A New Batch Access Scheme with Global QoS Optimization for Satellite-Terrestrial Networks

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***Abstract*—Continuously increasing demands from enhanced mobile broadband, machine-to-machine and internet of things pose a growing threat to 5G communication. Satellites integrated with 5G and beyond are pivotal to achieve global coverage, reliable and continuing service access, with the booming low-orbit satellite (LEO) constellations. While previous works largely focus on rural or remote areas, the orbiting satellites cover the ground evenly. This paper is then interested in unserved or underserved users in urban hotspots arising from large-scale access. Under the large delay of the ground-to-satellite link and the dynamic characteristic of satellites, we propose a satellite-terrestrial cooperative, geographical dispersed and regional centralized batch access control scheme. A data-driven QoS indicator, responsivity, is proposed to complement the semi-online batch scheme from a network perspective. It combines subsiding access control from LEO satellite to ground with LEO satellite resources to provide auxiliary access for higher responsivity users relatively. We model the on-demand batch access mechanism as a multidimensional knapsack problem (MKP) solved by a hybrid genetic algorithm. Collectively, the cooperative batch mechanisms compress signaling transmission and reduce optional power consumption. Simulation results show that the new indicator achieves a better balance between spectral efficiency and global QoS compared to existing methods.**

***Index Terms*—Satellite-terrestrial, on-demand access, large-scale access, uncertainty analysis, LEO satellite, MKP, hybrid genetic algorithm.**

I. Introduction

The capacity of densified fifth-generation (5G) terrestrial base stations would struggle with the explosive growth of smart devices and data traffic in the future, in both cost and control. The study of the sixth-generation (6G) is put on the agenda. A 6G system is envisaged as a large-scale autonomous global network capable of supporting massive wireless connections [1], [2]. Nowadays, hybrid and heterogeneous terrestrial networks bear massive service requirements from multiple devices and domains. To address massive access and alleviate the load of ground, satellite communications, such as large-scale LEO constellations, provide an important new impetus [3]. The satellite-terrestrial integration can extend wireless coverage into underpopulated areas, offload terrestrial network traffic, deliver emergency communications in the absence of on-ground infrastructure, and provide path diversity for high-speed mobile users [4], [5]. Consumers would benefit from the combination of terrestrial and non-terrestrial access to meet the targeted service performances in terms of data rate and/or reliability.

To date, satellites and 5G systems have been largely separate, and each adopts a different networking architecture and protocol system [6]. Large propagation delay between satellite and ground, expensive satellite spectrum resources, non-negligible transmission errors, and limited transmission power are another challenge [7]. It is particularly important to design a tailored access control protocol for LEO satellites, with low delay and less overhead, and high resource utilization. On two key aspects can satellites contribute to ubiquitous 5G access networks: direct access and backhaul [8]. For direct access, satellites working on low-frequency bands can offer lower power, and less costly RAN solutions [3]. In addition, software defined networking (SDN) and network function virtualization (NFV) provides the opportunity for the deep integration of the satellite network and the terrestrial network [9]. Therefore, with the satellites directly connecting the users and the virtualized functionalities, the existing infrastructure can be reused as much as possible, with minor updates on the terminal side to enable the satellite-terrestrial communication.

LEO satellites for large-scale connections in hotspot areas that are unserved or underserved have not been well studied. Many articles considered that users have no regular connections to the Internet in remote areas, maritime applications, and in emergency circumstances using satellites [10]. Random access (RA) of uncertain performance is more suitable for low-power devices in remote areas rather than high-density areas [11], not to mention the wide beam coverage, long propagation distance, and fast relative motion of LEO satellites [12]. Furthermore, the signaling of large-scale access needs to be considered. On-demand access provides a solution to the bursting, unequal and variable multimedia services [13]. It can track the dynamics of actual services, thereby effectively improving resource utilization. However, due to the propagation delay of satellite links, the service delay from the request/distribution process is increased. The competition between high resource utilization and low service delay is a core problem that needs to be solved [14].

This paper focuses on large-scale differentiated access in

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urban hotspots, and uses LEO satellites to complement terrestrial wireless resources to serve unserved and under-served users. We propose to relocate the access control function for the delay reduction of large-scale access in urban areas. Through the coordination between the ground base stations and satellites, on-demand batch access can bring a multi-faceted merit. Satellite and ground networks benefit from signaling compression and low computational cost of the satellite, while users' latency and transmission power to LEO satellites are reduced. On-demand batch access decisions depend on the current available resources and the requests diversification in a semi-online way. Batch processing considers the short time interval of various dynamic requests not just a single subframe in a holistic manner. The multi-dimensional QoS from user's perspective is transformed into a single evaluation index to provide systematic priority for base station decision-making. The contributions of this paper are summarized as follows:

- We propose a new satellite-terrestrial cooperative access protocol, which reduces the unnecessary delay and power consumption. The new protocol effectively copes with the long delay of the satellite-ground link and the high dynamic characteristics of LEO satellites.
- A global QoS index, called responsivity, is proposed based on large-scale dynamic access data through uncertainty analysis. This indicator guides the network to better utilize existing resources to serve users' preference changes in time.
- A batch access mechanism is designed to achieve the balance between satellite resource utilization and global QoS, hence reduce signaling overhead. The scheme adapts to semi-online stochastic behavior of networks where a batch of flows arrives in a time interval.

II. Network Model and Problem Formulation

In this paper, we assume that a LEO satellite as part of 5G access network accesses the SBA-based 5G core network together with the terrestrial cellular network access. The base station can obtain the overhead satellites information like resource occupancy through the satellite earth station. We use satellite referring to LEO satellites below.

A. Satellite-Terrestrial Integrated Scenario

Compared to LEO based Earth moving cells scenario where cells are moving on the ground, LEO based Earth fixed cells scenario refer to NTN that provide cells fixed with respect to a certain location on the Earth. This can be achieved with NTN platforms generating steerable beams which footprint is fixed on the ground according to 3GPP TR 38.821 [15]. There is thus always a virtual satellite serving the fixed cell, even though the high-speed movement of satellites leads to limited service time. Suppose that a single Earth fixed cell includes a macro base station (MBS) and multiple small base stations (SBS), as shown in Fig. 1. The satellite undertakes the access requests when the resources of the MBS and the surrounding SBSs are saturated. The MBS aggregates the needs of nearby small base stations through backhaul links,

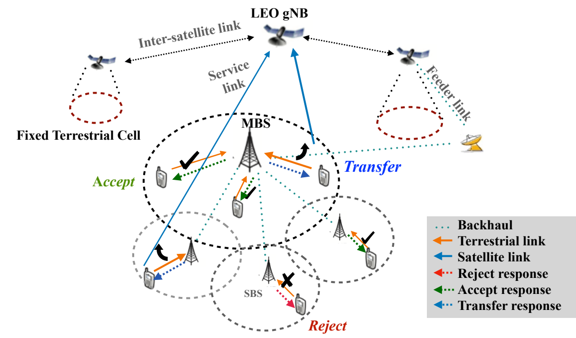

Fig. 1. The system model of cooperative access in an Earth fixed cell. Users rejected by both ground and satellite denote as cross mark, accepted by ground as check mark, accepted by satellite as shift mark.

and performs batch access and resource allocation on behalf of satellite. In the absence of satellite access, these requests are rejected or downgraded. Originating from the hotspot area, the large-scale access requests are suitable for batch periodic processing and the generation of a global view. Access or not is directly related to resource availability in regards to on on-demand access, where radio resources consist of two dimensions, i.e., time and frequency.

Without loss of generality, we assume that satellites operate in an exclusive frequency (S-band) with gNBs onboard. There are no interference between terrestrial base stations using C-band, and users are capable of establishing direct links to satellites consequently [16]. According to the SDN and NFV, the satellites' access functions could be virtualized and carried out remotely in the ground MBSs.

Each user can only be served by one satellite at a time. We hence assume that the capacity provided for Earth fixed cells from satellites is known and controllable. The batch access is based on perceived capacity. The content of geographic dispersed and regional centralized is exemplified by the following: There are a lot of adjoining and misaligned Earth fixed cells. Each has specific aggregated MBS, and the MBS aggregates intra-cell requests in the region, hence conducting the batch on-demand access.

B. Cooperative Access Process

In each round of the batch access cycle, the access control unit located in the MBS can synthesize various requests, and convert the multi-dimensional QoS of user requests into a single indicator named responsivity (RD) expressing relative access priority. Under limited network capacity, it is crucial to determine the service order. The higher the value of responsivity, the more the network tends to prioritize service. This metric changes with requests arrived in each round. Not only can it effectively deal with complex access types, but also facilitate access control. For more details, please see Section III-A.

In Fig. 2, we show the difference between the individual access to the satellites and the proposed cooperative batch access mechanism. The MBS aggregates requests arrived

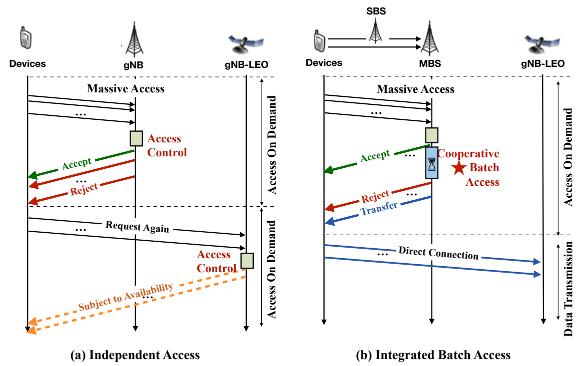

Fig. 2. Two types of on-demand access: (a) The process of individual access to satellites; (b) The streamlined process of cooperative decision with batch access and descending control unit.

within a time interval in a given area and then sends them to the satellite. The period of time is proportional to the traffic density in the area and average in-view time of a satellite. Based on RD and time-frequency resource requests, the control unit periodically makes the batch decision and returns the result to the users directly and to the satellite indirectly. The feedback to users is either rejection or satellite offloading when terrestrial radio resource is saturatied. The accepted users receive the satellite identification and authentication code, uplink and downlink spot beam numbers, time slot, frequency or codeword information, and resource allocation sent by the MBS through the control channel. The user can establish a direct data connection with the satellite. The authentication information carried by the user replaces partial interaction between the satellites and the base stations. After the connection is completed, the user terminal releases the channel, and the system recovers the allocated network resources. In this solution, two-step signaling transmissions are required to admit or deny access illustrated as Fig. 2.

The users prioritize the terrestrial cellular network over satellite access, due to a cost consideration and current infrastructure. After the first access attempt is denied due to ground system saturation, there will be at least another ground-satellite round trip to access the satellite for individual access, as shown in Fig. 2. Because the occupancy of the satellite resources are unknown, the pending access attempt could increase user power consumption and delay. Therefore, we propose a cooperative batch access method, where the MBS makes decisions periodically on behalf of the satellite. The MBS allows a subset of arrived requests to access the satellite according to the RD and available resources. The batch decision can substantially reduce the signaling by aggregating massive signatures into a periodical single message, hence reducing power consumption on the base station side. We also streamline the large-scale access cooperative mechanism. Users connecting to satellites are instructed by ground MBS rather than randomly attempt.

C. Batch Access Optimization Problem

The multi-dimensional access request model is $\mathbf{Q} = (D_p, P_r, T_d, R_t, R_b)$, which accounts for the size of the data packet, the revenue of the system after accepted, the delay threshold, the time and frequency resource requirement respectively. Suppose that there are a total of $\mathcal{N}$ requests and $\mathcal{I}$ types in one decision cycle, and $\mathbf{X}$ indicates the status regarding all requests $\mathbf{X} = (x_1, x_2, \ldots, x_N) \in \{0,1\}^N$, where $x_n = 1$ indicates access, $x_n = 0$ indicates otherwise. The MBS synthesizes the requests in one cycle, generates the corresponding response degree RD in (1), and makes the access decision. α provides the weighting coefficient of the corresponding attribute.

$$
\begin{aligned}
RD = \alpha_1 f\left(D_p\right) + \alpha_2 f(P_r) + \alpha_3 f\left(T_d\right) \\
+ \alpha_4 f(R_b) + \alpha_5 f\left(R_t\right).
\end{aligned} \tag{1}
$$

In this paper, the access resources of a fixed terrestrial cell covered by the satellites are modeled as a two-dimensional knapsack (2D-KP). The item's weight corresponds to the two-dimensional resource demand, the value to the RD, and the volume to the capacity of the Earth fixed cell from overhead satellites. The two dimensions of the knapsack are time-domain resources *TH* and frequency resources *BW*, respectively. The volume of the knapsack is expressed as $W = TH \cdot BW$ [17]. The considered problem maximizes the sum responsivity of the system as:

$$
\max_{\mathbf{X}, P_W(\mathbf{X})} \quad \sum_{i \in \mathcal{I}} RD_i \sum_{n \in \mathcal{N}} x_n^i \tag{2}
$$

$$
\begin{aligned}
\text{s.t.} \quad & \mathcal{S}\left(x_n^i\right) \cap \mathcal{S}\left(x_m^j\right) = \emptyset, \\
& \forall n \neq m, \forall n, m \in \mathcal{N}, \forall i, j \in \mathcal{I} && (3) \\
& \mathcal{S}\left(x_n^i\right) \subseteq \left\{\phi, R\left(x_n^i\right)\right\}, \forall i \in \mathcal{I}, \forall n \in \mathcal{N}, && (4) \\
& \mathcal{S}\left(x_n^i\right) \subset \mathbb{S}, \forall i \in \mathcal{I}, \forall n \in \mathcal{N}, && (5) \\
& x_n^i \in \{0,1\}, \forall i \in \mathcal{I}, \forall n \in \mathcal{N}, && (6) \\
& \sum_{i=1}^{|\mathcal{I}|} \sum_{n=1}^{|\mathcal{N}|} x_n^i R\left(x_n^i\right) \leq W, \forall i \in \mathcal{I}, \forall n \in \mathcal{N}. && (7)
\end{aligned}
$$

Here, $P_W\left(\mathbf{X}\right)$ coresponds the order of placed items in 2D-KP because items are put into a bin one by one. The RD_i and x_n^i represent the responsivity and the access status of the n_{th} access request of category i. The requested time-frequency resources are $R\left(x_n^i\right)$, and the actual allocated time-frequency resources is $S\left(x_n^i\right)$. $\mathbb{S}$ indicates the area of the knapsack defined for a fixed ground cell. Constraint (3) shows that the resources occupied by different services must not overlap. Constraint (4) indicates that a request is either satisfied in full, or rejected. Constraints (5) and (6) indicate the range of time-frequency resource allocation and binary decision, respectively. Constraint (7) means that the total amount of accepted requests must not exceed the volume of resources.

The considered problem is an unconstrained, orthogonal knapsack problem [18]. The problem is also semi-online, since that a batch of flows arrived in a time interval is concerned. The semi-online system can lookahead only next few flows, the total demand and duration are unknown a- priori. Due to a large number of visits to urban hotspots, the decision cycle is not long and can increase system revenue, and the

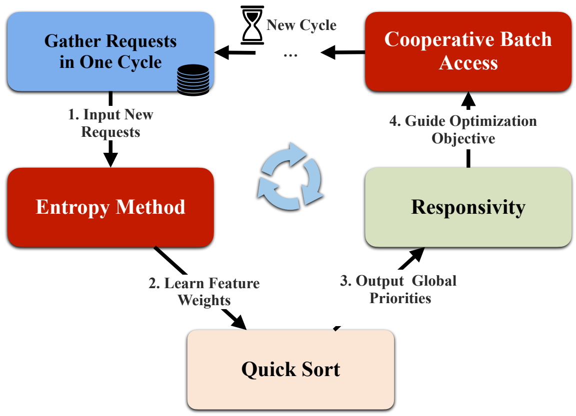

Fig. 3. Responsivity generation process. First, input QoS descriptions of requests into the entropy method. Different feature weights are determined afterwards. Next, the responses are sorted and mapped into responsivity. The global priorities guide the batch access at last.

impact on latency is controllable. The knapsack problem is an NP-complete problem in combinatorial optimization. Many studies have been conducted to develop efficient heuristics that approximate optimal solutions. Genetic algorithms can deal with multiple individuals at the same time, and are unlikely to fall into local optimal solutions instead of the reinforcement learning based pointer network with high computational complexity and long training time [19], [20]. We use a hybrid genetic algorithm for task ordering and then use a deterministic algorithm for allocation in Section III.

III. Entropy Method and Hybrid Genetic Algorithm

A. Entropy Method for Responsivity

The proposed indicator, responsivity, is the a multi-attribute decision problem in essence. The ranking provides an overall view of a set of objects, which is beneficial for the system to grasp the most important information in a short time. A crucial issue is the weight of each attribute in (1). However, the users' demands in dense areas change rapidly, and persistent weights are not suitable. Therefore, this paper uses uncertainty analysis methods to learn the weights of the RD from data, and update in real-time.

Generally speaking, the greater the data difference under a specific attribute, the more diverse the users' needs are. Large differences in data can provide more information and play a greater role in a comprehensive evaluation. If the values are all equal, the index does not work in the assessment. Therefore, this attribute has a higher weight and is vital to provide differentiated guarantee services. Moreover, the weight changes dynamically with the users' preference in each round. Because the randomness and disorder degree of an event can be judged by the value of entropy in information theory, we use the entropy method to calculate weights, as shown in Fig. 3.

The detailed process of the entropy method process is as follows: Standardize the n samples, calculate the weight P_{ij} of the i-th sample under the j-th index, and compute the index entropy value e_j as,

$$e_j = -K \cdot \sum_{i=1}^{n} \left(P_{ij} \cdot \ln \left(P_{ij} \right) \right), \tag{8}$$

where $K = \frac{1}{\ln(n)}$. The method calculates the difference coefficient $d_j = 1 - e_j$, the index weight $w_j = \frac{d_j}{\sum_{j=1}^{m} d_j}$, and finally calculates the comprehensive score of each sample as $z_i = \sum_{j=1}^{m} w_j x_{ij}$.

B. Hybrid Genetic Algorithm

There are two dominating types of algorithms for solving the two-dimensional knapsack problems: deterministic algorithm and non-deterministic algorithm. The former takes the bottom left algorithm and adopts online processing, i.e., the access order is the same as the arrival order. Although it has a low complexity, the near-sighted policy can be very poor in the worst-case scenario. The latter takes the genetic algorithm and uses probability to guide the search direction. Although the performance is improved compared to the former due to offline processing, it needs to design data structures to reflect the geometric relationship among the rectangles []. This paper combines the above two types of algorithms to achieve semi-online batch access. The hybrid genetic algorithm optimizes the access order of requests and maximizes the system QoS. Then, the algorithm based on the bottom left performs resource allocation to pursue the greatest possible resource utilization. This can adapt to the time-varying requests, and also save the effort to design additional data structures with a satisfactory solution in a short period. It can maximize system benefits while guaranteeing possible resource utilization.

The genetic algorithm is a heuristic computational model realized by simulating the process of a biological evolution. It converts the problem to a process similar to the crossover and mutation of chromosome genes in biological evolution through computer simulations. It requires the following components:

$$SGA = \left(\mathcal{C}, \mathcal{E}, \mathcal{P}_0, \mathcal{M}, \phi, \Gamma, \psi, \mathcal{T} \right), \tag{9}$$

where $\mathcal{P}_0$ represents the initial population, and $\mathcal{M}$ represents the population size. The termination condition of the simple genetic algorithm (SGA) is $\mathcal{T}$.

Coding $\mathcal{C}$ greatly affects the search effect and efficiency of the algorithm. This paper uses the permutation coding adapting to the RD. The fitness function $\mathcal{E}$ is the sum of the successful access RD. The selection operator ϕ is a mixture of Elitist selection and a roulette wheel. A two-point crossover Γ and exchange mutation ψ are adopted. According to the termination criterion proposed by Himmeblau, the convergence characteristics of the algorithm is measured by the difference in the mean values of fitness functions between generations as

$$\mathcal{C}_e(s) = \frac{1}{T} \sum_{t=1}^{T} \left[f_e(t+1) - f_e(t) \right], \tag{10}$$

where $f_e(t)$ denotes the average fitness function of the t-th generation in the environment e.

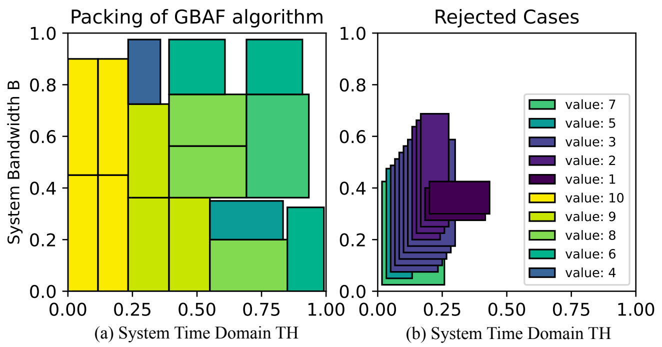

Fig. 4. The visualization of (a) resource occupation for successful access and (b) denied access.

IV. Simulation Results and Discussions

A. Simulation Parameters

The data size in the five-dimensional request obeys the upper truncated Pareto distribution, and its probability density function is

$$f(x) = \frac{\alpha\gamma^{\alpha}}{1-\left(\frac{\gamma}{\nu}\right)^{\alpha}}x^{-\alpha-1}, \quad \gamma \leq x \leq \nu, \tag{11}$$

with $\alpha = 1.1, \gamma = 80$ and $\nu = 200$. The available time-frequency resources obey the uniform distribution $R_b, R_t \sim \mathbb{U}[10, 40]$, the delay threshold T_d is moderately distributed in $\{15, 20, 25, 30\}$. This paper considers ten types of requests, i.e. $RD \in \{1, 2 \cdots 10\}$. The parameters of the genetic algorithm are as follows: the population size *Popsize* $= 40$, crossover probability $p_c = 0.4$, the mutation probability $p_m = 0.1$, and the maximum number of iterations $NC_{max} = 150$. The proportion of initial population generation P_0 is $2:1:2$ for responsivity orientation, random arrangement, and "large task + small task" strategy. Suppose that any request is completed within one batch decision cycle.

B. Simulation Results

Simulation results are discussed from the perspectives of access results, convergence performance, system benefits and RU of the five algorithms, including sequential access, greedy access and three hybrid deterministic genetic algorithms (GBAF, GBL and MRBL) [21]. Sequential access makes online decisions in the same order as the arrivals. Greedy access sorts all requests in one cycle based on their RD, and then allocates resources to requests with higher value. The other three algorithms conform to the aforementioned constraints, but the rules of placing the backpack objects are different. Finally, a qualitative analysis of the delay and power consumption saved by this mechanism is given.

Fig. 4 shows the access situation of the GBAF-based genetic algorithm. At this time, there are 28 normalized access requests in 10 categories. Fig. 4(a) shows the access request and its resource allocation location, and Fig. 4(b) shows the rejected request. Brighter colors indicate higher RD, and darker colors indicate the lower RD. This visualization shows that the hybrid algorithm does prioritize higher responsivity requests and achieve highest possible resource utilization.

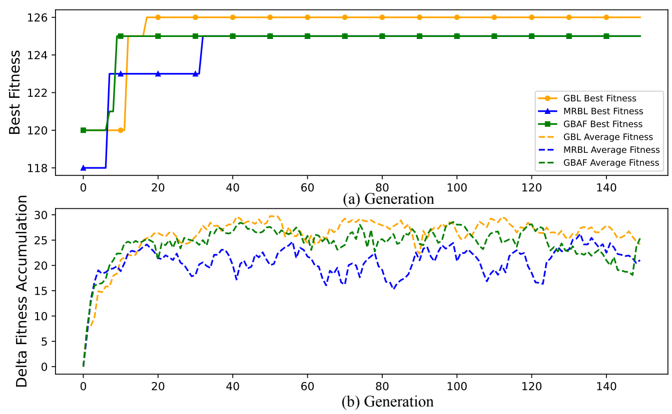

Fig. 5. The evolution of three kinds of hybrid genetic algorithms: (a) The convergence performance and (b) the average fitness per generation.

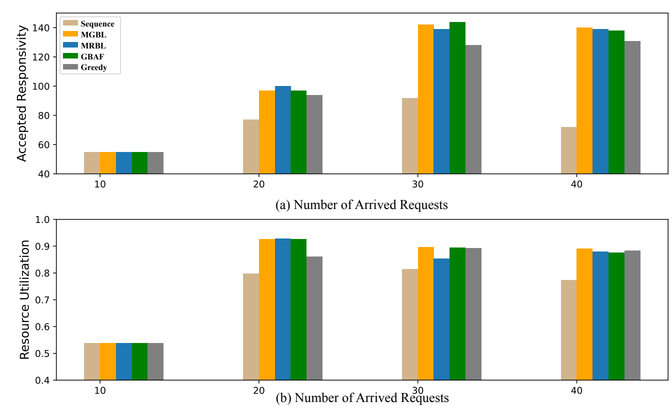

Fig. 6. Comparison of (a) system performance and (b) resource utilization under sequential access, RD-based greedy access and three kinds of genetic algorithm based batch access.

Fig. 5 shows the convergence of three deterministic algorithms based on a genetic algorithm. Fig. 5(a) shows the trend of the best individual fitness function. All three algorithms can converge within 40 generations, of which GBL has the best performance, but MRBL has the fastest convergence performance. Fig. 5(b) provides the average fitness per generation calculated according to the Himmelblau criterion. The general trend is similar to Fig. 5(a), but there are still varying degrees of fluctuation after convergence. This is because the genetic algorithms are not satisfied with local solutions and continue to explore. This is also illustrated by the two-step change in the best fitness of the three algorithms. A network manager can tune the fluctuation range to terminate the search with a satisfactory result.

Fig. 6 shows the performance of the five algorithms on RD and RU under different types and numbers of arrived requests. It is noted that when the total amount of requests is less than the resource envelope, no request is rejected. Each request has the same on RD and RR (the number of arrivals is 10). It is clear that the three mechanisms based on the genetic algorithm are superior to sequential access in RR and RD, and better than greedy access in RD. In most cases, it is better than greedy access in terms of RU. However, in the special case where 30 requests arrive in the third histogram of Fig. 6(b), the RR improvement based on the genetic algorithm is limited. This shows that among the randomly generated 30 arrivals, the user's time-frequency resource requirements are highly dispersed, and the RD is herewith highly correlated with the time-frequency resource requirements. In this case, the greedy algorithm can achieve better RR and RD. Specific performance improvement data is shown in Tab. I. It should be noted that the performance gain is related to a specific arrival situation, and only one kind of arrival is shown here. The third histogram also shows the trade-off relationship between RR and RD, i.e., the RD improvement based on the genetic algorithm is the most prominent 57% and 13%, at the expense of RU 10% and 0.5%. Compared with other arrivals, the increase of RU is the lowest. The uncertainty analysis is currently based on categories, and the specific quantities under different categories can be further considered.

TABLE I
THE PERFORMANCE IMPROVEMENT OF HYBRID GENETIC ALGORITHM BASED BATCH ACCESS.

Compared Algorithm	**Responsivity**			**Resource Utilization**		
	N=20	**N=30**	N=40	N=20	**N=30**	N=40
Sequential Access	+ 30%	**+ 57%**	+ 95%	+ 16%	**+ 10%**	+ 15%
RD based Greedy Access	+ 6%	**+ 13%**	+ 7%	+ 8%	**+ 0.5%**	+ 1%

This paper trades computing power consumption for the benefit of the majority relative to sequential access. And the greedy algorithm based on RD also shows good performance, hence ensuring a balance between RD and RR. Under the specific satellite constellation ground infrastructure capability, a). The time taken by the MBS (collection + decision-making) is shorter, than or similar to the round-trip delay of massive requests between the satellite and the ground; b). The batch decision-making power consumption is lower than the power consumption of the satellite connection from the user group. If the above two conditions are satisfied, the cooperative batch access proposed in this paper can be advantageous.

V. CONCLUSION

This paper proposed a satellite-terrestrial cooperative access mechanism solved by a hybrid genetic algorithm. Exploiting the natural strengths of batch processing and uncertainty analysis, we proposed a global QoS index, responsivity, originating from dynamic large-scale access. It ensured a balance between users and networks benefits. By coordinating multiple users accessing satellites, the proposed scheme could reduce access delay and user power consumption through streamlined process and batch scheme. The scheme considered effectively the reuse of existing network structure and reduced satellite communication deployment costs, paving the way for the large-scale application of satellites.

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