Performance Analysis of Task Offloading in Double-Edge Satellite-Terrestrial Networks

Peng Wang(✉), Xing Zhang, Jiaxin Zhang, and Zhi Wang

Wireless Signal Processing and Networks Lab (WSPN),
Key Laboratory of Universal Wireless Communication,
Beijing University of Posts and Telecommunications (BUPT), Beijing, China
PWang@bupt.edu.cn

Abstract. With the rapid development of wireless networks, the growing number of mobile applications results in massive computation task to be processed. Multi-access edge computing (MEC) can efficiently minimize computational latency, reduce response time, and improve quality of service (QoS) by offloading tasks in the access network. Although lots of MEC task offloading schemes have been proposed in terrestrial networks, the integrated satellite-terrestrial communication, as an emerging trend for the next generation communication, has not taken MEC offloading into consideration. In this paper, we proposed a cooperative offloading scheme in a double-edge satellite-terrestrial (DESTN) network. Performance of offloading efficiency and energy consumption are derived analytically. Simulations show that the proposed offloading scheme in the double-edge satellite-terrestrial outperforms the traditional terrestrial-only offloading scheme by approximately 18.7%. Our research provides an insight for following studies in task offloading of double-edge satellite-terrestrial networks.

Keywords: Satellite-terrestrial network · Offloading scheme · Edge computing

1 Introduction

Recent years have witnessed the explosive growth of communication traffic, and a new communication network architecture is required to provide continuous geographic coverage for services and break the limitation of shortage in local communication and computation resources, saving up energy that services cost, connecting the global especially the remote area and meanwhile, reducing the average service time cycle [1]. To meet the demand resulted from this dramatic change, more effective resource cooperation deployments and distributed task offloading schemes should be proposed [2].

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Satellite communication systems, with the merits of wide coverage and flexible multiple-link capability, break the limitations of terrestrial network and deliver resilient and high-speed connectivity across the globe [3]. Scholars have already envisaged the idea of constructing an integrated satellite-terrestrial communication system to make full use of different resources [4–6]. Many new innovations have already been deployed in the integrated satellite-terrestrial communication, providing higher spectral efficiency of the overall system. Software Defined Networking (SDN) and Network Function Virtualization (NFV) technologies is also used for the realization of End-to-End Traffic Engineering in a combined satellite-terrestrial network used for mobile backhauling [7] and for supporting flexible and customized resource scheduling [8]. Recently there are some explorations on satellite task processing. Challenges and opportunities of onboard computers for small satellites are presented in [9] and the writer focuses upon ideas of hybrid computing and reconfigurable computing. While the emerging technologies mentioned above start to play vital roles in the new 5G system architecture, multi-access edge computing, named by the European Telecommunications Standards Institute (ETSI) [10], has emerged to provides cloud computing capabilities and IT service environments at the edge of the access network. New applications, e.g., interactive gaming, virtual reality, natural language processing and the Internet of Vehicles (IoV), put forward more requirements on the manageability and scalability of the system. Specifically, mobile edge networks provide computing and caching capabilities at the edge of cellular networks [11].

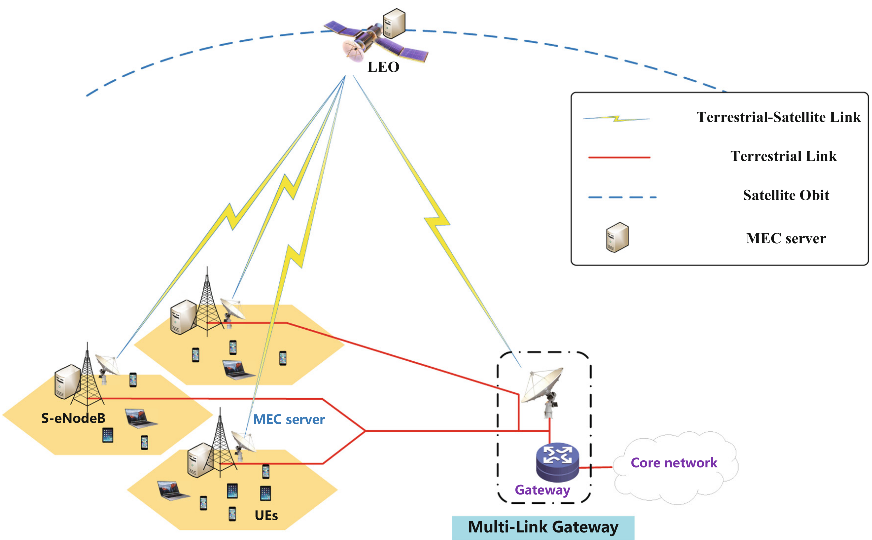

Fig. 1. Double-edge satellite-terrestrial network architecture

Taking advantages of computing ability, multi-access edge computing is a deployment to sink communication resources in the proximity of mobile user equipment (UE), at the same time, allowing users offloading computation tasks to MEC servers and thus enhancing the services experience, especially decreasing the service respond time. Currently there are lots of research works on offloading computation tasks to MEC in communication system. In [12], MEC network is designed to offload the traffic and tackle the backhaul congestion. In [13], each user equipment (UE) offloads its computation tasks to the MEC or cloud server for better performance. In [14], the communication, computing and caching resources are optimized together. Considering small cell network architecture, authors in [15] proposed an offloading scheme by solving energy optimization problem.Although many advancing technologies are deployed in integrated satellite-terrestrial network, few researchers take MEC computing and task offloading into consideration. As MEC server provides extra computation resources, in this paper, we analyze the task offloading efficiency of double-edge satellite-terrestrial networks and evaluate the energy consumption of our proposed scheme in the novel network architecture.

The rest of this paper is organized as follows. The system model of double-edge satellite-terrestrial network is described in Sect. 2. In Sect. 3, we proposed a task offloading scheme according to the new network architecture. Offloading efficiency and energy consumption are derived in Sect. 4. Numerical results are obtained and analyzed in Sect. 5. Finally, we conclude the paper in Sect. 6.

2 System Model

In this section, the double-edge satellite-terrestrial network architecture and the system model are introduced to describe the probability of the number of UEs that a randomly chosen satellite eNodeB (S-eNodeB) has.

2.1 Double-Edge Satellite-Terrestrial Architecture

The proposed double-edge satellite-terrestrial architecture is depicted in Fig. 1. Satellites, equipped with MEC server, form a space network edge of caching and computation resources. Covering the terrestrial base stations from a high altitude, they leverage distributed spot beams offering a continuous service to the specified area. On the terrestrial network edge, each S-eNodeB has a bidirectional link to communicate with satellites, connecting the space and terrestrial parts as an integrated one. Therefore, the proposed architecture has the double-edge network structure to meet computing and caching requirements of various services. Multi-link gateway is utilized in order to connect satellite and terrestrial backhaul for acquiring resources from evolved packet core (EPC) network.

Employing multiple beams over different geographical regions, satellites make use of space division multiplexing effectively for continuous handover. When UEs offload tasks to S-eNodeB, MEC servers distributed in double-edge satellite-terrestrial network will provide cooperative computation capability to reduce service latency.

2.2 System Model

In this section, we consider a double-edge satellite-terrestrial network wherein M S-eNodeBs are located in the coverage of a spotbeam of a satellite, each S-eNodeB has K UEs, which are denoted by $\mathcal{U} = \{1, \ldots, K\}$, we apply CDMA access scheme so that UEs share the same spectrum. Assuming that UE i has a task $Task_i = \{s_i, r_i, t_i^d\}$, $i \in \mathcal{U}$, as notations listed in Table 1. Typically, we assume that in the coverage of one satellite, both S-eNodeB and UE are distributed as classical homogeneous Spatial Poisson Point Processes (SPPP) distribution F. So the probability that a random chosen S-eNodeB have UEs access at the same time is [16]

$$P[N = n] = \frac{3.5^{3.5} \Gamma(n + 3.5)(\lambda_u/\lambda_b)^n}{\Gamma(3.5) n! (\lambda_u/\lambda_b + 3.5)^{n+3.5}}, \tag{1}$$

where $\Gamma(x) = \int_0^\infty \exp(-t) t^{x-1} dt$ is the gamma function, λ_b and λ_u refer to the density of S-eNodeB and UE, respectively.

Table 1. Notation summary.

Notation	Description
$\mathcal{U}$	UE set
s_i	Data size of UE i's computation task (bits)
r_i	Computation resources needed for UE i's task (CPU cycles)
t_i^d	Tolerable delay upper bound of the task (s)
λ_b	Density of S-eNodeB (1/m^2)
λ_u	Density of UE (1/km^2)

Tasks from UEs should be processed by the cooperation of satellite and terrestrial MEC servers, initially it should be transmitted to terrestrial MEC server located in S-eNodeB, the data rate of UE i received by the S-eNodeB is derived as

$$R_i^t = W_t \log_2 \left(1 + \frac{p_{i,m} g_{i,m}}{\sigma^2 + \sum\limits_{l=1}^{M} \sum\limits_{j=1, j \neq i}^{K} p_{j,l} g_{j,m}} \right), \tag{2}$$

where W_t is the wireless channel bandwidth, $p_{i,m}$ refers to transmission power of UE i to the S-eNodeB and $g_{i,m}$ the channel gain, σ^2 is the Gaussian noise.

Similarly, the data rate of terrestrial-satellite uplink m is

$$R_m^{su} = W_s \log_2 \left(1 + \frac{p_{m,s} g_{m,s}}{\sigma^2 + \sum\limits_{l=1, l \neq m}^{M} p_{m,s} g_{m,s}} \right), \tag{3}$$

where W_s is the channel bandwidth between satellite and terrestrial S-eNodeB, $p_{m,s}$ refers to transmission power of S-eNodeB m to the satellite and $g_{m,s}$ the channel gain.

3 Offloading Scheme

The offloading procedure can be divided into two phases: task transmission and task computation. In the double-edge satellite-terrestrial architecture, we propose a cooperative offloading scheme for more effective and reasonable task computation. As Fig. 2. shows, UEs transmit all tasks to the terrestrial MEC server in S-eNodeB, S-eNodeB calculate the priority index of the tasks and decide the task size to be processed in distributed MEC servers, tasks computation operate parallelly at terra and satellite. On the satellite, tasks queue and wait for computing, after finishing the task computation, the results will be converged back to S-eNodeB and are delivered to UEs. Taking up less computation resources, the tasks which have smaller size and are more sensitive to time delay should be served in the first place, at the same time, satellite with computation ability help compute part of tasks. When S-eNodeB receives the tasks from UEs, it sorts the tasks according to priority index β_i, which is denoted as

$$\beta_i = t_i^d / (r_i \cdot s_i) \tag{4}$$

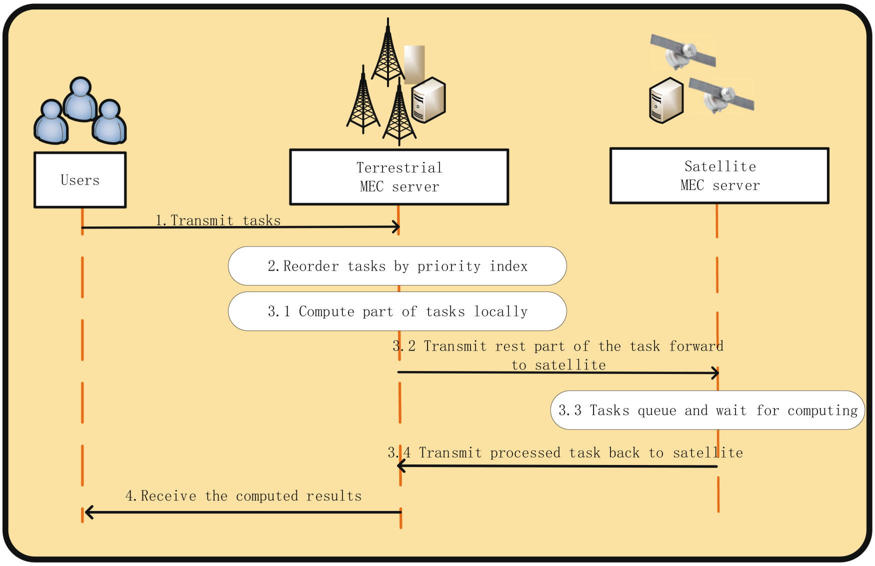

Fig. 2. Offloading scheme of double-edge satellite-terrestrial networks

In the proposed offloading scheme, each task should be divided into two parts according to parameter α. Here we define

$$\alpha = \frac{\beta_i - \beta_{min}}{\beta_{max} - \beta_{min}} \tag{5}$$

Then α percentage of the task should be transmitted and computed at satellite MEC server, remaining the rest of the task to be processed locally. When UE i's task priority index is the minimum β_{min}, then $\alpha = 0$, that means the task should be processed in terrestrial MEC server directly. For UE i's task priority index is the β_{max}, that means the task can tolerate the largest time delay, have the biggest file size and need the most computation resources, we can derive that $\alpha = 1$, then the whole task should be transmitted to MEC server on satellite.

The total time cost for task of UE i can be denoted by

$$T_i = T_i^P + T_i^{TR} + T_q, \tag{6}$$

where T_i^P refers to time cost of UE's task for being completely computed T_i^{TR} denotes transmission time which need to finish the task, and T_q is the time delay when task waits in the queue, if $T_i > t_i^d$, then UE's task will be abandoned.

Besides, we define task need to be computed in $T_i^c = r_i/f_0$, where f_0 is the computation capability of MEC server.

4 Performance Analysis

4.1 Total Latency

In our proposed architecture, from a systematic perspective, we mainly focus on the ability of offloading scheme efficiency, which means the ability of network to process tasks during a period of time. Thus UE's queuing time can be ignored, UE i's total latency will be calculated by $T_i = T_i^P + T_i^{TR}$, as task should be first transmitted to terrestrial MEC server, the transmission time cost is $T_i^{TR} = s_i/R_i^t$, tasks from UEs will be computed parallelly at satellite and terrestrial MEC servers, the computing time cost in terrestrial MEC server T_t^c and satellite MEC server T_s^c will be

$$T_t^c = (1-\alpha)r_i/f_{\mathrm{t}} \qquad T_s^c = \alpha r_i/f_s, \tag{7}$$

where f_{t} stands for computation capability of terrestrial MEC server, and f_{s} the computation capability of satellite MEC server. And the time cost for transmitting tasks uplink to satellite $T_s^{tr\_up}$ and downlink from satellite $T_s^{tr\_down}$ are

$$T_s^{tr\_up} = \alpha s_i/R_m^{su} \qquad T_s^{tr\_down} = \alpha s_i/R_m^{sd}, \tag{8}$$

where R_m^{su} is uplink transmission rate of satellite and R_m^{sd} refers to downlink transmission rate. Finally, the time cost for task is calculated as

$$T_i^P = max\left\{T_t^c, T_s^{tr\_up} + T_s^{tr\_down} + T_s^c\right\} \tag{9}$$

In the proposed scheme, tasks from UEs are divided into two parts, one is for terrestrial MEC servers, the other is for satellite MEC server. UE's whole task time will be

$$T_{total}^{c} = max\left\{ \sum_{i=1}^{K} \frac{(1-\alpha_i)r_i}{E\{f_t\}}, \sum_{i=1}^{K} \left(\frac{\alpha_i r_i}{E\{f_s\}} + \frac{\alpha_i s_i}{R_m^{su}} + \frac{\alpha_i s_i}{R_m^{sd}} \right) \right\}, \tag{10}$$

the first part is the time cost of MEC server on terra and the second part refers to time cost on satellite, therefore, the total time for the task is

$$\begin{aligned} T_{total} = E\{\sum_{i=1}^{K} T_i^{TR}\} + T_{total}^{c} &= P[N=K]\sum_{i=1}^{K} T_i^{TR} + \sum_{i=1}^{K} T_i^{P} \\ &= \frac{3.5^{3.5}\Gamma(K+3.5)(\lambda_u/\lambda_b)^K}{\Gamma(3.5)K!(\lambda_u/\lambda_b+3.5)^{K+3.5}}\sum_{i=1}^{K} T_i^{TR} + \sum_{i=1}^{K} T_i^{P} \end{aligned} \tag{11}$$

To evaluate the performance of offloading scheme, offloading efficiency is defined as

$$\eta = r_{total}/T_{total} = \sum_{i=1}^{K} r_i/T_{total} \tag{12}$$

4.2 Energy Consumption

The total energy consumption is comprised of energy cost for transmitting tasks and the energy for task computation in MEC servers, for UE i, energy can be derived as:

$$e_i = p_{i,m}T_i^{TR} + p_{m,s}T_s^{tr} + p_c r_i, \tag{13}$$

where p_c is the power of MEC server when computing the tasks. The total energy consumption in the system is the sum of each UE's energy consumption e_i

$$E = \sum_{i=1}^{K} e_i \tag{14}$$

5 Numerical Results

In this section, simulation results are proposed in comparison with conventional terrestrial architecture which takes no satellite MEC server into consideration. The simulation is based on Matlab R2016b. In Table 2, we list important parameters. For simplicity, we consider 1 satellite MEC server, 1 terrestrial MEC server. λ_b and λ_u are 1/km^2 and 2/km^2, respectively. The total wireless bandwidth is 5 MHz, and the transmission power is ranging from 50 mW to 100 mW randomly. CPU Cycles required by UE's task is randomly distributed between 0.1 G and 2 G, we assume that terrestrial and satellite MEC computing capability is $f_t, f_s \in (1, 10)$, respectively. For LEO satellite uplink, Effective isotropic radiated power (EIRP) and bandwidth is 54.4 dBW and 3 MHz while the downlink

Table 2. Simulations parameter values [15].

Parameter	Min	Default	Max
UEs access to S-eNodeB	5	–	35
Task size	1 Mb	–	30 Mb
Background noise	–	100 dBm	–
Pathloss factor	–	4	–
Energy cost of MEC server	–	4 J/Hz	–

40.2 dB and 5 MHz, taking Eutelsat KA-SAT for reference, the downlink transmission rate is 20 Mbits/s, the wavelength of the carrier is 137.3 mm and the satellite operating altitude is 800 km, here we ignore the rain attenuation.

Figure 3 illustrates the offloading performance between the offloading scheme which simply leverage terrestrial MEC server and cooperative scheme we proposed in the double-edge satellite terrestrial architecture. The UE's task sizes are randomly distributed between 1 to 5 Mbits, 5 to 15 Mbits and 15 to 35 Mbits.The results show that the relationship between the number of UE and the offloading performance, from the results, we can make a conclusion that the offloading scheme performance which we proposed can improve approximately 18.7% than terrestrial MEC server only offloading scheme. It also illustrates that when number of UEs is small, transmission rate is high, so tasks with bigger data size have a better offloading performance. As the number of UEs and the amount of task size become larger, transmission bit rate on backhauls become lower thus transmission time would be the mainly part of the whole-time cost, although it can affect offloading efficiency, under this circumstance, the proposed scheme still gets a better performance.

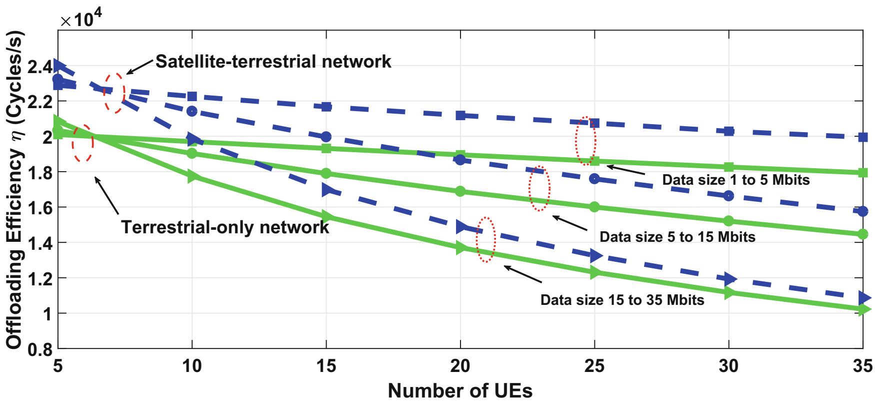

Fig. 3. Comparison of offloading efficiency η between terrestrial-only offloading scheme and double-edge satellite-terrestrial offloading scheme with different numbers of UE

In Fig. 4., we also evaluate the energy consumption in our proposed scheme versus number of UE. When the size of the task becomes larger, the energy consumption also increases, the reason of this phenomenon main lies in the transmission cost and computation cost.

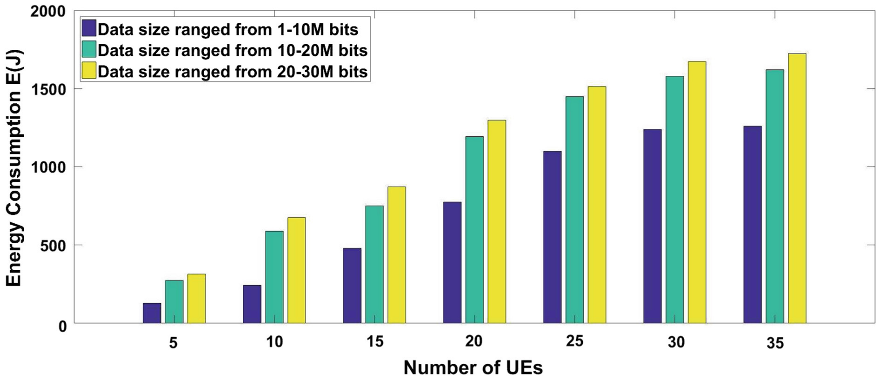

Fig. 4. Energy consumption versus the size of the offloading data in double-edge satellite-terrestrial networks

In summary, compared with the traditional terrestrial-only offloading scheme, the offloading scheme we proposed in the double-edge satellite and terrestrial architecture could improve the average offloading efficiency by nearly 18.7%, as the number of UE and the tasks' size increase, the energy consumption of the proposed offload-ing scheme will also become larger.

6 Conclusion

In this paper, under the background of a new architecture of DESTN, by using terrestrial and satellite MEC server, we analyze two key performance indicators of offloading scheme considering satellite and terrestrial resource cooperation. The simulation results show that the proposed scheme in satellite-terrestrial network can improve the average offloading efficiency by nearly 18.7% than terrestrial-only scheme and the energy consumption of the proposed offloading scheme will also become larger. In future, more complicated cooperative task offloading schemes between satellite constellations and terrestrial networks will be proposed.

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