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# Sensing-Aided Hierarchical Beam Search in Low Earth Orbit Satellite Communications

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**Abstract:** Low earth orbit (LEO) satellite communication which can provide global wireless service plays a critical role in the future wireless communication networks. However, due to the high speed of satellite motion, numerous narrow beams, and complex satellite-terrestrial channels, the initial access between the LEO satellites and user terminals (UEs) becomes more complicated. To establish a stable link, a beam search is required between the satellite and the UE. However, traditional beam search methods (e.g., exhaustive search) have high time complexity which is not suitable in high-speed scenarios. Therefore, in this paper, a sensing-aided hierarchical beam search method is proposed, which is performed in two stages. In the first stage, wide beam scanning is performed to find the optimal angular range. In the second stage, after determining the directions of narrow beams via sensing the direction of arrival (DOA) of satellite signals, the narrow beams generated at estimated directions are used to sweep the satellite beams. This method can help fast beam alignment and obtain high beam search accuracy, which is verified by simulation results. Moreover, we analyze the gain of beam alignment from the two-stage beam search method.

**Keywords:** low earth orbit satellite communication; beam search; initial access; sensing-aided communication

## 1 Introduction

In recent years, low earth orbit (LEO) satellite communication, which can provide extended service coverage capabilities and is barely influenced by natural disasters, has received wide attention from academia and industry. Starting from the Release 15 standard [1], 3rd generation partnership project (3GPP) has incorporated non-terrestrial network (NTN) technology as an important supplement to terrestrial cellular communication technologies. In the future networks, seamless global coverage can be achieved by integrating satellite communication networks with terrestrial networks, overcoming geographical and topographical limitations. This will lead to the formation of an integrated space-air-ground network.

In satellite-terrestrial networks, LEO satellites are equipped with phased array antennas to provide a large number of spot beams [2] for wide-area and high-capacity coverage. Considering the long satellite-terrestrial transmission distance, complex channel environments, and the high speed of satellite motion in satellite communication systems, the user terminal (UE) must align with high-gain directional beams of satellites to establish reliable communication links [1, 3, 4]. In satellite-terrestrial networks, the UE can achieve beam alignment based on ephemeris information [3]. The satellite transmits the navi-

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gation messages including ephemeris information. Subsequently, the UE can obtain the ephemeris information by decoding, and derive the beam direction towards the satellite based on ephemeris. If the information is not successfully downloaded due to complex environments (e.g., indoor UEs, UEs on the roads, etc.), the downloading process must be repeated. After obtaining the beam direction, the UE waits until the satellite enters the UE's visibility range, and the UE can capture and track the satellite, completing the beam alignment process.

In lots of scenarios, due to complex environments and limited UE resources, the ephemeris is unavailable or outdated because of prolonged periods without updating. Generally, it requires 12.5 min for the first time to receive the whole navigation message [5]. Moreover, since the signal acquisition and demodulation capabilities of the UE are limited, even more time may be required at the UE. Consequently, adopting the "ephemeris download-decoding-data processing" strategy in no-ephemeris conditions is inefficient for achieving rapid initial beam alignment. In such cases, beam alignment must rely on beam scanning methods. In terrestrial networks, the conventional approaches for initial beam alignment consist of exhaustive beam search [6], codebook-based beam search [7, 8], and hierarchical beam search [9]. Additionally, researchers have explored adaptive search methods [10–17] and beam search methods based on direction of arrival (DOA) estimation [18, 19] to meet the requirements of initial beam alignment since traditional beam search methods cannot adapt to all communication scenarios. In [10, 11], an Agile-Link beam searching algorithm was proposed to rapidly find the correct alignment of the beams. Additionally, a beam alignment problem was formulated as a sparse encoding and phaseless decoding problem in [12], which was solved by a sparse bipartite graph code method. In [13] the beam search was interpreted as a multiple hypothesis testing to reduce the cost of search. To study more applicable adaptive search methods, an adaptive beam search algorithm with iterative deactivation and beam shifting (IDBS) was proposed in [14] by discarding the weaker beams and scanning the remaining beams based on a probabilistic criterion. In [15], the limitation of the flexibility of IDBS was pointed, and a new adaptive algorithm with low time complexities was proposed by choosing the candidate beams based on upper-confidence-bound (UCB). Furthermore, an adaptive hierarchical search algorithm [16] was proposed to refine the beam search intervals and select the beams using generalised likelihood ratio test (GLRT). In [17], a sequential competition search algorithm was proposed by reducing the search time based on a sequential competition test. The comparison among these iterative beam search methods is shown in Tab. 1. Furthermore, the beam search can be based on DOA estimation, such as the DOA estimation algorithm based on low-dimensional spatial covariance matrix multiplication [18] and 2-dimensional DOA estimation strategy [19], which reduces more search time by estimating the DOA of the signal from the transmitter.

However, in LEO satellite communication systems, challenges arise from high satellite mobility, large elevation angle variations, numerous narrow beams, and more complex satellite-terrestrial channels. These factors make the scanning search process significantly more challenging than that in terrestrial communication systems, as it requires larger search ranges, dealing with more random and rapidly changing beam direction information, and handling complex channel conditions. Therefore, it is essential to develop a rapid and high-precision beam alignment technique. This paper proposes a sensing-aided hierarchical beam search method to build a stable and efficient LEO satellite communication system and our main contributions are summarized as follows.

**Tab. 1 Research works considering adaptive beam search methods**

| Proposed solution | Computational complexity | Adaptability in dynamic scenarios | Performance tradeoff |
|---|---|---|---|
| Discarding weaker beams from beam set $\mathcal{L}(t)$ based on a probabilistic criterion [14] | $O(\sum_{t=1}^{n}\|\mathcal{L}(t)\|)$ | Automatically adjusting the overhead for measurements in $\mathcal{L}(t)$ under different SNRs | • Latency: reducing search time by discarding beams up to probability threshold<br>• Accuracy: best beam being discarded due to probability threshold selection |
| Discarding weaker beams from set $\mathcal{L}$ with $L$ beams and choosing the candidate beams from $\mathcal{L}(t)$ based on UCB [15] | $O(n(L-1))$ | Adjusting the candidate beam set and the overhead for measurements in $\mathcal{L}(t)$ under different SNRs | • Latency: reducing search time by discarding beams up to probability threshold and choose candidate beams from $\mathcal{L}(t)$<br>• Accuracy: best beam being discarded due to probability threshold selection |
| Refining the beam search intervals based on GLRT for a $K$-layer hierarchical search [16] | $O(nK)$ | Adjusting beam search time for each layer in different channel conditions | • Latency: reducing the search time by increasing test threshold<br>• Accuracy: higher test threshold resulting in the inaccuracy |
| Identifying the best beam from $M$ beams after $n$ observations by a sequential competition test [17] | $O(nM)$ | Adjusting the search time of $M$ beams for different SNRs | • Latency: reducing the search time by adjusting the number of observations and decreasing the test threshold<br>• Accuracy: lower test threshold resulting in the inaccuracy |

1) A hierarchical beam search process is developed in the LEO satellite communication system, which is performed in two stages. In the first stage, the wide beams are generated to scan the whole space to obtain the best wide beams. In the second stage, narrow beams generated based on the sensing data from the best wide beams are used to sweep the beams of the satellite to improve search accuracy.

2) The sensing-aided hierarchical beam search method is proposed. After the first-stage search, the UE can obtain the DOA information from the sensing data, i.e., the received satellite signal at the best wide beams. Then, the directions of narrow beams can be set based on the DOA information, which can reduce the search time.

3) The simulation results verify that compared with the exhaustive search, the proposed method can reduce 50% beam search time without much loss of accuracy.

The rest of this paper is organized as follows: Section 2 analyzes the LEO satellite communication system model and signal model. Section 3 provides a detailed explanation of the proposed beam search algorithm. Section 4 examines the efficiency of the proposed algorithm. Finally, Section 5 concludes the paper.

## 2 System and Signal Models

In this section, the LEO satellite communication system is presented, and the signal model is also provided.

### 2.1 System Model

Without loss of generality, we consider a system operating at the Ka-band and consisting of an LEO satellite and a UE, as depicted in Fig. 1. The satellite and UE are equipped with a uniform rectangular array (URA) of $N_{\mathrm{s}} \times N_{\mathrm{s}}$ and a URA of $N_{\mathrm{u}} \times N_{\mathrm{u}}$, respectively. The satellite can generate up to $K$ beams to provide high data rates. Meanwhile, $M$ wide beams are generated at the UE to scan the whole space. After the refinement of beam search intervals, $N$ narrow beams are generated at the UE and only $N_{\mathrm{candi}}$ beams are used in each search interval for further search.

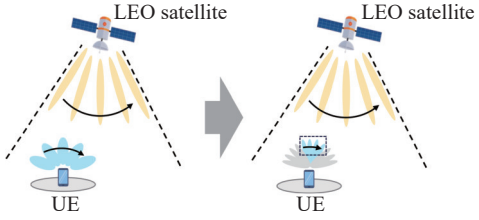


Fig. 1 Illustration of the system model

This paper considers that when ephemeris is unavailable or outdated, there is no prior information for the UE at the beginning. Thus, during the initial access the beam search is adopted to find the optimal access link. The considered 5G non terrestrial network (NTN) system supports orthogonal frequency division multiplexing (OFDM) technology, and the initial access is performed by transmitting synchronization signal block (SSB) carried by different beams in a 5 ms window. A set of SSBs representing different beam directions is referred to as an SSB burst lasting for 20 ms. At a given moment, only one transmitted and received beam pair may be created between the LEO satellite and UE. Therefore, the UE requires a large number of explorations, i.e., switching between the satellite beams and the UE beams during the initial access until the best beam pair is found to establish a stable link between the satellite and UE. In our model, a sensing-aided beam search at the UE is proposed. The signal transmitted from the satellite can be regarded as sensing data, and the DOA information is obtained through the analysis of the sensing data to help choose the candidate beams and reduce beam search time. The detailed process is introduced in Section 3.

### 2.2 Signal Model

#### 2.2.1 LEO Satellite Channel Model

We adopt the frequency selective fading tapped delay line (TDL) channel in the 3GPP TR 38.811 protocol [1] for simulating non terrestrial network (NTN) scenarios, which takes both the Doppler shift due to the UE motion and satellite motion into account. The channel response in time-delay domain can be represented as [20]

$$h(t,\tau)=\sum_{n=1}^{P} h_n \mathrm{e}^{\mathrm{j}2\pi\epsilon_{\mathrm{D}}\Delta f t}\delta(\tau-\tau_n) \qquad (1)$$

where $\delta$ is Dirac Delta, $P$ is the number of paths, $h_n$ and $\tau_n$ are the complex path gain and propagation delay of $i$-th path, respectively. Furthermore, $\varepsilon_{\mathrm{D}}=f_{\mathrm{D}}/\Delta f$ is the normalized Doppler frequency with respect to OFDM sub-carrier-spacing (SCS) denoted as $\Delta f$. $f_{\mathrm{D}}$ is the Doppler shift due to UE and satellite motion.

#### 2.2.2 Received Signal Model

We consider an end-to-end communication scenario, where the satellite transmits the signal $s(t)$ to the UE with power $P_t$. The beamforming vectors at the satellite and the UE are $\boldsymbol{w}_{\mathrm{s}}\in\mathbb{C}^{N_{\mathrm{s}}\cdot N_{\mathrm{s}}\times 1}$ and $\boldsymbol{w}_{\mathrm{u}}\in\mathbb{C}^{N_{\mathrm{u}}\cdot N_{\mathrm{u}}\times 1}$, respectively. Then, the received signal at the UE is given by

$$y(t)=\boldsymbol{w}_{\mathrm{u}}^{H}\boldsymbol{H}\boldsymbol{w}_{\mathrm{s}}\sqrt{P_t}s(t)+\boldsymbol{w}_{\mathrm{u}}^{H}\boldsymbol{n}(t) \qquad (2)$$

where $\boldsymbol{H}\in\mathbb{C}^{N_{\mathrm{u}}\cdot N_{\mathrm{u}}\times N_{\mathrm{s}}\cdot N_{\mathrm{s}}}$ is the channel matrix between the satellite and UE, which is composed of $h(t)$. $h(t)$ is the discrete-time channel impulsive response of (1). $\boldsymbol{n}(t)$ is the white Guassian noise at the UE receiver.

## 3 Sensing-Aided Hierarchical Beam Search Method

In this section, we investigate a sensing-aided beam search method which can adjust the UE beam width to select the optimal transmit-receive beam pair, supporting the beam search under the unknown non terrestrial network (NTN) channel environment.

### 3.1 The Process of Beam Search

During the initial acquisition, the beam search is performed by the UE to select the best beam pair. As shown in Fig. 2, the beam search procedures at the physical and medium access control layer include signal detection, time-frequency offset synchronization, UE beam sweeping, beam synchronization signal-reference signal received power (SS-RSRP) measurement, and beam determination.

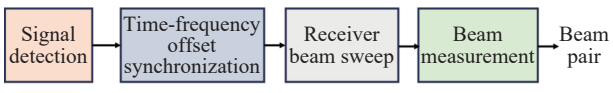


Fig. 2 Beam search model procedures

To be specific, the UE transmits beams sweeping all directions in a burst set at regularly defined intervals. Firstly, when the signals are received at the UE side, it is necessary to detect

whether the signals are actual signals. Accordingly, a signal detection threshold $S_{\text{th}}$ is set to ensure the effectiveness of the received signal. Then, by using the primary synchronization signal (PSS), the secondary synchronization signal (SSS), and specific synchronization algorithms [21, 22], the UE can estimate and compensate the time and frequency offsets [23]①. Firstly, the coarse time synchronization and PSS detection are realized based on the differential cross-correlation synchronization algorithm between the received signal and the locally generated PSS time-domain signal. Secondly, the frequency synchronization procedure consists of the fractional frequency offset estimation based on the auto-correlation algorithm using cyclic prefix and integer frequency offset estimation based on the cross-correlation algorithm. Lastly, the SSS detection can be realized based on the frequency-domain cross-correlation algorithm. Since the PSS and SSS can be detected, the cell ID can be computed.

After synchronization and demodulation, the SSB index can be extracted. Then, according to the generated reference signal, the SS-RSRP of the transmit-receive beam pair can be obtained [24]. These steps repeat for each received beam and transmitted beam, after which the best beam pair is defined. The SS-RSRP beam measurements are stored in a matrix of SSBs.

### 3.2 The Process of DOA Estimation

Since the DOA information can be used to obtain optimal beam direction quickly, we will adopt the estimation of signal parameters via rotational invariance techniques (ESPRIT), which is a subspace-based DOA estimation algorithm. It does not involve an exhaustive search through all possible steering vectors to estimate DOA and significantly reduces the computational and storage requirements. The goal of the ESPRIT technique is to exploit the rotational invariance in signal subspace which is created by two arrays with a translational invariance structure [25].

The steps of the ESPRIT algorithm are sumarized as follows:

**Step 1** Obtain an estimate matrix of covariance matrix $\boldsymbol{R}$ from the measurements $y(t)$ at receiver, denoted by $\hat{\boldsymbol{R}}$, which includes the space information of satellite signal. The estimate matrix $\hat{\boldsymbol{R}}$ can be derived as

$$\hat{\boldsymbol{R}} = E[y(t)y^{\mathrm{H}}(t)] \tag{3}$$

**Step 2** Perform eigen decomposition on $\hat{\boldsymbol{R}}$.

$$\hat{\boldsymbol{R}}\overline{E} = \Lambda\overline{E} \tag{4}$$

where $\Lambda = diag\{\lambda_1, \cdots, \lambda_{N_u^2}\}, \lambda_1 \geqslant \cdots \geqslant \lambda_{N_u^2}$ represents the eigenvalues and $\overline{E} = [e_1, \cdots, e_{N_u^2}]$ represents the eigenvectors.

**Step 3** Select the largest $C$ (i.e., the number of signal sources) eigenvalues to obtain the estimated signal subspace $E_{\text{s}}$ and decompose it into two sub-array matrices, denoted by $E_X$ and $E_Y$, where

$$E_{\text{s}} = \begin{pmatrix} E_X \\ E_Y \end{pmatrix} \tag{5}$$

**Step 4** Construct a new function and compute the eigen decomposition to obtain the eigenvalues matrix $\boldsymbol{E}$.

$$E_{XY}^{\mathrm{H}} E_{XY} \overset{\text{def}}{=} \begin{pmatrix} E_X^{\mathrm{H}} \\ E_Y^{\mathrm{H}} \end{pmatrix} (E_X E_Y) = \boldsymbol{E}\Lambda\boldsymbol{E}^{\mathrm{H}} \tag{6}$$

and partition $2C \times 2C$ matrix $\boldsymbol{E}$ into $C \times C$ sub-matrices,

$$\boldsymbol{E} = \begin{bmatrix} \boldsymbol{E}_{11} & \boldsymbol{E}_{12} \\ \boldsymbol{E}_{21} & \boldsymbol{E}_{22} \end{bmatrix} \tag{7}$$

**Step 5** Calculate the maximum eigenvalue $\lambda$ of rotational invariant $\Psi = -\boldsymbol{E}_{12}\boldsymbol{E}_{22}^{-1}$, which includes the information of DOA.

**Step 6** Estimate the DOA as

$$\widehat{\theta} = \arcsin\sqrt{x^2 + y^2} \tag{8}$$

$$\hat{\phi} = \arctan\sqrt{\left(\frac{2\arctan \mathrm{Im}(\lambda)}{2\arctan(\mathrm{Re}(\lambda))}\right)} \tag{9}$$

where $m = 2\dfrac{\lambda_k}{2\pi d}$, $x = m\arctan(\mathrm{Re}(\lambda))$, and $y = m\arctan(\mathrm{Im}(\lambda))$. $d$ is the distance of antenna

①In our model, we focus on the beam search process and the classic downlink synchronization procedure is performed between a LEO satellite and a UE. When a UE accesses multiple satellites in cooperative scenarios, the time synchronization procedure in [23] can be adopted.

array element, $\lambda_k$ is the signal wavelength, $\hat{\theta}$ is the elevation, and $\hat{\phi}$ is the azimuth.

### 3.3 The Sensing-Aided Hierarchical Beam Search Algorithm

This subsection elaborates on the proposed sensing-aided beam search method. With the adjustable beam width, the proposed fast beam search scheme for beam alignment contains the first-stage search, candidate beam decision, and second-stage search three processes. The detailed search process is shown in Fig. 3.

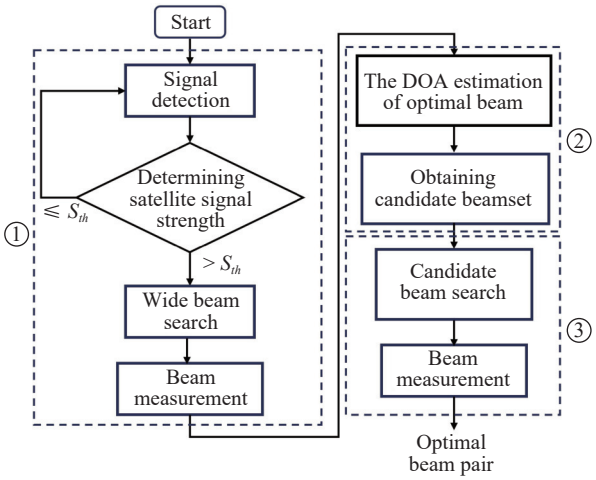


Fig. 3 Process of proposed beam search scheme

According to the search procedure as shown in Fig. 3, in the first-stage search, the satellite beams transmit signals firstly. Then the UE uses $M$ wide beams which can cover all directions to search for satellite signals based on the energy detection method. If the detected signal energy is larger than the threshold $S_{\text{th}}$, the receiver signals are synchronized in time and frequency and the wide beams at the receiver perform searching. If the UE fails to successfully detect the satellite signal, the process of signal detection will be repeated until the detected energy is larger than the energy threshold. Next, the search repeats for each received wide beam and transmitted beam, and beam measurement is performed to obtain the SS-RSRP set. Based on the SS-RSRP set, we can select the best wide beams corresponding to the max $L$ SS-RSRP values, (i.e. the search intervals for DOA estimation).

In the process of candidate beam decision, the DOA estimation will be performed in the direction of each best wide beam. To improve the accuracy of beam search, narrow beams are generated in the second-stage search, and the directions of narrow beams can be obtained based on the results of DOA estimation. Due to the complex satellite-terrestrial channel, the effectiveness of DOA estimation is limited. Thus, we select other $N-1$ narrow beams for each narrow beam selected based on DOA estimation according to the spatial correlation of beams, which can be calculated as

$$Q = \text{abs}(\boldsymbol{w}_{1,\text{u}}^{\text{H}} \boldsymbol{w}_{2,u}) \tag{10}$$

where $\boldsymbol{w}_{1,\text{u}}$ and $\boldsymbol{w}_{2,\text{u}}$ are beamforming vector for two beams at the UE, respectively.

In the second-stage search, the search repeats for each candidate narrow beam and each transmitted beam, after which the best beam pair is defined, i.e., the optimal transmit-receive beam pair of the satellite and UE.

Combining the above processes, we design the algorithm of the proposed beam search. The algorithm's implementation procedures are provided in Algorithm 1. This scheme aims to achieve low complexity and high precision by employing a hierarchical beam search approach. This method significantly reduces the number of scanning beams, thereby decreasing the time required for beam alignment. Utilizing narrow beams for scanning also achieves higher search accuracy. Selecting candidate narrow beams based on DOA estimation further enhances search precision, balancing search time and accuracy effectively.

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**Algorithm 1** The proposed sensing-aided hierarchical beam search

1: **Input:** The system parameters, the number of wide beams $M$, the energy threshold $S_{\text{th}}$, the number of candidate narrow beams $N_{\text{candi}}$, the number of search intervals for DOA estimation $L$.

2: **for** $i$=1 to $M$ **do**

3: **while** detected energy $> S_{\text{th}}$ **do**

4: Time-frequency synchronization;
5: Perform beam search;
6: Perform beam measurement to obtain the SS-RSRP;
7: **end while**
8: **end for**
9: Sort SS-RSRP values in descending order;
10: Select the received beams corresponding to the $L$ largest SS-RSRP values;
11: Perform DOA estimation at the selected search intervals;
12: Obtain the set of candidate narrow beams in the estimated DOA directions based on (10);
13: **for** $i$=1 to $N_{\text{candi}}$ **do**
14: Perform beam search;
15: Perform beam measurement to obtain the SS-RSRP;
16: **end for**
17: Select the received beams corresponding to the largest SS-RSRP values;
18: **Output:** The optimal transmit-receive beam pair.

## 4 Simulation Results

The simulations are carried by the directional link estimation between the satellite and UE at the initial access stage. Tab. 2 shows the beam search simulation model parameters for the LEO satellite communication system with one LEO satellite and one UE. The carrier frequency is set to 36 GHz, and specifies Case D SSB pattern with 120 kHz SCS. Beam measurement uses SSS with DMRS in the PBCH, as depicted in Fig. 4. Moreover, the channel model is constructed with non terrestrial network (NTN) TDL-D. Since the number of beams at the satellite is set to 64, the transmitted SSB burst occupies $64 \times 4$ OFDM symbols. Unless otherwise stated, the network parameters are set as follows. The number of wide beams $M$ is 8, and the number of search intervals for DOA estimation $L$ is 3. The number of narrow beams $N$ is 64. The number of candidate narrow beams $N_{candi}$ in each search interval is 8.

**Tab. 2 Simulation Parameters**

| Parameters | Values |
|---|---|
| Carrier frequency, $f_{\text{c}}$ | 36 GHz |
| Number of satellite URA elements, $N_{\text{s}} \times N_{\text{s}}$ | $4 \times 4$ |
| Number of UE URA elements, $N_{\text{u}} \times N_{\text{u}}$ | $4 \times 4$ |
| SCS, $f_{SCS}$ | 120 kHz |
| TDL type | non terrestrial network (NTN) TDL-D |
| Number of satellite beams, $K$ | 64 |
| Number of UE wide beams, $M$ | 8 |
| Number of UE narrow beams, $N$ | 64 |
| Number of signal sources, $C$ | 1 |
| Number of search intervals for DOA estimation, $L$ | 3 |
| Number of narrow beams in each search interval, $N_{\text{candi}}$ | 8 |

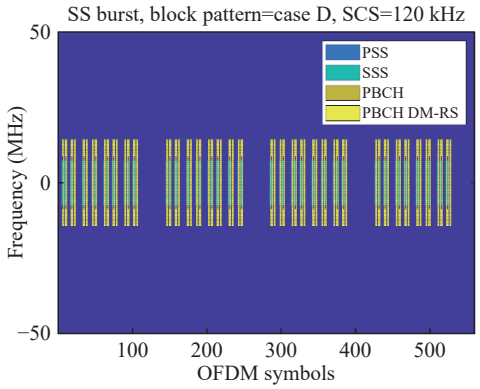


Fig. 4 Synchronization signal burst Case D block pattern

At the UE side, the UE performs receive beamforming, synchronization, demodulation, SSB extracting, and SS-RSRP measuring. These steps repeat for each received beam and the SS-RSRP beam measurements are stored. Finally, the best beam pair can be obtained based on the SS-RSRP measurements. The transmit and receive array patterns of the best beam pair are illustrated in Fig. 5 and Fig. 6, respectively.

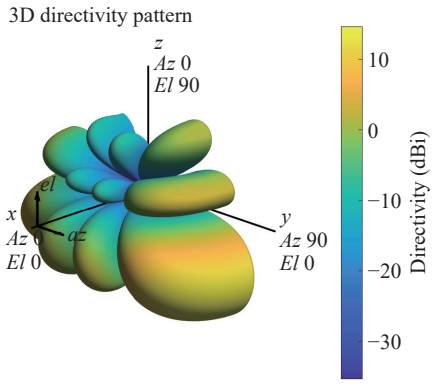


Fig. 5 Transmit array pattern

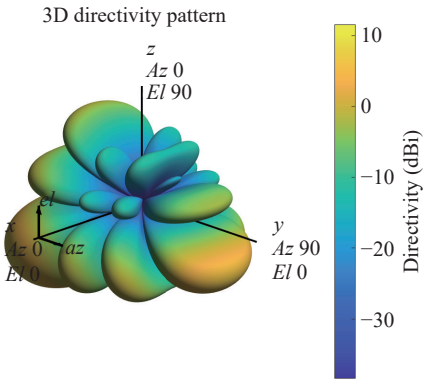


Fig. 6 Receive array pattern

### 4.1 Comparison of the Initial Access Accuracy

To verify the accuracy of the beam search algorithm proposed in our model, we compare the SS-RSRP measurements of the optimal beam pair obtained from the exhaustive search method and the proposed method. As depicted in Fig. 7, the error between two different methods is small, which can be computed as $\epsilon = 0.05\%$. It shows that the proposed algorithm has high beam search accuracy.

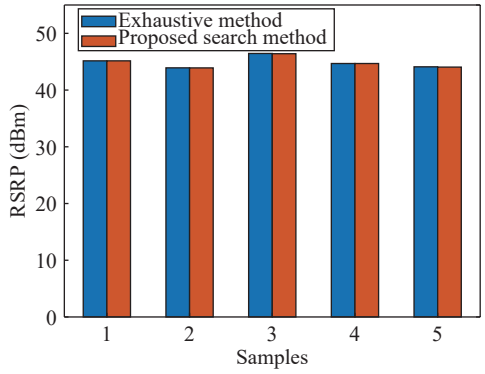


Fig. 7 The comparison of initial access accuracy between exhaustive search and the proposed search method in our model

Furthermore, we compare the results of SS-RSRP measurements of two stages during the beam search as shown in Fig. 8. It verifies the effectiveness of the hierarchical beam search since the narrower beams can obtain higher beam gain and accuracy.

### 4.2 Comparison of the Initial Access Delay

Since the high speed of satellite motion, we need a beam search method with lower time complexity, we compare the initial access delay between

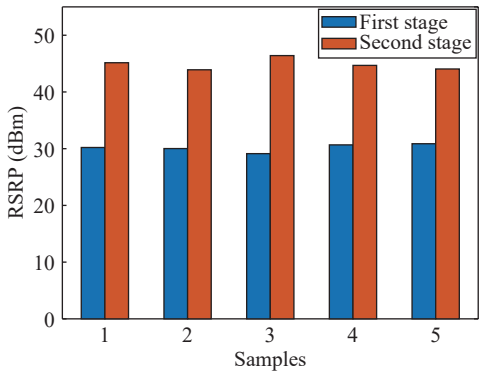


Fig. 8 The gain of two-stage beam search

exhaustive search and the proposed search method in our model. The number of narrow beams is 64 in the exhaustive beam search, while in our proposed method the number of beams used to sweep the satellite beams is 32. Thus, the beam search time, i.e., the initial access time, can reduce 50%, as shown in Fig. 9. Furthermore, according to Fig. 7 and Fig. 9, there is a tradeoff between the beam search accuracy and delay, i.e., sacrificing beam search accuracy to reduce the beam search time.

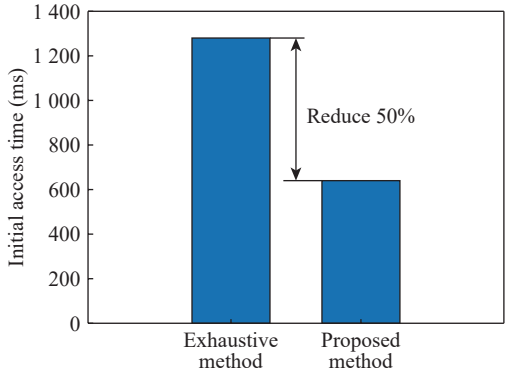


Fig. 9 The comparison of the initial access time between exhaustive search and the proposed search method in our model

## 5 Conclusion

In this paper, a sensing-aided hierarchical beam search method is proposed. We first develop the beam search process in the LEO satellite communication system, containing signal detection, time-frequency offset synchronization, UE beam sweeping, beam SS-RSRP measurement, and beam determination. Based on the framework, we

adopt the two-stage beam search method. After the first-stage beam search, we can obtain the best wide beam pairs. Then, the DOA is sensed from the received satellite signals at the best wide beams, which is based on the ESPRIT algorithm. Thus, during the second-stage beam search, the narrow beams are transmitted at the UE based on the results of DOA estimation. Based on this method, the beam search time can significantly decrease and high search accuracy can be guaranteed, which can be verified by simulation results.

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