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Resource allocation for uplink grant-free access in beam-hopping based LEO satellite systems①

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Abstract

The low earth orbit (LEO) satellite system provides a promising solution for the global coverage of Internet of Things (IoT) services. Confronted with the sporadic uplink transmission from massive IoT terminals, this work investigates the grant-free access scheme and resource allocation algorithm for the beam-hopping (BH) based LEO satellite systems. To improve the packet success rate, the time slots are pre-allocated to each cell according to the number of terrestrial terminals and the probability of packet arrival. When the packets arrive, the terrestrial terminals perform contention-free or contention-based grant-free access with packet repetition in the time slots allocated to their cells. The analytical expression of the packet collision probability for the grant-free access scheme is derived to provide reference for the resource allocation. To reduce the computational complexity, a heuristic resource allocation algorithm is proposed to minimize the maximum cell packet collision probability in the system. Simulation results show that the proposed resource allocation scheme achieves lower packet collision probability and higher resource utilization ratio when compared with the uniform resource allocation scheme.

Key words: low earth orbit (LEO) satellite system, grant-free access, beam-hopping (BH), resource allocation, collision

0 Introduction

With the development of the Internet of Things (IoT) technology, a variety of IoT applications are emerging and massive IoT terminals are deployed around the world. Although the IoT system based on terrestrial networks is mature, it is challenging and costly to provide services for the IoT terminals deployed in the remote and isolated areas[1]. As an important part of the sixth-generation (6G) mobile communication systems, the satellite communication systems can be regarded as the complement and expansion of the terrestrial networks[2]. Due to the advantages of the global coverage and the low orbital altitude, the low earth orbit (LEO) satellite communication system provides a promising solution for the remote IoT services[3]. However, the satellite-based IoT system also faces the problems of the high propagation delay, the uneven distribution of uplink traffic demands and the limited processing capability of the LEO satellite, which bring great challenges to the uplink access and resource allocation schemes.

Considering the high propagation delay, the conventional grant-based access scheme, which requires the issue of a scheduling request and the receipt of an uplink grant before the packet transmission, is not suitable for the satellite-based IoT system[4]. Instead, the grant-free access scheme is more adapted to the sporadic short packet transmission of the IoT terminals because of its low access delay and signaling overhead[5]. In the grant-free access scheme, each terminal is pre-allocated a number of uplink resources and transmits its packet in an 'arrive and go' manner. To improve the resource utilization, multiple terminals can contend to access some shared resources, but the packet collision may occur. The contention-based grant-free access with packet repetition has been investigated to reduce the packet collision probability[6-7]. The expressions of the collision probability for contention-based access with and without repetition were derived in Ref. [6], where a terminal can transmit the same packet in several consecutive time slots. The transceiver design for the contention-based access was presented in

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Ref. [7], where the packet replicas can be transmitted in randomly selected time slots in a frame, but the analytical expression of the collision probability has not been provided.

In addition to the packet repetition mechanism, the packet success rate can be further improved by optimizing the resource allocation scheme[8]. Considering the uneven distribution of traffic demands in the satellite systems, the limited resources should be allocated reasonably according to traffic demands in different cells. Due to the flexibility of resource allocation in the time dimension, the beam-hopping (BH) technology has been widely studied in the satellite systems[9-13]. In the BH-based satellite systems, the number of spot beams is far less than the total number of cells, and the spot beams can illuminate distinct cells in different time slots. The BH mechanisms in Refs [9-13] dynamically selected the illuminated cells and allocated the downlink resources according to the downlink traffic demand of each cell, so that the transmission resources and the practical demands can achieve better matching. Nevertheless, the resource allocation for uplink grant-free access in the BH-based LEO satellite systems has not been investigated.

In this work, the grant-free access scheme for the BH-based LEO satellite system is investigated, and a resource allocation algorithm is proposed to minimize the packet collision probability of the system. In the proposed grant-free access scheme, the LEO satellite periodically allocates the time slots and determines the grant-free access mode for each cell according to the number of terrestrial terminals and the probability of packet arrival. When the packets arrive, the terrestrial terminals perform contention-free or contention-based grant-free access with packet repetition in the time slots allocated to their cells. The analytical expression of the packet collision probability for the proposed contention-based access scheme is derived, where the terrestrial terminals can transmit one or multiple packet replicas in randomly selected time slots. The collision probability obtained from the analytical expression matches the simulated results perfectly, which provides valuable reference for the resource allocation. In consideration of the limited computing capability of the LEO satellite, a heuristic resource allocation algorithm with low complexity is proposed to minimize the maximum cell packet collision probability in the system. Simulation results show that the proposed resource allocation scheme achieves lower packet collision probability and higher resource utilization ratio when compared with the uniform resource allocation scheme.

The rest of this work is organized as follows. Section 1 describes the system model of the BH-based LEO satellite communication system. The uplink grant-free access scheme and the collision probability analysis for the proposed scheme are presented in Section 2. In Section 3, the resource allocation problem is formulated, and a heuristic algorithm with low complexity is proposed. Simulation results are presented in Section 4. Section 5 concludes this work.

1 System model

As shown in Fig. 1, the uplink transmission scenario in an LEO satellite communication system is considered. The footprint of the LEO satellite is divided into N_c cells indexed by the set $\Psi = \{1, \cdots, N_c\}$. There are M_i terrestrial terminals in the i-th cell ($i \in \Psi$). For each terrestrial terminal in the i-th cell, the packet arrives sporadically in a certain time window with the probability $P_a(i) \ll 1$.

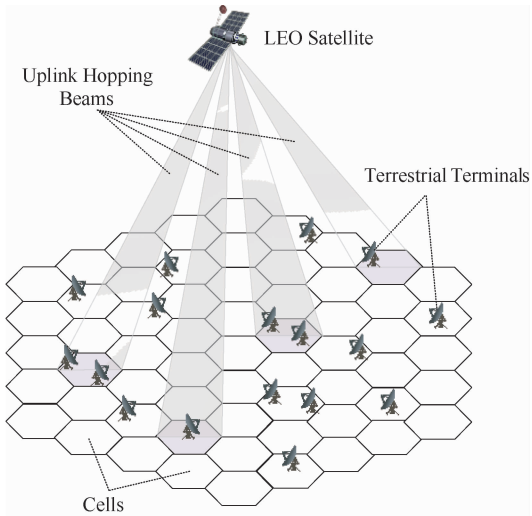

Fig. 1 An illustration of the LEO satellite system in the uplink

The LEO satellite is equipped with a phased array antenna[14], which can form N_b spot beams in the uplink. These spot beams reuse the full transmission bandwidth and illuminate the cells by the BH manner. It is assumed that a BH time window consists of T_s time slots indexed by the set $\Gamma = \{1, \cdots, T_s\}$, and the transmission bandwidth is equally divided into R subchannels. A combination of a time slot and a subchannel is defined as a resource block (RB), which can be used for the transmission of a single packet. Let $\alpha_{i,t} \in \{0, 1\}$ indicate whether the i-th cell is illuminated by a spot beam in time slot $t \in \Gamma$. If the i-th cell is illuminated and the terrestrial terminals in this cell can perform uplink grant-free access in time slot t, $\alpha_{i,t} = 1$;

otherwise, $\alpha_{i,t} = 0$. In each time slot, at most N_b cells can be illuminated by the spot beams, which can be expressed as

$$\sum_{i=1}^{N_c} \alpha_{i,t} \leqslant N_b, \ \forall t \in \Gamma \tag{1}$$

Full frequency multiplexing helps to make full use of the frequency resources. However, due to the side-lobe effect of the antenna radiation pattern[9], the co-channel interference (CCI) may be generated between the spot beams pointing to adjacent cells, which will significantly degrade the received signal to interference plus noise ratio (SINR) of the LEO satellite. To avoid the CCI of the full frequency multiplexing system, a distance threshold d_{th} is introduced to ensure the isolation between different beams. It means that the distance between any two cells illuminated in the same time slot should not be shorter than d_{th}. Define $C_i = (x_i, y_i, z_i)$ as the coordinates of the center of the i-th cell in the spatial rectangular coordinate system[10]. If the i-th cell and the j-th cell are illuminated in time slot t, the constraint on the distance between the two cells can be written as

$$|C_i C_j| = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \geqslant d_{th} \tag{2}$$

2 Uplink grant-free access in BH-based LEO satellite system

In this section, a grant-free access scheme for the BH-based LEO satellite system is proposed first, and then the packet collision probability of the proposed scheme is derived and analyzed.

2.1 Grant-free access scheme

In the proposed grant-free access scheme, the LEO satellite periodically allocates the time slots to the cells according to the number of terrestrial terminals and the probability of packet arrival. When the packets arrive, the terrestrial terminals perform grant-free access in the time slots allocated to their cells. The details can be described as follows.

First, the LEO satellite collects the number of terrestrial terminals and the probability of packet arrival in each cell. The probability of packet arrival can be obtained through historical data analysis.

Based on the acquired information, the LEO satellite allocates the time slots in a BH time window to the cells. Let T_i denote the total number of time slots allocated to cell $i \in \Psi$ in a BH time window, which can be expressed as

$$T_i = \sum_{t=1}^{T_s} \alpha_{i,t} \tag{3}$$

The grant-free access mode adopted by the terrestrial terminals in cell i is determined according to the following criteria.

(1) If the total number of available RBs in a BH time window is larger than or equal to the number of terrestrial terminals in cell i, i. e. , $T_i R \geqslant M_i$, each terrestrial terminal in cell i is assigned a dedicated RB and adopts the contention-free access mode.

(2) Otherwise, all terrestrial terminals in cell i share all the available RBs and adopt the contention-based access mode.

Then, the grant-free access patterns, which include the resource allocation results in a BH time window and the grant-free access modes, are broadcasted to the terrestrial terminals in each cell. The patterns will repeat periodically until new patterns are received.

When the packets arrive, the terrestrial terminals perform uplink grant-free access according to their respective access modes as follows.

(1) Contention-free access: the terrestrial terminal transmits its packet on the dedicated RB without collision.

(2) Contention-based access: let $L_{\max} \geqslant 1$ denote the maximum allowable repetition times. The terrestrial terminal in cell i first randomly selects $L = \min(L_{\max}, T_i)$ time slots from the T_i time slots allocated to cell i in a BH time window, and then randomly selects a RB from R RBs in each selected time slot. The terrestrial terminal transmits the same packet on L selected RBs. If all of the L transmission attempts collide with the transmission attempts from other terminals in cell i, the packet is considered collided.

2.2 Collision probability analysis

Based on the system model described in Section 1, the expression of the packet collision probability for the contention-based grant-free access in subsection 2.1 is derived as follows.

First, it is assumed that the terrestrial terminals in cell $i \in \Psi$ adopt the contention-based access without repetition, i. e. $L = 1$. When a packet arrives, the terminal χ in cell i first randomly selects a time slots t_1 from the T_i time slots, and then transmits the packet on a shared RB in the time slot t_1.

The probability that m terminals (from the other $M_i - 1$ terminals in cell i) also transmit packets in the same time window is[6]

$$P_m(i) = \binom{M_i - 1}{m} (P_a(i))^m (1 - P_a(i))^{M_i - m - 1} \tag{4}$$

The probability that these m terminals do not select the same RB as terminal $\mathcal{X}$ in the given time window is

$$P_{uc,m}^{t_1}(i,1) = \left(1 - \frac{1}{T_i R}\right)^m \quad (5)$$

Therefore, the probability of no collision between the terminal $\mathcal{X}$ and any other terminals in cell i is

$$P_{uc}(i,1) = \sum_{m=0}^{M_i-1} P_m(i)\, P_{uc,m}^{t_1}(i,1)$$
$$= \sum_{m=0}^{M_i-1} \binom{M_i-1}{m} (P_a(i))^m (1-P_a(i))^{M_i-m-1} \left(1 - \frac{1}{T_i R}\right)^m \quad (6)$$

Based on the binomial theorem, Eq. (6) can be simplified as

$$P_{uc}(i,1) = \left[P_a(i)\left(1 - \frac{1}{T_i R}\right) + 1 - P_a(i)\right]^{M_i-1}$$
$$= \left(1 - \frac{P_a(i)}{T_i R}\right)^{M_i-1} \quad (7)$$

For the terrestrial terminals in cell i, the packet collision probability for the contention-based access without repetition ($L=1$) is

$$P_c(i,1) = 1 - P_{uc}(i,1) = 1 - \left(1 - \frac{P_a(i)}{T_i R}\right)^{M_i-1} \quad (8)$$

Then, it is assumed that the terrestrial terminals in cell i adopt the contention-based access with the repetition times $L=2$. The terminal $\mathcal{X}$ first randomly selects two time slots t_1 and t_2 from the T_i time slots, and then randomly selects a RB in each selected time slot to transmit the same packet twice.

For $L=2$, the probability that a terminal selects a given time slot from T_i time slots is $2/T_i$. Thus, when there are m terminals (besides the terminal $\mathcal{X}$) in cell i transmitting packets in the same time window, the probability that n terminals from these m terminals select the time slot t_1 is

$$P_{m,n}^{t_1}(i,2) = \binom{m}{n}\left(\frac{2}{T_i}\right)^n \left(1 - \frac{2}{T_i}\right)^{m-n} \quad (9)$$

Let $\mu = 1 - 1/R$ denote the probability that a terminal does not select the given RB from R RBs in a time slot. The probability that the transmission attempt from the terminal $\mathcal{X}$ in the time slot t_1 does not collide with the transmission attempts from the other m terminals is

$$P_{uc,m}^{t_1}(i,2) = \sum_{n=0}^{m} P_{m,n}^{t_1}(i,2)\,\mu^n = \left(1 - \frac{2}{T_i R}\right)^m \quad (10)$$

Then, the transmission attempt from the terminal $\mathcal{X}$ in the time slot t_2 is considered. When there are n terminals selecting the time slot t_1, the probability that k_1 terminals from these n terminals select the time slot t_2 is

$$P_{n,k_1}^{t_2}(i,2) = \binom{n}{k_1}\left(\frac{1}{T_i-1}\right)^{k_1}\left(1 - \frac{1}{T_i-1}\right)^{n-k_1} \quad (11)$$

Considering the other terminals which do not select the time slot t_1, the probability that k_2 terminals from these $m-n$ terminals select the time slot t_2 is

$$P_{m-n,k_2}^{t_2}(i,2) = \binom{m-n}{k_2}\left(\frac{2}{T_i-1}\right)^{k_2}\left(1 - \frac{2}{T_i-1}\right)^{m-n-k_2} \quad (12)$$

Combining the above two cases, when there are n terminals selecting the time slot t_1, the probability that the transmission attempt from the terminal $\mathcal{X}$ in the time slot t_2 does not collide with the transmission attempts from the other m terminals is

$$P_{uc,m|n}^{t_2}(i,2) = \sum_{k_1=0}^{n}\sum_{k_2=0}^{m-n} P_{n,k_1}^{t_2}(i,2)\, P_{m-n,k_2}^{t_2}(i,2)\,\mu^{k_1+k_2}$$
$$= \left(1 - \frac{1}{(T_i-1)R}\right)^n \left(1 - \frac{2}{(T_i-1)R}\right)^{m-n} \quad (13)$$

Therefore, the probability that the transmission attempt from the terminal $\mathcal{X}$ in the time slot t_1 collides, but the transmission attempt in the time slot t_2 does not collide is

$$P_{uc,m}^{t_2}(i,2) = \sum_{n=0}^{m} P_{m,n}^{t_1}(i,2)(1-\mu^n)P_{uc,m|n}^{t_2}(i,2)$$
$$= \left(1 - \frac{2}{T_i R}\right)^m - \left(1 - \frac{4}{T_i R} + \frac{2}{(T_i-1)T_i R^2}\right)^m \quad (14)$$

For the terrestrial terminals in cell i, the packet collision probability for the contention-based access with $L=2$ is

$$P_c(i,2) = 1 - \sum_{m=0}^{M_i-1} P_m(i)(P_{uc,m}^{t_1}(i,2) + P_{uc,m}^{t_2}(i,2))$$
$$= 1 - 2\left(1 - \frac{2P_a(i)}{T_i R}\right)^{M_i-1} + \left(1 - \frac{4P_a(i)}{T_i R} + \frac{2P_a(i)}{(T_i-1)T_i R^2}\right)^{M_i-1} \quad (15)$$

The packet collision probability for the contention-based access with the repetition times $L>2$ can be derived in a similar way. It is assumed that the terminal $\mathcal{X}$ randomly selects L time slots $t_1, \cdots, t_l, \cdots, t_L$ from the T_i time slots, and then randomly selects a RB in each selected time slot to transmit the same packet for L times.

In this case, the probability that a terminal selects a given time slot from T_i time slots is L/T_i. Thus, when there are m terminals (besides the terminal $\mathcal{X}$) in cell i transmitting packets in the same time window, the probability that n terminals from these m terminals select the time slot t_1 is

$$P_{m,n}^{t_1}(i,L) = \binom{m}{n}\left(\frac{L}{T_i}\right)^n\left(1 - \frac{L}{T_i}\right)^{m-n} \quad (16)$$

The probability that the transmission attempt from the terminal $\mathcal{X}$ in the time slot t_1 does not collide with the transmission attempts from the other m terminals is

$$P^{t_1}_{uc,m}(i, L) = \sum_{n=0}^{m} P^{t_1}_{m,n}(i, L)\mu^n = \left(1 - \frac{L}{T_iR}\right)^m \quad (17)$$

Then, the probability that the transmission attempt from the terminal χ in the time slot t_1 collides, but the transmission attempt in the time slot t_2 does not collide is

$$P^{t_2}_{uc,m}(i, L) = \sum_{n=0}^{m} P^{t_1}_{m,n}(i, L)(1 - \mu^n)\left(1 - \frac{L-1}{(T_i - 1)R}\right)^n \left(1 - \frac{L}{(T_i - 1)R}\right)^{m-n} = \left(1 - \frac{L}{T_iR}\right)^m - \left(1 - \frac{2L}{T_iR} + \frac{L(L-1)}{(T_i - 1)T_i R^2}\right)^m \quad (18)$$

By analogy, the probability that all the transmission attempts from the terminal χ in the time slot t_1, $\cdots$, $t_{l-1}(2 \leqslant l \leqslant L)$ collide, but the transmission attempt in the time slot t_l does not collide with the transmission attempts from the other m terminals is

$$P^{t_l}_{uc,m}(i, L) = \sum_{q=0}^{l} (-1)^{q-1}\binom{l-1}{q-1} \times \left(1 - \sum_{u=1}^{q} (-1)^{u-1}\binom{q}{u}\frac{\prod_{v=0}^{u-1}(L - v)}{\prod_{v=0}^{u-1}((T_i - v)R)}\right)^m \quad (19)$$

For the terrestrial terminals in cell i, the packet collision probability for the contention-based access with $L \geqslant 1$ is

$$P_c(i, L) = 1 - \sum_{m=0}^{M_i-1}\left(P_m(i)\sum_{l=1}^{L} P^{t_l}_{uc,m}(i, L)\right) = 1 - \sum_{q=1}^{L} (-1)^{q-1}\binom{L}{q} \times \left(1 - \sum_{u=1}^{q} (-1)^{u-1}\binom{q}{u}\frac{P_a(i) \times \prod_{v=0}^{u-1}(L - v)}{\prod_{v=0}^{u-1}((T_i - v)R)}\right)^{M_i-1} \quad (20)$$

To validate the analytical expression of the packet collision probability, Fig. 2 provides the comparison of the analytical and simulated results with varying time slot number T_i and maximum repetition times $L_{\max}$ for $M_i = 100$, $P_a(i) = 10^{-3}$ and $R = 6$. The figure shows a perfect match, so that the analytical results can be used as the reference for the resource allocation in the next section.

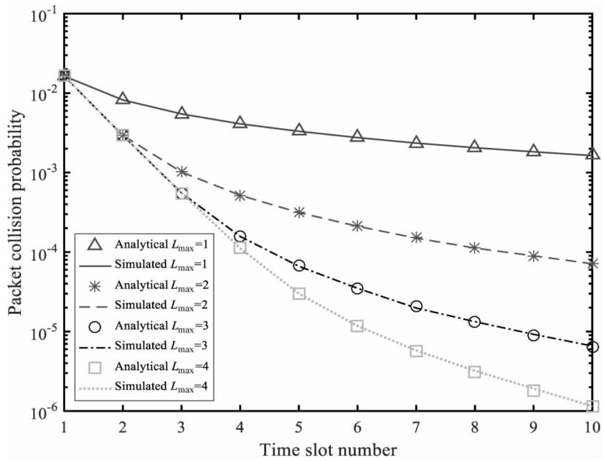

Fig. 2 Validation of the analytical expression of packet collision probability

3 Resource allocation for grant-free access

Based on the grant-free access scheme in Section 2, the resource allocation problem in the BH-based LEO satellite system is formulated, and a heuristic algorithm is proposed to solve the problem with low computational complexity.

3.1 Problem formulation

The objective of the resource allocation is to minimize the maximum packet collision probability of the N_c cells by allocating the time slots in a BH time window to these cells. Thus, the resource allocation problem can be formulated as

$$\min_{\{\alpha_{i,t}\}} \max_{i \in \Psi}(P_{ga}(i)) \quad (21)$$

$$\text{s.t. } P_{ga}(i) = \begin{cases} 0 & T_iR \geqslant M_i \\ P_c(i, L) & T_iR < M_i \end{cases}, \ \forall i \in \Psi \quad (21a)$$

$$\alpha_{i,t} \in \{0, 1\}, \ \forall i \in \Psi, t \in \Gamma \quad (21b)$$

$$\sum_{i=1}^{N_c} \alpha_{i,t} \leqslant N_b, \ \forall t \in \Gamma \quad (21c)$$

$$|C_i C_j| \geqslant d_{th}, \text{ if } \alpha_{i,t} = \alpha_{j,t} = 1, i \neq j, \ \forall i, j \in \Psi, t \in \Gamma \quad (21d)$$

where, $P_{ga}(i)$ denotes the packet collision probability of cell i when the terrestrial terminals in cell i adopt the contention-free or contention-based grant-free access, as defined in constraint Eq. (21a). Constraint Eq. (21b) defines the optimization variable $\alpha_{i,t}$, $\forall i \in \Psi$, $t \in \Gamma$, which indicates whether the cell i is illuminated in time slot t. Constraint Eq. (21c) states that at most N_b cells can be illuminated in each time slot. Constraint Eq. (21d) means that the distance between any two cells illuminated simultaneously should be longer than or equal to d_{th}.

The optimization problem in Eq. (21) is a nonlinear integer programming problem. Solving the optimal solution of this problem will lead to extremely high computational complexity and long computational time, which is not practical for the real-time resource scheduling in the satellite systems. Therefore, a heuristic resource allocation algorithm with low complexity is proposed in subsection 3.2.

3.2 Resource allocation algorithm

The main idea of the resource allocation algorithm can be described as follows: each time slot in a BH time window is allocated to at most N_b cells, where the cells with higher packet collision probability and activity metric will have the priority of the time slot allocation. The activity metric of cell $i \in \Psi$ is defined as the probability that any one or more terminals in cell i transmit packets in a BH time window, which can be expressed as

$$A(i) = 1 - (1 - P_a(i))^{M_i} \quad (22)$$

On the basis, the overall flowchart of the resource allocation algorithm is shown in Fig. 3.

Before allocating the time slots, the packet collision probability of each cell should be initialized as

$$P_{ga}(i) = \begin{cases} 1 & M_i > 0 \\ 0 & M_i = 0 \end{cases}, \ \forall i \in \Psi \quad (23)$$

And the optimization variables $\{\alpha_{i,t}\}$ are initialized to 0.

For each time slot $t \in \Gamma$, at most N_b cells are selected to be illuminated by the spot beams. Let Φ denote the set of the candidate cells which can be illuminated in time slot t. If the packet collision probability of cell i is equal to 0, cell i should not be included in Φ, since cell i does not need to be allocated more resources. Thus, the set Φ can be initialized as

$$\Phi = \{i \mid P_{ga}(i) > 0, i \in \Psi\} \quad (24)$$

In each iteration, if Φ is not empty and the number of illuminated cells in time slot t is less than N_b, the time slot t is allocated to one of the candidate cells as follows.

(1) Find the cells with the maximum packet collision probability in Φ, which can be indexed by

$$\Omega = \{i \mid P_{ga}(i) = \max_{j \in \Phi}\{P_{ga}(j)\}, i \in \Phi\} \quad (25)$$

(2) Allocate the time slot t to the i^*-th cell with the maximum activity metric in Ω, i. e. $\alpha_{i^*,t} = 1$, where

$$i^* = \text{argmax}_{i \in \Omega}\{A(i)\} \quad (26)$$

(3) Update the packet collision probability of cell i^*. Specifically, if the total number of available RBs is larger than or equal to M_{i^*}, the contention-free access mode is adopted and $P_{ga}(i^*) = 0$; otherwise, the contention-based access mode is adopted and $P_{ga}(i^*) = P_c(i^*, L)$, which can be calculated by Eq. (20).

(4) Remove cell i^* from Φ, so that cell i^* will not be selected in the next iteration.

(5) Update the set Φ to avoid the CCI between different beams. Specifically, if the distance between cell i^* and cell $j \in \Phi$ is shorter than d_{th}, cell j is removed from Φ, so that cell j will not be illuminated in time slot t.

Repeat the above processing until all time slots are allocated.

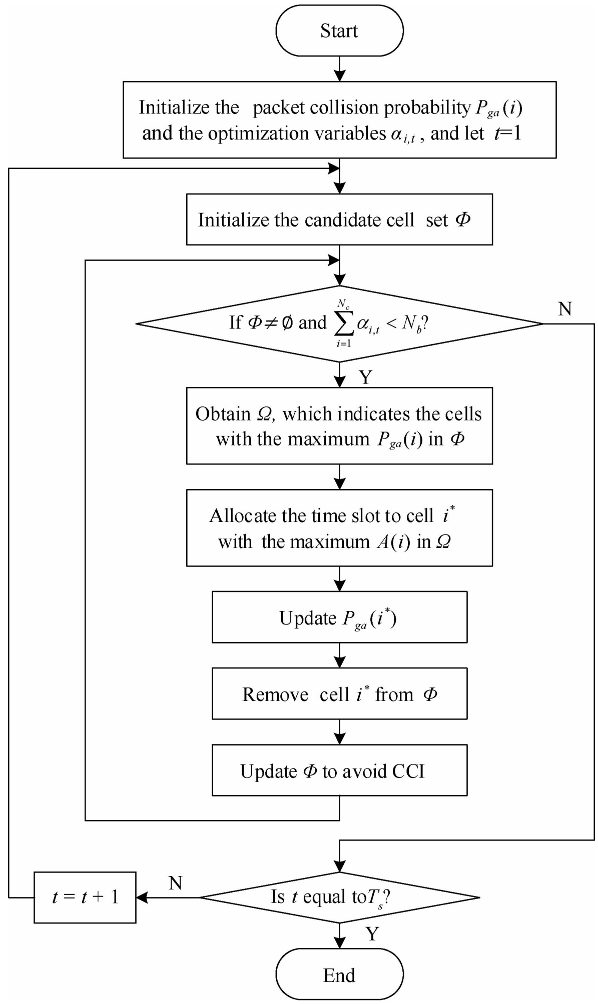

Fig. 3 The flowchart of the resource allocation algorithm

The computational complexity of the resource allocation algorithm is quantified in terms of the number of operations in computing the packet collision probability of each cell. The worst-case complexity of the resource allocation algorithm is $O(T_s N_b)$ since there are T_s time slots and it requires at most $O(N_b)$ operations to compute the packet collision probability when allocating a time slot to N_b cells. In practice, the complexity can be further reduced since the allocation of a time slot will terminate if the set Φ is empty.

4 Simulation results

In this section, simulations are carried out to evaluate the performance of the proposed scheme in the BH-based LEO satellite communication system. The cell distribution of the LEO satellite system in Ref. [10] is considered, where the number of cells is set to 91 and the radius of each cell is set to 52 km. The phased array antenna of the LEO satellite can form $N_b = 16$ spot beams in the uplink[15]. The number of terrestrial terminals and the probability of packet arrival in each cell are randomly generated, respectively, which make the distribution of the uplink traffic demands uneven. According to the analysis in Ref. [9], the distance threshold d_{th} is set to twice the inter-cell distance, so that the CCI between different beams can be ignored. Each BH time window consists of T_s = 40 time slots, and the transmission bandwidth is divided into R = 6 subchannels[6]. The simulation parameters are summarized in Table 1.

Table 1 Simulation parameters

Parameter	Symbol	Value
Number of time slots in a time window	T_s	40
Number of cells	N_c	91
Number of spot beams	N_b	16
Number of subchannels	R	6
Radius of each cell		52 km
Distance threshold	d_{th}	180 km
Maximum repetition times	$L_{\max}$	1, 2, 4

Fig. 4 depicts the maximum packet collision probability, i. e., $\max_{i\in\Psi}(P_{ga}(i))$, as a function of the average number of terrestrial terminals in each cell. The average probability of packet arrival is 10^{-3}. Compared with the proposed resource allocation scheme, the performance of the uniform resource allocation scheme with fixed BH pattern is also shown in Fig. 4[13]. In this scheme, all cells are allocated the same number of time slots, regardless of the traffic demands in the cells. It can be seen that the maximum packet collision probability of the proposed resource allocation scheme is always lower than that of the uniform resource allocation scheme. Specifically, the proposed algorithm results in 46%, 57% and 65% improvement on average with $L_{\max}$ = 1, 2 and 4, respectively.

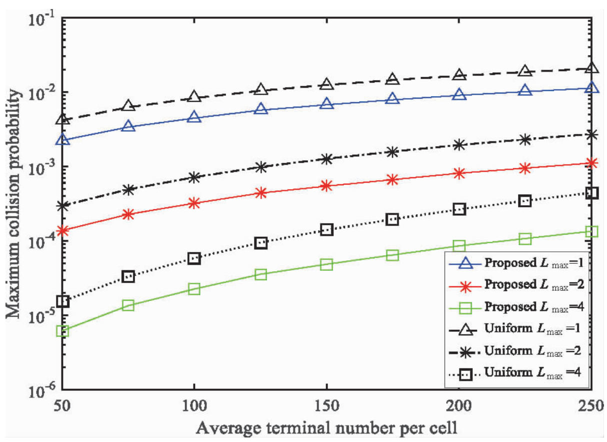

Fig. 4 Maximum packet collision probability with varying average terminal number per cell

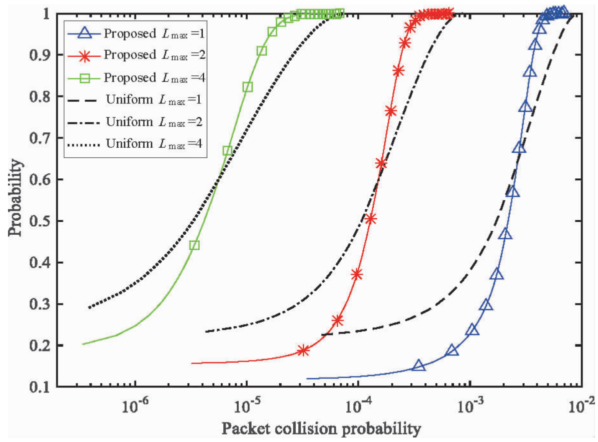

Fig. 5 CDF of packet collision probability

Fig. 5 shows the cumulative distribution function (CDF) of the packet collision probability of each cell when the average number of terrestrial terminals is 100. Compared with the proposed resource allocation scheme, the uniform resource allocation scheme provides not only a larger number of cells with high collision probability, but also a larger number of cells with low collision probability. This is because that the uniform resource allocation scheme is unable to flexibly schedule the resources according to the traffic demands, so that the cells with more terminals and higher transmission probability cannot obtain enough resources, whereas the RBs allocated to the cells with less terminals and lower transmission probability may be wasted. By comparison, the proposed scheme can control the packet collision probability within a desirable range by allocating appropriate number of time slots to each cell, which implies that the traffic demands and the transmission resources achieve better matching.

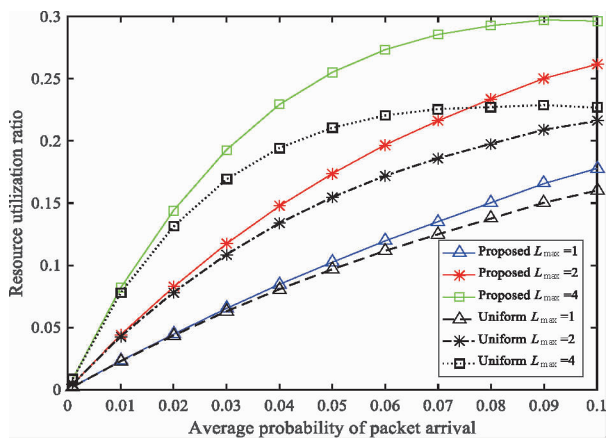

Fig. 6 Resource utilization ratio with varying average probability of packet arrival

Fig. 6 presents the resource utilization ratio with varying average probability of packet arrival when the average number of terrestrial terminals in each cell is 100. The resource utilization ratio is defined as the ratio of the number of successful transmission attempts to the total number of RBs. As the probability of packet arrival increases, the performance gap between the proposed resource allocation scheme and the uniform resource allocation scheme becomes larger. This is because that the packet collision probability of the cells with high traffic demands increases dramatically when using the uniform resource allocation scheme, which leads to more collided transmission attempts. The proposed scheme can balance the packet collision probability of all cells in the system, which improves the packet success rate of the cells with high traffic demands. Therefore, the proposed resource allocation scheme has better adaptability to the uneven distribution of traffic demands.

5 Conclusion

The grant-free access scheme and resource allocation algorithm have been investigated for the BH-based LEO satellite systems. After obtaining the number of terrestrial terminals and the probability of packet arrival in each cell, the LEO satellite allocates the time slots and determines the grant-free access mode for each cell. When the packets arrive, the terrestrial terminals perform grant-free access according to their respective access patterns. Moreover, based on the derived expression of the packet collision probability, a heuristic resource allocation algorithm with low complexity has been proposed to minimize the maximum cell packet collision probability in the system. Simulation results show that the proposed resource allocation scheme achieves lower packet collision probability and higher resource utilization ratio than the uniform resource allocation scheme when the traffic demands are unevenly distributed.

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