$$

$$\begin{aligned}X(3)= {} & x(4m)+x(4m+1)*e^{-j3\pi/2}\\ & +x^{*}(4m+2)*e^{-j3\pi}+x^{*}(4m+3)e^{-j9\pi/2}\\ = {} & \left(\sin(\varepsilon\pi/2)+j\cos(\varepsilon\pi/2)*e^{-j\Delta\omega'}\right)\\ & {}^{*}\left(1+e^{-j2\Delta\omega'}\right)*e^{j\left(4m\Delta\omega'+\varepsilon\Delta\omega'+\varphi0\right)}\end{aligned} \tag{14}$$

Also there:

$$\begin{aligned}X(1)\times jX(3)^{*}= {} & \left|\left(1+e^{j2\Delta\omega'}\right)\right|^{2}\\ & *\left[-\cos(\varepsilon\pi)-j\sin(\varepsilon\pi)\cos\left(\Delta\omega'\right)\right]\end{aligned} \tag{15}$$

Substitute this into the following equation:

$$\begin{aligned}\tau &= \text{angle}\left(X(1)\times jX(3)^{*}\right)/\pi\\ &= \text{angle}\left[-\cos(\varepsilon\pi)-j\sin(\varepsilon\pi)\cos\left(\Delta\omega'\right)\right]/\pi\end{aligned} \tag{16}$$

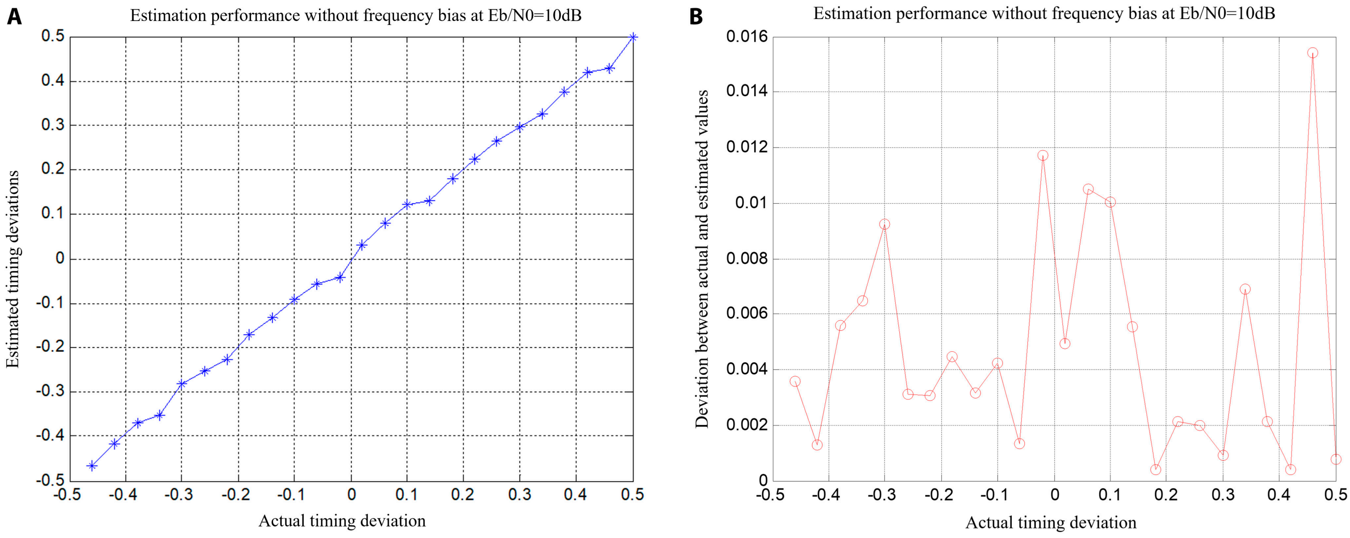

Fig. 22. Eb/N0=10dB, estimation performance without frequency and phase differences.

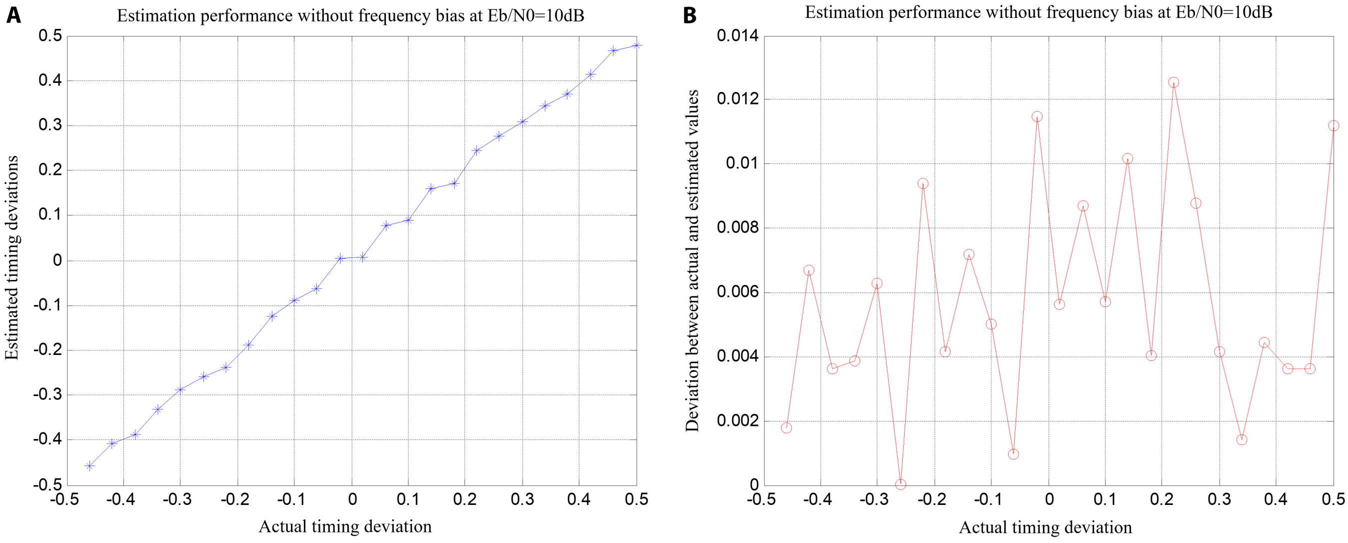

Fig. 23. Eb/N0=10dB, estimation performance with no frequency difference and random phase difference.

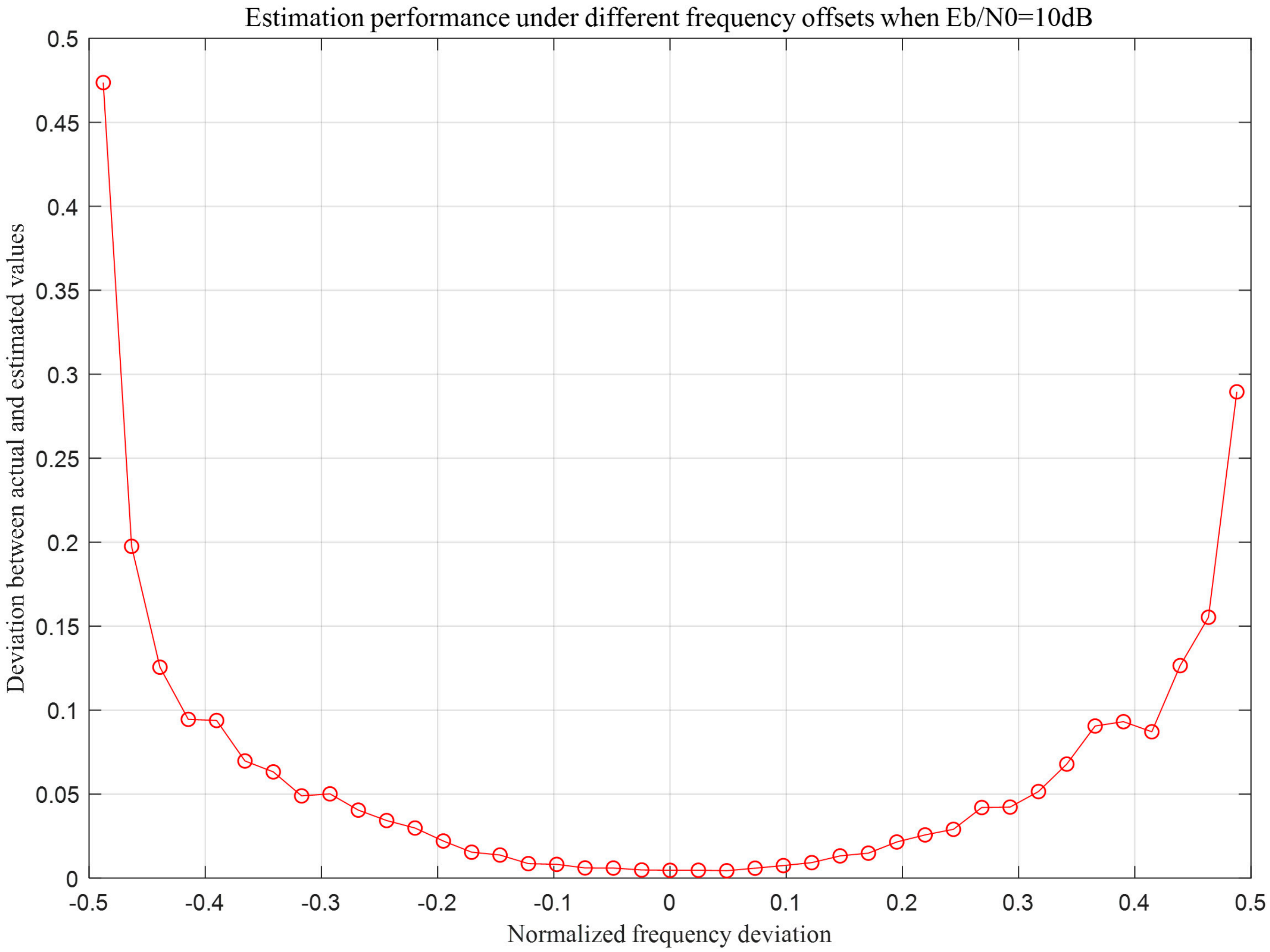

Fig. 24. Estimation performance of the algorithm under different frequency deviations (Eb/N0=10dB).

When $\cos(\Delta\omega') \approx 1$ is relatively small, $\cos(\Delta\omega') \approx 1$ the above equation can be changed to:

$$\begin{aligned}\tau &= \text{angle}\left[-\cos(\varepsilon\pi)-j\sin(\varepsilon\pi)\right]/\pi \\ &= \text{angle}\left(-e^{j\varepsilon\pi}\right)/\pi \\ &= \varepsilon\end{aligned} \tag{17}$$

From Eq. 17, τ is an unbiased estimator of the timing deviation ε. As a our-sample point estimation algorithm for clock deviation in this paper is as follows:

$$\tau = \frac{1}{\pi}\text{angle}\left\{\begin{array}{l}\left[x(4m)-x(4m+2)-jx(4m+1)-jx(4m+3)\right] \\ *\left[x(4m)-x(4m+2)+jx(4m+1)+jx(4m+3)\right]\end{array}\right\} \tag{18}$$

Let $A = x(4m) - x(4m+2)$, $B = x(4m+1) + x(4m+3)$, then:

$$\tau = \frac{1}{\pi}\text{angle}\left[(A-jB)(A+jB)\right] = \frac{1}{\pi}\text{angle}\left(A^2+B^2\right) \tag{19}$$

The block diagram of the algorithm implementation is shown in Fig. 21.

Results and Discussion

For the mathematical expression of the proposed algorithm, simulation evaluation of the algorithm is carried out in this paper, the modulation method is selected as BPSK, the shaping coefficient is 0.35, the length of the sequence is 64, and the normalized simulation sampling parameters are set: $T_S = 100$, $T = 400$, and the values of ε are taken in $[0, 1]$, and the values of δ are taken in $[-0.5, 0.5]$. The simulation results are as follows:

The simulation results in Fig. 22 as well as Fig. 23 show that the estimation accuracy of timing deviation can reach within 2% without frequency bias under the condition of Eb/N0=10dB. As shown in the simulation results of Fig. 24, the carrier phase deviation has no effect on the algorithm. The algorithm is more adaptable to the carrier frequency bias, and the estimation performance of the algorithm is consistent when the normalized frequency bias is in the range of ±10%. The performance comparison results of the algorithm with the digital square filtering method are given in Fig. 25, and the estimation variance of the algorithm is significantly smaller under simulation conditions. According to the above analysis, the time synchronization sequence in the beam hopping synchronization control signal given in Fig. 13 adopts the auxiliary sequence of 0011...0011 alternately, and according to the performance of the timing deviation estimation algorithm analyzed and simulated in this section, it not only improves the time synchronization accuracy of the beam-hopping system, but also reduces the complexity of the processing, compared to that of the traditional method of adopting the digital squared filter. The algorithm given in this paper has the significant advantages of high estimation accuracy and lightweight engineering implementation for the application background.

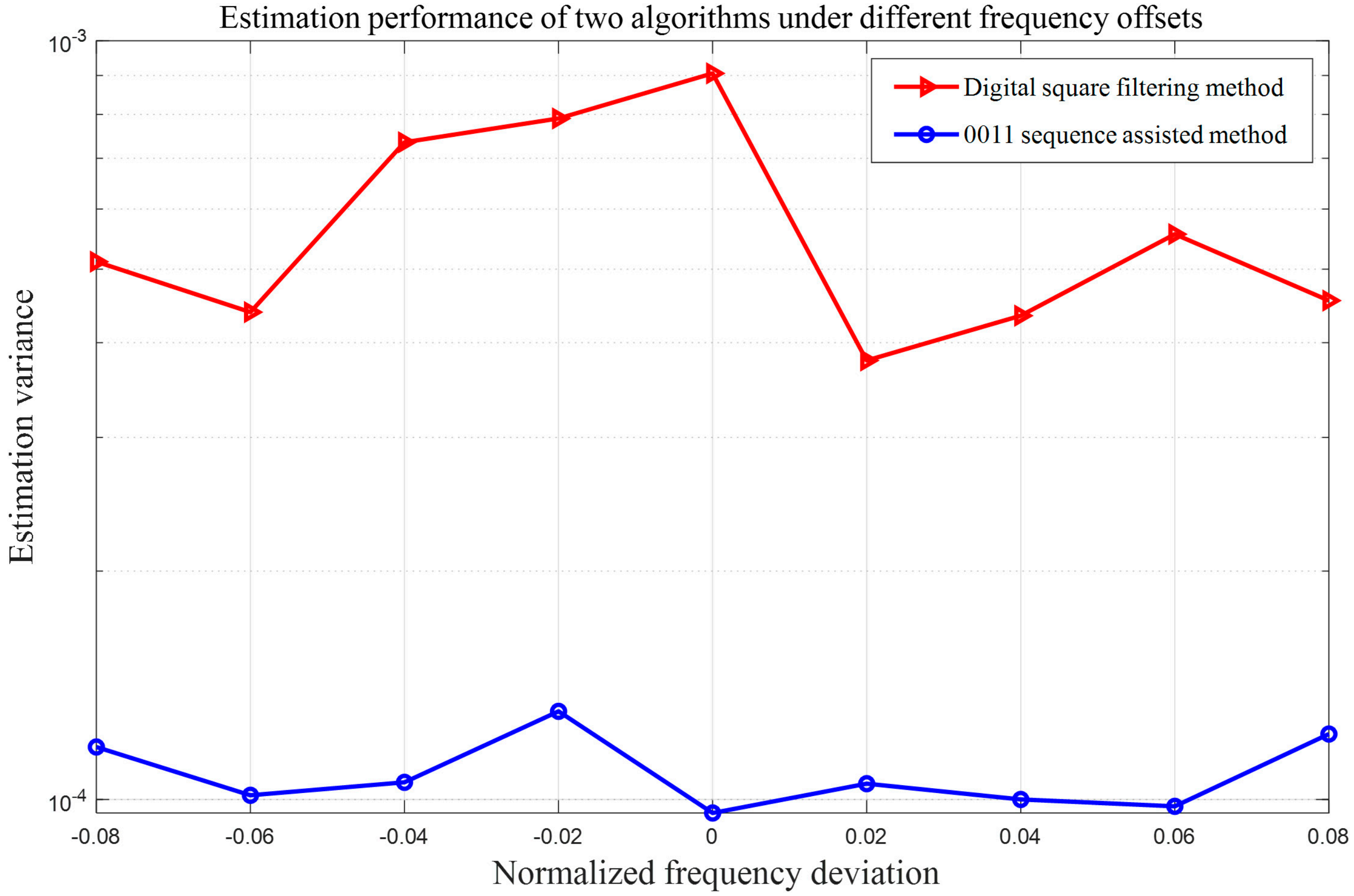

Fig. 25. Performance comparison analysis and simulation of 2 algorithms (Eb/N0=10dB).

Conclusion

This paper introduces the principle of high-throughput satellite hopping beam synchronization. Based on this principle, the synchronization schemes for hopping beam systems are compared and analyzed, and a fast hopping beam synchronization method between the signaling gateway station and the satellite is proposed. Additionally, to address the requirements of hopping beam synchronization for high-probability detection of burst signals and high-precision time deviation estimation, a fast capture algorithm for the burst signaling signal based on differential demodulation correlation is investigated. Furthermore, a lightweight and high-precision time deviation estimation algorithm is proposed through optimized design, which is carefully studied and simulated to demonstrate its performance.

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Data Availability

The data of this study are available from the corresponding author upon request.

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