Towards High Energy Efficiency Contact Plan Design in Collaborative Data Offloading in Space Information Network

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Abstract. Space information network (SIN) consisting of communication satellites plays an important role in information acquisition and transmission. An increasing volume of data produced by different space missions is forwarded by satellites to ground stations (GSs), which leads to satellites that are responsible for forwarding being overload and data cannot be timely downloaded to GS. Moreover the dynamic and complex SIN operating environment deteriorates the performance of data downloading. Thus, for improving data downloading, it is a key to realize data load balance. That means extra data is offloaded to other satellites having extra downloading capacity with an effective scheduling method. To this end, we modeled collaborative data offloading problem as multi-objective mixed integer nonlinear programming (MOMINLP) problems based on developing time-evolving graph (TEG) and contact plan. Due to its computational complexity, we proposed a heuristic approach with phasing based on contact plan, i.e., phased offloading algorithm (POA) operating on a slot-by-slot basis, to jointly schedule data offloading among the satellites and data downloading from satellites to the GS. Simulation results demonstrate that, in many cases, the proposed algorithms can guarantee relatively high data downloading throughput and low energy consumption produced by data offloading.

Keywords: Space information networks · Data offloading · Contact plan design · Optimization

1 Introduction

Recently, with deep exploration of space, space information network (SIN) gradually attracts human's attention and becomes hot research field [1]. A SIN may consist of many satellites or satellite constellations at different orbits. These satellites separately or cooperatively accomplish different space missions, such as earth observation, scientific measurement and so on [2]. And a large volume of data would be generated (e.g., the NASA Earth observing system is able to totally collect 27.9 TB/day data from diverse observing missions [3]). Through the SIN, these data from different space missions can be real-timely transmitted to ground stations (GSs) and processed on orbit with cooperative mechanisms. It is well-known that Low Earth Orbit (LEO) satellites

M. Jia et al. (Eds.): WiSATS 2019, LNICST 280, pp. 412–424, 2019.
https://doi.org/10.1007/978-3-030-19153-5_43

are significant part of SIN for this reason that they have many advantages of shorter propagation and better signal quality [4]. However, LEO satellite's downlink contact time is limited. For instance, a typical LEO satellite can access a certain GSs location for less than 10 min within the system period of approximately 100 min [5]. The problem of data offloading during data downloading can be regard as a transmission scheduling problem that focus on data exchanging from satellite nodes to one or more GSs. Most of the existing work pays attention to scheduling algorithms to schedule data exchanging (or download) from satellites to a single or multiple GSs. In literature [6], the concept of Satellite Range Scheduling (SRS) is first proposed to describe the problem of scheduling data communication. Usually, satellites have limited resources such as data buffer, energy buffer and so on. Based on the resource constraints, Gooley et al. modeled this problem using Mixed Integer Programming (MIP), and designed a heuristic algorithm to solve it. In literature [7], Barbulescu et al. firstly analyzed Single-Resource Range Scheduling (SiRRS) problem and proved that it is NP-complete. Then they studied the Multi-Resource Range Scheduling (MuRRS) problem, a genetic algorithm is proposed to find near-optimal solutions. From inspiration of the contact graph routing (CGR) scheme, an event-driven time-expanded graph (EDTEG) is employed to characterize multi-resource variations over the dynamic space environment [8]. And based on the EDTEG, observation resource and transmission resource are jointly considered, and an integer linear programming optimization problem is formulated to maximize the sum priorities of successfully scheduled tasks. However, above research work hardly consider the inter-plane links (ISLs) to improve the performance of data downloading. In [9], Jia et al. designed a collaborative scheme that allows satellites to offload data among themselves using inter-satellite links (ISLs). And simulations based on cooperated simulated software were carried out. The simulation results showed that their scheme can promote the performance of data downloading significantly. However, their work for the problem of data downloading has no generic mathematical model and they only consider the data downloading throughput without energy consumption from data offloading. To sum up, for data downloading, existing work hardly consider ISLs helping data downloading to the GS meanwhile considering energy consumption.

The main contributions of this paper are summarized as follows. Firstly, based on contact plan and time-expanded graph, we formulate a offloading data problem with the aim of maximizing network throughput and minimizing energy consumption produced by data offloading coupling multiple time slots as a multi-objective mixed-integer linear programming (MOMINLP). Secondly, by exploiting the predictable mobility of satellites, we design a heuristic approach to improve data throughput and meanwhile reduce energy consumption.

The remainder of this paper is organized as follows. Section 2 describes the system model. An offloading data problem is formulated as a multi-objective optimization problem on the contact plan to trade off throughput and energy consumption in Sect. 3. Then in Sect. 4, we analyze structure of optimization problem and characteristics of offloading in SIN. We design a heuristic algorithm to improve performance of offloading under the limited resources network. Section 5 presents a series of simulation and analysis results. Finally, conclusions are drawn in Sect. 6.

2 System Model

2.1 Network Model

As shown in Fig. 1, some users (aircrafts, satellites et al.) utilize the relay satellite network to indirectly deliver their information to GSs which are defined as $G = \{g_1, g_2 \ldots, g_n\}$. The relay satellite network consists of a set of satellites $S = \{s_1, s_2 \ldots, s_n\}$, which have ability of high speed communication and data transmission. These space missions are modeled in data traffic, which is defined as $F = \{f_1, f_2 \ldots, f_n\}$. We mainly focus on data offloading during data downloading. Satellites download data only when they move into the coverage of the GSs. Besides the establishment of ISLs also need satisfying some conditions [10]. Due to dynamic and predictive motion of satellite, we exploit Time-Evolving Graph (TEG) [11] to characterize network resources and capture the topology evolution of the network duration data offloading.

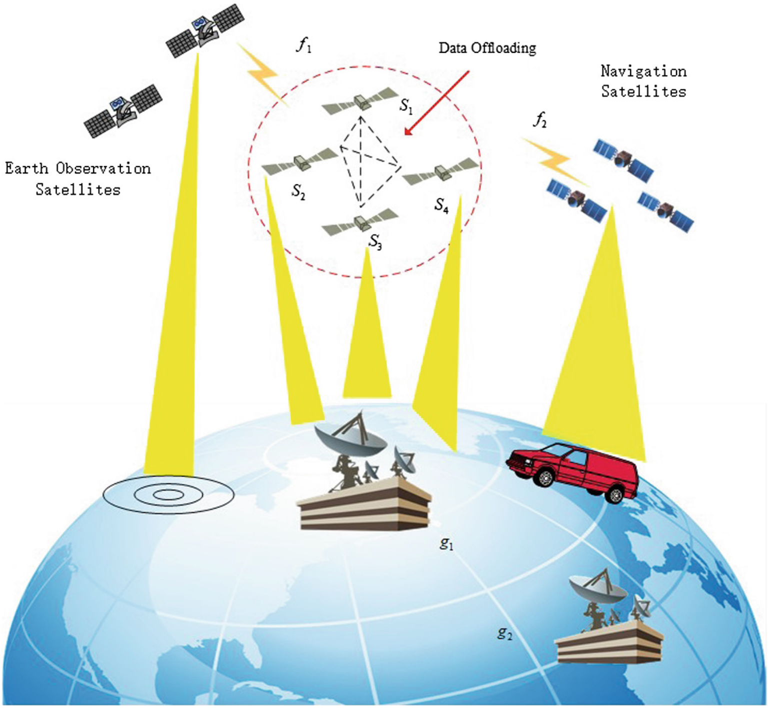


Fig. 1. Space backbone network model

2.2 Graph Model

The TEG consists of T layers which represent consecutive time slots indexed by $t \in \Gamma = \{1, 2 \ldots k \ldots T\}$. The time of data offloading lasts T slots. Each time slot lasts duration of τ and in every slot network states is regard to keep unchanged. We donate the TEG as $G(V^t, E^t)$, where V^t and E^t represent the set of vertices and edges in t-th layer. Figure 2 shows data offloading and downloading in terms of TEG.

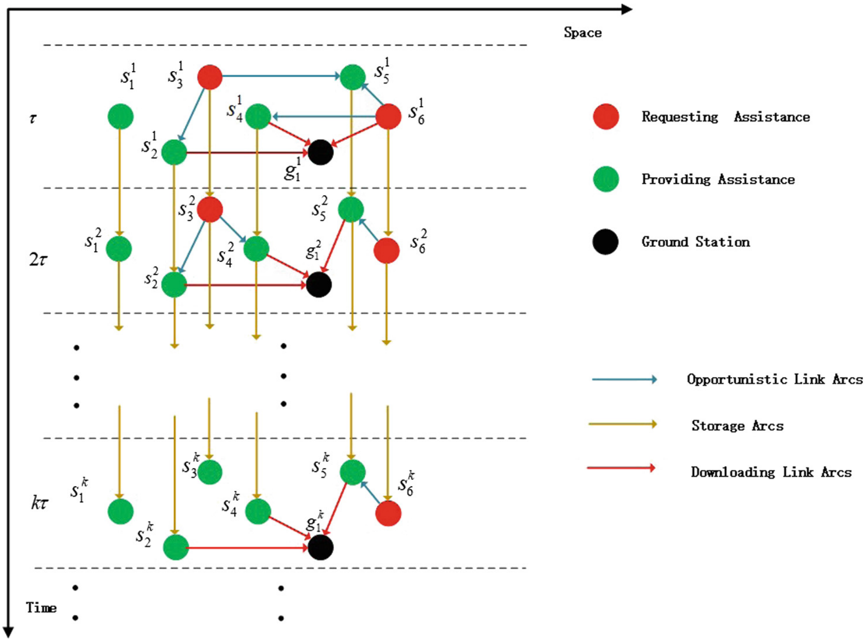


Fig. 2. Time-evolving graph (Color figure online)

For each slot, the vertices of correspond to the replicas of satellites and GSs denoted as $V = V_s \cup V_g$, where $V_s = \left\{ s_i^t | s_i \in S, 1 \le t \le T \right\}$ and $V_g = \left\{ g_i^t | g_i \in G, 1 \le t \le T \right\}$. These vertices representing satellites have two states depending on the mismatching level of data volume being downloaded and downloading capacity. Actually, each satellite contacts with the GS with limited time. The length of contact window represents its downloading capacity under a certain downloading data rate. Whether the satellite providing assistance helping data offloading or not depends on its data load when the satellite accesses to a station ground (e.g., when the data volume carried in the satellite exceeds the downloading capacity, the satellite offloads data to other satellite with lighter data load). Thus satellites keeping in coverage of GS have two states: one is called 'Requesting Assistance' where $V_{s-r}^t = \{ s_i^t | s_i \in S, 1 \le t \le T \}$, s_i^t requests to offload their data in the t-th slot; another is 'Providing Assistance' where $V_{s-p}^t = \{ s_i^t | s_i \in S, 1 \le t \le T \}$, s_i^t can help other satellites offloading data in the t-th slot. These satellites will form a bipartite graph shown in Fig. 3. During data offloading, satellites in V_{s-r}^t may form a pair with those in V_{s-p}^t in each slot.

In Fig. 2, there are three kinds of arcs, i.e., opportunistic link arcs (blue arcs), downloading link arcs (red arcs) and storage arcs (brown arcs). Opportunistic link arcs

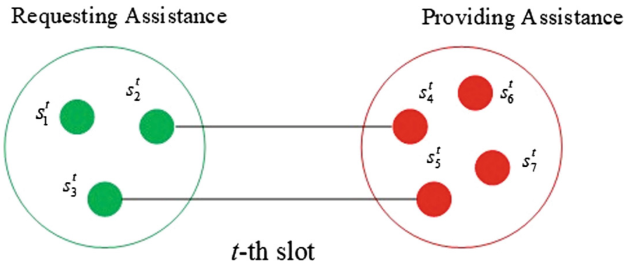


Fig. 3. Bipartite graph in the t-th slot

are potential communication links among satellites, i.e., satellite to satellite (S2S) in each time slot, where $E_{ss} = \{(s_i^t, s_j^t)|1 \leq t \leq T\}$, s_i^t and s_j^t can establish an ISL in t-th slot$\}$. And the weight of opportunistic link arcs denoted as $W = \{w_{ij}^t|1 \leq t \leq T\}$ w_{ij}^t is transmission cost from s_i^t to s_j^t, $s_i^t \in V_{s-r}^t, s_j^t \in V_{s-p}^t\}$ represents the cost of transmitting data. The downloading link arcs are denoted as $E_{sg} = \{(s_i^t, g_j^t)|1 \leq t \leq T\}$, s_i^t is in the coverage of g_i in the t-th slot. Denoted as $E_d = \{(s_i^t, s_i^{t+1})|s_i^t \in V_s, 1 \leq t \leq T\}$, storage arcs represent the ability of satellites to store data between the consecutive time slots. According to the work [12], discussion in later sections is based the assumption that satellites have two transponders for other one satellite and a GS respectively. And the GS can establish links within a certain number of satellites at the same time.

3 The Problem Definition

In data downloading, we formulate the data offloading problem to maximize downloading data and minimize energy consumption under constraints of data buffer, transponders and satellite' orbiting movement as an optimization problem.

Contact Constraints: In each slot, a satellite has a chance to establish several potential ISLs with other satellites. However, according to Sect. 2, each satellite has only one transponder for ISL in one slot. Thus, concerning with data offloading among satellites, we introduce a set of boolean variables

$$x(s_i^t, s_j^t) = \{0, 1\}, (s_i^t, s_j^t) \in E_{ss} \tag{1}$$

$x(s_i^t, s_j^t)$ is equal to 1 if and only if link (s_i^t, s_j^t) is active in t-th time slot and 0 otherwise. Due to the fact that each satellite connects other one satellite, we impose

$$\sum_{s_j^t \in V_{s-p}^t} x(s_i^t, s_j^t) \leq 1 \quad \forall \quad s_i^t \in V_{s-r}^t \tag{2}$$

$$\sum_{s_j^t \in V_{s-r}^t} x(s_j^t, s_i^t) \leq 1 \quad \forall \quad s_j^t \in V_{s-p}^t \tag{3}$$

And for restricting bi-directionality on the contact selection of satellite to satellite links, we have

$$x(s_i^t, s_j^t) = x(s_j^t, s_i^t) \tag{4}$$

Transmission Constraints: Signal transmitted is affected by the attenuation, ambient noise, transmission power and so on. Assuming additive white Gaussian noise (AWGN) channel, Shannon's capacity formula provides the achievable transmission rate [13] as

$$R = W \log_2(1 + \frac{P_{ij}^t h_{ij}^t}{\sigma^2}) \tag{5}$$

Where W is the bandwidth and σ^2 is the noise power. P_{ij}^t and h_{ij}^t are the transmission power and the channel gain between the satellite i and j respectively in t-th time slot. h_{ij}^t is a function of, free-space attenuation, sensitivity of receiver and antenna gain. In this paper, we mainly consider contribution of free-space attenuation to transmission power.

For simplifying problem, based on the formula (5), we utilize transmission power P_{ij}^t to control the volume of delivering data in each slot. Moreover, on the condition of limited resource, we consider each satellite joining offloading has a limited data buffer which is equal to itself downloading capacity $C_s = C_{s-r} \cup C_{s-p}$ where C_{s-r} and C_{s-p} correspond to state of 'Requesting Assistance' and 'Providing Assistance' defined in Sect. 2.

$$\sum_{s_i^t \in V_{s-r}, (s_i^t, s_j^t) \in E_{ss}}^{T} x(s_i^t, s_j^t) * \tau * \log_2(1 + \frac{P_{ij}^t h_{ij}^t}{\sigma^2}) \leq C_{s-p} \quad \forall \quad s_j^t \in V_{s-p} \tag{6}$$

$$\sum_{s_j^t \in V_{s-p}, (s_i^t, s_j^t) \in E_{ss}}^{T} x(s_i^t, s_j^t) * \tau * \log_2(1 + \frac{P_{ij}^t h_{ij}^t}{\sigma^2}) \geq \beta_i C_{s-r} \quad \forall \quad s_i^t \in V_{s-r} \tag{7}$$

Where τ is length of a slot. Satellites' capacity of receiving data is varying with time. During the offloading process, we are deserved to forbid data overflow in each satellite from V_{s-p} shown in constraint (6). The constraint (7) denotes that satellites from V_{s-r} need to guarantee a certain volume of data to offload to others, where β_i is scale factor.

Optimization Problem Formulation: According to the above depicted constrains, we formulate the effectively collaborative data offloading problem based on TEG. The problem is to select and schedule a subset of satellites to balance data load in energy-efficient slot window so that data can be download to GSs as much as possible. Two objectives are proposed: one is to maximize throughput of downloading data; another is to minimize energy consumption produced by offloading data. The throughput maximization and energy consumption minimization (TMEMP) can be formulated as follows:

$$\begin{aligned} &\max \sum_{(s_i^t, s_j^t)\in E_{ss}}^{T} x(s_i^t, s_j^t) * \tau * W * \log_2\left(1 + \frac{P_{ij}^t h_{ij}^t}{\sigma^2}\right) \\ &\min \sum_{(s_i^t, s_j^t)\in E_{ss}}^{T} x(s_i^t, s_j^t) P_{ij}^t \tau \\ &s.t \quad (1) - (7) \end{aligned} \tag{8}$$

From the formulation (8), we can observe that the problem falls into the category of multi-objective mixed integer nonlinear programming (MOMINLP) problems [14] which is computationally intractable. It's well known that MOMINLP is a NP-hard problem whose computational complexity depends on the number of integer variables [15]. Based on TEG and contact window, multi-phase collaborative scheduling is applied to data offloading, which can decrease the computational complexity.

4 Algorithm

The data offloading algorithm runs on the TEG and the bipartite graph. In reality, the GS does not know the data load of each satellite until it accesses to the GS. We limit the offloading operation occurring in a set of satellites which are contacting with GS and within one hop [9]. And data should be offloaded as soon as possible. Based on above assumptions, we can divide the contact window graph during time T into several phases (numbering these from 1 to n) so as to efficiently balance data load and conform to reality. The dividing criterion is that, the moment of each satellite accessing GS is set as beginning moment of each phase shown in Fig. 4.

In every phase, we introduce to a bipartite graph as discussed in Sect. 3 to reflect that satellites can join data offloading. For every satellite, we need to keep track of its initial load state at the beginning of each phase. For the phase $m \in [1, n]$, we introduce the following notations summarized in Table 1:

At the beginning of each phase, satellites would report these load state F_i^m to GS. And then the GS put satellites into different groups as described in Fig. 3. When $F_i^m > C_i^m$, v_i^m is belongs to V_{s-r}^m; When $F_i^m < C_i^m$, $v_i^m \in V_{s-p}^m$ means having more download time to help others. After insuring the scope of satellites joining in offloading data, in each phase, we exploit to hybrid particle swarm optimization (HPSO) [16] combining with penalty function to solve MOMINLP. Due to the fact that the multi-objective optimization problem involves maximizing data throughput and minimizing total energy consumption produced by offloading data, we utilize energy efficiency to choose ideal solutions.

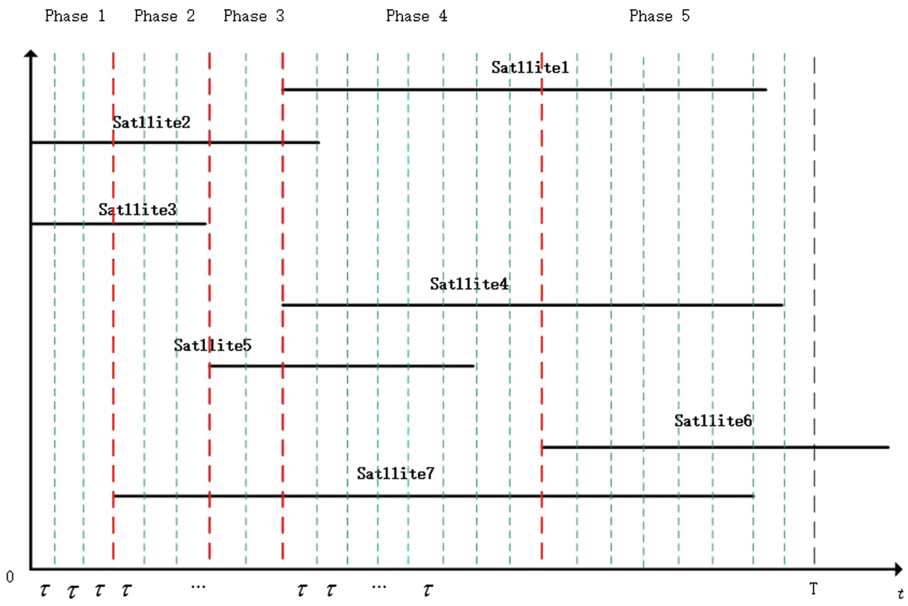


Fig. 4. Phasing of data offloading

Table 1. I Notations used in our algorithm

Symbol	Definition
v_i^m	Satellite i in phase m
V_{gs}	Subset of V_s that have contact with the GS $V_{gs} = \{V_{gs}^1, \ldots, V_{gs}^n\}$ and $V_{gs}^m = \{v_1^m, \ldots, v_j^m\}$ in phase m
V_{s-r}^m	Subset of V which request to offload data to others in phase m
V_{s-p}^m	Subset of V which help other satellites offloading data in phase m
V_{s-n}^m	Subset of V do not participate in data offloading in phase m
T^m	Period of phase m
F_i^m	Amount of remaining data of S_i at beginning of phase m
C_i^m	Downloading capacity in phase m

$$\eta^m = \frac{E^m}{O^m} \tag{9}$$

Where E^m and O^m are energy consumption produced by offloading data and offloading data volume respectively. The algorithm is described as followed

Algorithm 1 Phased Offloading Algorithm (POA)

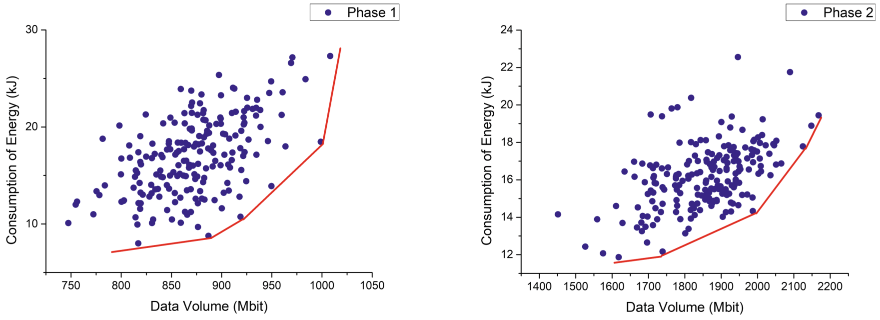
```
// Initialization
for $s_i \in S$ do
    Initial allocation of $F_i$;
end
// Insure the scope of satellites joining in offloading data
for $m<n$ do
    For $v_i^m \in V_{gs}^m$ do
        Classify $v_i^m$ into $V_{s-r}^m$ or $V_{s-p}^m$
    end
    / /data offloading
    Construct Time-Evolving Graph.
    Construct a bipartite graph for node sets for phase $m$
    Solve the TMEMP, and obtain the solutions $x^m(t)$ and $P^m(t)$ based on maximum energy efficiency.
    Update $F_i^{m+1}$, $\forall$ $v_i^{m+1} \in V_{gs}^{m+1}$;
    m=m+1
end
```

5 Simulation Results

Our simulations are conducted on the Globalstar constellation [9] with 8 orbital planes and 6 satellites each. The inter-plane is 60°. And satellite orbit height is 1414 km with an orbit inclination angle of 52°. We assign bandwidths of 16.5 MHz and 33 MHz for ISL communication and satellite-ground communication respectively. The GS is set at Xi'an (34°N, 108°E). We build up Globalstar constellation based on STK that can produce a contact plan. And the optimization algorithm operated in MATLAB is used to find the solutions of scheduling problem. The time slot period τ is set as 10 s. And we choose a period from 19 Jul, 2018 at 04:00:00 UTC to 19 Jul, 2018 at 04:30:00 UTC as simulation time. The data in satellites is collected in advance. Besides, we normalize data load as a ratio of receiving capacity of GS and fix data downloading rate of each satellite. Thus, we defined the volume of which excessive data can be downloaded to GS successfully as downloading throughput concisely called throughput

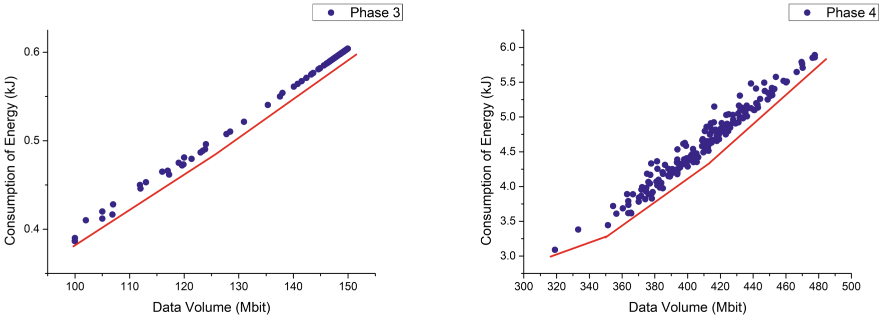
$$Throughput = \sum_{i=1}^{N} (F_i^o - \hat{F}_i^o) / \sum_{i=1}^{N} F_i^o \tag{10}$$

Where, for the satellite s_i, F_i^o is data volume excessing its downloading capacity before scheduling corresponding to that $\hat{F}_i^o$ after scheduling. And during the period of simulation, we randomly choose some satellites as those needing to offload data to others. The data volume is set at 80–100% of downloading capacity of satellites. According to the simulation results, this process of data offloading lasts six phases. Some feasible solutions of each phase shown in Fig. 5



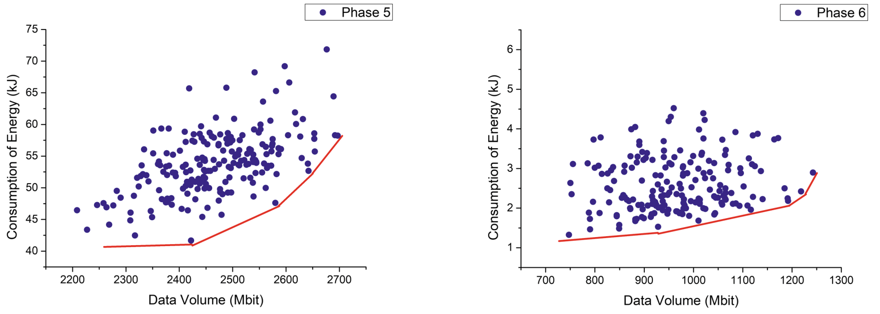
(a) Phase 1

(b) Phase 2



(c) Phase 3

(d) Phase 4



(e) Phase 5

(f) Phase 6

Fig. 5. Solutions of data offloading (Color figure online)

Due to the fact that the data offloading problem is MOMINLP, there exists trade-off between transmitting data volume and energy consumption during the period of data offloading. For each phase, the different length of scheduling time decides on the difference of the number of optimization variables. And our developing HPSO with penalty function can effectively find the Pareto Fronts [14] of TMEMP in each phase shown as red line in Fig. 5. In each phase, the choosing of ideal solution is based on max energy efficiency. Moreover, to evaluate the performance of the proposed POA, we compare them with the CoDld proposed in the literature [9] on the condition of data load which are 30%, 60% and 90% of downloading capacity called 'low overload', 'medium overload' and 'high overload' respectively. These results of throughput and energy consumption are presented in Figs. 6 and 7.

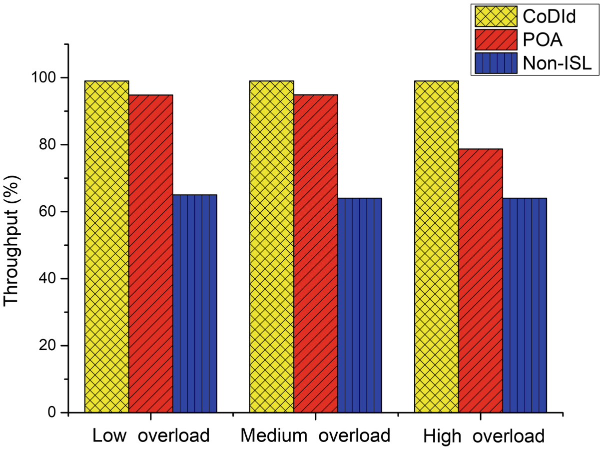


Fig. 6. Throughput under different overloads

From the Fig. 6, under three levels of overload, the CoDld method has best performance of data offloading which can nearly approach to 100% throughput. The proposed POA can help satellites downloading almost 90% overload data to GS under low overload and medium overload. When the overload data volume is high (reaching 90%), the throughput still reach 80% based on the POA. Although the performance of the POA has a small gap comparing with the CoDld under high overload, the POA is far better than the scheduling without ISLs (Non-ISL). Actually, the target of saving energy should be responsible for the gap between CoDld and POA. From the Fig. 7, with increasing of overload, offloading data need more and more energy. However, under each level of overload, energy consumption using POA is less than that using CoDld. Especially under low and medium overload, energy consumption using CoDld is the nearly double of that using POA,which are 45.4 kJ and 67.6 kJ correspond to 23 kJ and 32 kJ. This is because, based on TEG, our algorithm can make use of slots of having low transmission energy cost to deliver data among satellites.

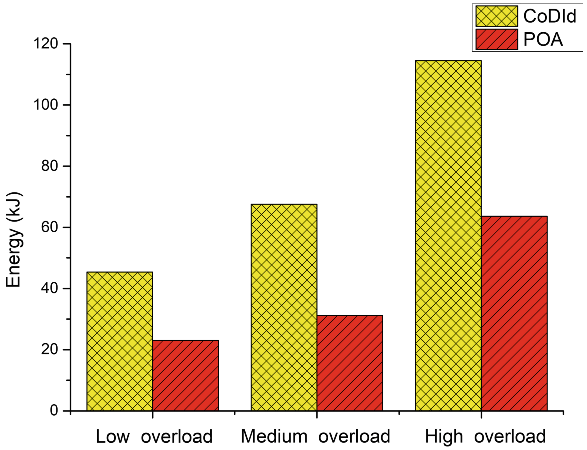


Fig. 7. Energy consumption under different overloads

6 Conclusion

In this paper, we investigate the problem of data offloading during the period of data downloading, such that satellites carrying a large number of data will offload data to these with low data load according to the length of their contact time with GS. The target is that the throughput of data downloading will increase and meanwhile energy consumption will be reduced as much as possible. We combine phasing based on contact plan and a heuristic approach, i.e., POA operating on a slot-by-slot basis, to achieve high performance of data offloading. Extensive simulations have been conducted evaluate to newly proposed POA based on Satellites Took Kit (STK) and MATLAB. Comparing with CoDld and data downloading without ISLs, the POA can guarantee relatively high throughput and low energy consumption produced by data offloading.

Acknowledgement. This paper is supported by program 'National Key R&D Program of China' (2016YFB0502402).

References

1. Du, J., Jiang, C., Guo, Q., et al.: Cooperative earth observation through complex space information networks. IEEE Wirel. Commun. **23**(2), 136–144 (2016)
2. Sheng, M., Wang, Y., Li, J., et al.: Toward a flexible and reconfigurable broadband satellite network: resource management architecture and strategies. IEEE Wirel. Commun. **24**(4), 127–133 (2017)
3. The role and evolution of NASA' s earth science data systems [EB/OL]. http://ntrs.nasa.gov. Accessed 21 June 2018
4. Jian, Y., Yuan, Z., Zhigang, C.: Reverse detection based QoS routing algorithm for LEO satellite constellation networks. Tsinghua Sci. Technol. **16**(4), 358–363 (2011)

5. Du, J., Jiang, C., Qian, Y., Han, Z., Ren, Y.: Resource allocation with video traffic prediction in cloud-based space systems. IEEE Trans. Multimed. **18**(5), 820–830 (2016)
6. Gooley, T., Borsi, J., Moore, J.: Automating air force satellite control network (AFSCN) scheduling. Math. Comput. Model. **24**(2), 91–101 (1996)
7. Barbulescu, L., Watson, J.P., Whitley, L.D., et al.: Scheduling space-ground communications for the air force satellite control network. J. Sched. **7**(1), 7–34 (2004)
8. Wang, Y., Sheng, M., Zhuang, W., et al.: Multi-resource coordinate scheduling for earth observation in space information networks. IEEE J. Sel. Areas Commun. **36**(2), 268–279 (2018)
9. Jia, X., Lv, T., He, F., Huang, H.: Collaborative data downloading by using-satellite links in LEO satellite networks. IEEE Trans. Wirel. Commun. **16**(3), 1523–1532 (2017)
10. Wu, T.Y., Wu, S.Q.: Performance analysis of the inter-layer inter-satellite link establishment strategies in two-tier LEO/MEO satellite networks. J. Electron. Inf. Technol. **30**(1), 67–71 (2008)
11. Zhou, D., Sheng, M., Wang, X., et al.: Mission aware contact plan design in resource-limited small satellite networks. IEEE Trans. Commun. **65**(6), 2451–2466 (2017)
12. Sandau, R., Roeser, H.P., Valenzuela, A.: Small Satellite Missions for Earth Observation. Springer, Heidelberg (2010). https://doi.org/10.1007/978-3-642-03501-2
13. Alagoz, F., Gur, G.: Energy efficiency and satellite networking a holistic overview. Proc. IEEE **99**(11), 1954–1979 (2011)
14. Mela, K., Koski, J., Silvennoinen, R.: Algorithm for generating the pareto optimal set of multiobjective nonlinear mixed-integer optimization problems. In: Aiaa/asme/asce/ahs/asc Structures, Structural Dynamics, and Materials Conference (2007)
15. Zhu, R., Wang, H., Gao, Y., Yi, S., Zhu, F.: Energy saving and load balancing for SDN based on multi-objective particle swarm optimization. In: Wang, G., Zomaya, A., Perez, G. M., Li, K. (eds.) ICA3PP 2015. LNCS, vol. 9530, pp. 176–189. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-27137-8_14
16. He, Y.J., Chen, D.Z.: Hybrid particle swarm optimization algorithm for mixed_-integer nonlinear programming. J. Zhejiang Univ. (Eng. Sci.) **42**(5), 747–751 (2008)