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Fast lightweight reconfiguration of virtual constellation for obtaining of earth observation big data

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Abstract Earth observation (EO) big data is playing the increasingly important role in spatial sciences. To obtain adequate EO data, *virtual constellation* is proposed to overcome the limitation of traditional EO facilities, by combining the existing space and ground segment capabilities. However, the current configuration pattern of virtual constellation is tightly coupled with the specific application requirements. This leads to the costly reconfigurations. Although the pattern of software defined satellite network can decouple topology reconfigurations from application requirements, it cannot be directly applied to the reconfigurations of virtual constellations because of some drawbacks. To address the problem, we propose a model of LEO-ground links control-covering (LGLC) to implement fast and lightweight reconfiguration for virtual constellation. LGLC uses a bipartite graph model to formalize the dispatch problem of the control information of virtual constellation reconfiguration, and the optimum solution can be got by the classical algorithm in polynomial time. According to the strategy obtained, only if a few satellites and stations receive the control information, virtual constellation can be reconfigured quickly. We also establish some metrics to evaluate the effect of LGLC. Extensive experiments are conducted to confirm the above claims.

Keywords Earth observation big data · Virtual constellation · Software defined satellite network · Network topology reconfiguration

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Nomenclature

$\mathcal{T}$	The set of timeslots
V_G	The set of GEO satellites
V_L	The set of LEO satellites
U_L	The set of LEO satellite-footprints ($U_L = V_L \times \mathcal{T}$)
V_S	The set of ground stations
$C_m^{(l)}(t)$	The VCL consumption of satellite l covering m ground stations in timeslot t
$C_{(s)}^n(t)$	The VCL consumption of station s covered by n LEO satellites in timeslot t
$Q_1(g,u)$	The burden rate of the controlling endpoint g on CTL $\langle g,u\rangle$ ($g \in V_G, u \in U_L$)
$Q_2(g,u)$	The burden rate of the controlled endpoint u on CTL $\langle g,u\rangle$ ($g \in V_G, u \in U_L$)
Q_I	The global burden rate of controlling endpoints
Q_{II}	The global burden rate of controlled endpoints
$Q_c(g,u)$	The burden rate of CTL $\langle g,u\rangle$ ($g \in V_G, u \in U_L$)
Q_C	The global burden rate of CTLs
Q_F	CTL fairness
$v \vdash t$	CTL fairness
OHL	The one-hop link between a LEO satellite and a ground station
ISL	The link between two LEO satellites
IGL	The link between two ground stations
CTL	The control link between a GEO satellite and a LEO satellite (or ground station)
VCL	Virtual covering link
UTVG	Unifying time-varying graph
TVG	Time-varying graph
CC	Control-covering

ICC	Immediate control-covering
EO	Earth observation
MWVC	The minimum weighted vertex cover

1 Introduction

With the help of advances in spatial information technologies, earth observation (EO) has entered the era of *big data* [1–4], and EO big data will play an important role in the decision-making of spatial sciences [5,6]. Currently, EO data primarily is from scientific satellites. As it is difficult to address EO data from single satellite sensors or platforms due to the limitation of data availability and sensor capabilities, *virtual constellation* [7] has been proposed to overcome this limitation by combining and panning existing observations [8–10]. The Committee on Earth Observation Satellites (CEOS) defines virtual constellation as a "set of space and ground segment capabilities that operate in a coordinated manner to meet a combined and common set of Earth Observation requirements." As application-oriented EO systems, virtual constellations will have different topologies when facing different requirements [8,11–13]. This leads to that the topologies of virtual constellations often need to be reconfigured for obtaining adequate EO big data. The current work about the configurations of virtual constellations is based on the specific application requirements. For example, the virtual constellation for monitoring the ocean surface topography and the virtual constellation for global terrestrial monitoring have the different configuration patterns [8,11], and different applications need different panning and scheduling [9,14,15]. Since the configurations of virtual constellations are tightly coupled with the application requirements, frequent topology reconfigurations will increase the burden of segments and waste much resources [8].

The reconfiguration costs of virtual constellations can be reduced if a uniform pattern independent of applications is implemented. Therefore, we utilize the pattern of software defined satellite network (SDSN) [16–18] to reconfigure virtual constellations. SDSN, as the application instance of software defined networks (SDN) [19,20] in satellite networks [21–24], decouples data plane functions from control plane functions in satellite networks [16]. A typical SDSN architecture [17,18] is shown in Fig. 1. Geostationary Orbit (GEO) satellites and Network Operations Control Center (NOCC) compose the *control plane* [18] that generates the the control information of topology reconfigurations; the service satellites (Low Earth Orbit (LEO) satellites, mostly) and ground facilities compose the *data plane* which just needs to receive and forward the control information and execute the reconfigurations [17,25]. The dispatch of reconfiguration information is in charge of GEO satellites by broadcasting, since three GEO satellites can implement global coverage [17,18]. In this paper, the control information of virtual constellation reconfigurations is called the ***GEO control information*** (GCI).

Current SDSN pattern cannot still be directly applied to the reconfigurations of virtual constellations because of some drawbacks. Primarily, as the altitude of GEO is much higher than that of LEO but the number of GEO satellites is much less than that of LEO satellites and ground stations, to keep fast control all the time, GEO satellites usually need larger transmitting power to lower signal attenuation; LEO satellites and ground stations also need larger antennas to receive signal. This may bring much work-load burden for satellites and stations [26]. Moreover, since virtual constellation is based on the existing facilities, extra control facilities is usually not be allowed as in the traditional SDSN. To control all the topologies of virtual constellations, GEO satellites have to cover all the segments by broadcasting in real-time, even though some segments may be unsuitable for receiving GCI sometimes (e.g. the restriction of energy consumption). This may bring more waste of link resources. These drawbacks will be harmful to the reconfigurations of virtual constellations, because they reduce the flexibility and efficiency of virtual constellations and harden the resource management in virtual constellations.

To address these problems, this paper proposes a model of *LEO-ground links control-covering* (LGLC) to implement the fast lightweight reconfiguration of virtual constellation. According to the LGLC model, GEO satellites use multicast but not broadcast to dispatch GCI; only a few *suitable* LEO satellites and ground stations are selected to receive GCI from GEO satellites, and then they forward the GCI to others by fast links. By this way, our work bring the following contributions:

- As it is not necessary to cover all the LEO satellites and ground stations all the time for GEO satellites, the onboard burden of satellites and stations is reduced.
- As only the *most suitable* LEO satellites and ground stations receive GCI from GEO satellites, the utilization of communication links are increased.

Both items are in favor of that GCI is fast spread to update the reconfigurations of virtual constellations in real time.

The reminder of this paper is organized as follows. We introduce the backgrounds and problem in Sect. 2. Section 3 proposes the corresponding mathematic model. The specific methodology is explored in Sect. 4 and the evaluation metrics are established in Sect. 5. In Sect. 6, we evaluate the performance of LGLC by experiments. The paper is concluded in Sect. 7.

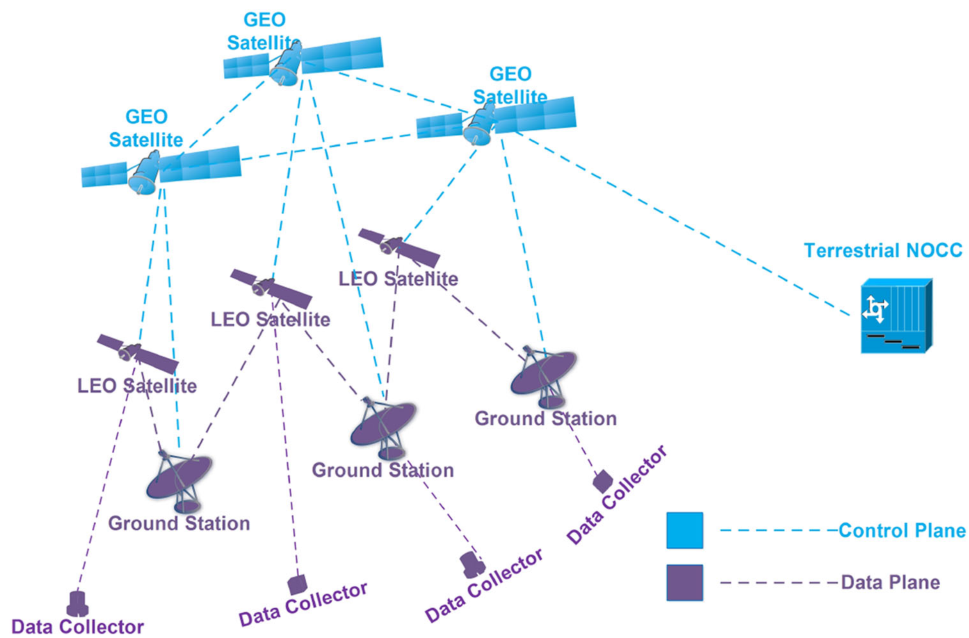

Fig. 1 The typical SDSN architecture. The control plane is composed of GEO satellites and NOCC, where NOCC is in charge of the computation and generation of the *control information* of virtual constellation reconfigurations, and GEO satellites dispatch the *control information* to the data plane. The data plane consists of LEO satellites and ground facilities which can include ground stations and kinds of data collection terminals (data collectors)

2 Backgrounds and problem

2.1 Preliminaries

To accurately describe the problem in our work, we first introduce some important concepts about SDSN.

Definition 1 *SDSN Segments.* An SDSN is composed of three **segments**: the GEO satellites, the LEO satellites and the ground stations. Besides, because SDSN is time-varying, the time should be considered. The corresponding sets are defined as: V_G, the set of GEO satellites; V_L, the set of LEO satellites; V_S, the set of ground stations, and $\mathcal{T}$, the set of timeslots.

In this work, we consider four kinds of links in SDSN, as shown in Fig. 2: the One-hop Link (OHL, as defined in Definition 2) between LEO satellite and ground station, the inter-satellite link (ISL) between LEO satellites, the inter-ground-station link (IGL) between ground stations, and the control link (CTL) which straightly dispatches the GCI from GEO satellite to LEO satellite (or ground station). The GEO satellites are called the ***controlling endpoints***; the LEO satellites and the ground stations of CTLs are called the ***controlled endpoints***.

Definition 2 *One-hop Link (OHL) between LEO satellite and ground station.* The link without any relay between a LEO satellite and a ground station is called a one-hop link (an OHL) and a pair of nodes (LEO satellite and ground station) of an OHL are considered to be adjacent.

Moreover, we propose two presumptions to simplify the work.

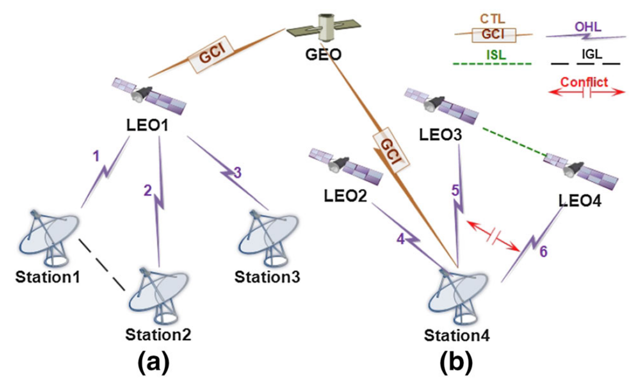

Fig. 2 The scenario of four kinds of links in SDSN. **a** A GEO satellite covers LEO1 which covers three ground stations. There is one CTL and three collision-free OHLs (1,2,3), and an IGL exists between two neighbouring stations without collision. **b** The GEO satellite also covers Station4 which is covered by three LEO satellites (2,3,4). There is one CTL and three OHLs. A collision exist between OHLs 5 and 6 which can communicate with each other by an ISL

P1 Only if a LEO satellite can cover a station in a timeslot, there is an OHL between them.

P2 If two OHLs sharing the same LEO satellite (or ground station) conflict with each other, there should be an IGL (or ISL) between their respective ground stations (or LEO satellites).

Remark 1 P1 means that an OHL can only exist between a LEO satellite and a ground station which are visible to each other. However, it does not indicate that there must be $n (n > 1)$ OHLs when a LEO satellite can cover n ground stations (or n satellites cover a station). In the real-world applications, some constraints such as the swinging range of antenna, the power constraint and so on, can bring the conflict between two OHLs. To tune the effects of constraints in this paper, we pose P2 to simplify the work.

Remark 2 P2 suggests that two neighbouring LEO satellites (or ground stations) could exchange data by their local link. It is agreement with the principle of SDSN construction that the small-scale update of links should utilize ISL and IGL [17]. As LEO satellite runs fast and the overpass time is very short, two satellites (or stations) with conflicted OHLs are usually close to each other, and then ISL (or IGL) can work. Note that ISL or IGL can exist only if two satellites or stations are close to each other, whether there are conflicted OHLs or not.

To describe the states of LEO satellites and ground stations receiving GCI by different links, the following definition is proposed.

Definition 3 *Control-covering (CC) & Immediate Control-covering (ICC).*

(1) The LEO satellites and ground stations receiving the GCI are called control-covering (CC) nodes. Specially, if a CC node can by CTL receive the GCI from the GEO satellite, it is called an immediate control-covering (ICC) node.
(2) If an ICC node $v \in V_L \cup V_S$ can forward the received GCI to its adjacent nodes in a timeslot $t \in \mathcal{T}$ by OHL, it is expressed as $v \vdash t$; moreover, any CC node v' (may be v) receiving the GCI is expressed as $v' \Vdash t$.

As shown in Fig. 2, all LEO satellites and ground stations are the CC nodes, but only LEO1 and Station4 are the ICC nodes which receive the CGI straightly from GEO.

2.2 LGLC problem

Our task is to find a lightweight pattern to fast spread GCI in SDSN. The term "*lightweight*" means that the selected controlled endpoints should have the least resource consumption; the term "*fast*" means that all GCI should be spread on the one-hop links by the controlled endpoints. In this section, we bring forward a *LEO-ground links control-covering* (LGLC) model to quantitatively describe this problem.

Based on Definition 3, the relation schema about different satellites and stations can be simplified as a bipartite graph, which can clearly express the problem of the GCI multicast of SDSN. To build the graph, we first propose the definition of virtual covering link.

Definition 4 *Virtual Covering Link (VCL).* The virtual covering link between LEO satellite and ground station is defined as:

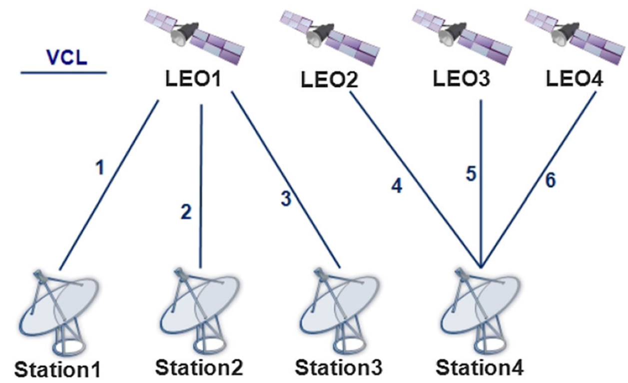

Fig. 3 The VCLs in SDSN, corresponding to the scenario in Fig. 2. Assume that link 5 but not link 6 is used because a collision between them, as shown in Fig. 2. VCLs 1,2,3,4,5 is physically equivalent to links 1,2,3,4,5 in Fig. 2 because there is no collision between links 1,2,3,4,5. In this situation, VCL 6 can be established to represent the relation between Station4 and LEO4. Note that VCL 6 does not exist physically, and it is essentially a logical combination of link 5 and the ISL between LEO3 and LEO4 in Fig. 2

(1) if LEO satellite l is an ICC node that covers m ground stations in a timeslot t, it is considered that there are m VCLs between l and m stations. The resource consumption of the VCLs (*VCL consumption*) of l is expressed as $C_m^{(l)}(t)$;
(2) if ground station s is an ICC node that is covered by n LEO satellites in a timeslot t, it is considered that there are n VCLs between s and n satellites. The VCL consumption of s is expressed as $C_{(s)}^n(t)$;

Remark 3 Definition 4 means that: if the OHLs between a CC node and its adjacent nodes are collision-free, the VCLs are equivalent to the physical OHLs; if there are the conflicted OHLs between a CC node and its adjacent nodes, the VCL denotes the logical but not physical relation which is physically composed of an OHL and some ISLs (or IGLs). Furthermore, as the communication among satellites and stations is usually bidirectional, for simplification, all the VCLs in this paper are treated as undirected links unless otherwise specified.

An example of VCL is shown in Fig. 3.

Based on the concepts above, we bring forward the definition of *LGLC*.

Definition 5 *LEO-ground links control-covering (LGLC).* Given a set of LEO satellites, V_L, and a set of ground stations, V_S, and a set of timeslots of LEO-Ground links, $\mathcal{T}$, how to find a group of ICC nodes from V_L and V_S, which have the minimum total VCL consumption, to make all VCLs between V_L and V_S exist. LGLC can be expressed as:

minimize:

$$\sum_{l \in V_L, t \in \mathcal{T}}^{l \vdash t} C_m^{(l)}(t) + \sum_{s \in V_S, t \in \mathcal{T}}^{s \vdash t} C_{(s)}^{n}(t), \tag{1}$$

subject to:

$$\forall v \in V_L \cup V_S, \exists t \in \mathcal{T}, v \Vdash t, \tag{2}$$

where operators $\cup$ and $\Vdash$ is consistent with the significations in Definition 3: $V_L \cup V_S$ signifies the union of V_L and V_S, and $v \Vdash t$ signifies that v can receive the GCI in timeslot t.

It can be seen from Formulas (1) and (2) that the physical meaning of LGLC is to select the controlled endpoints with the least resource consumption ("*lightest*") to spread GCI on the one-hop links ("*quickly*").

3 The multicast model vis bipartite graph

As the LGLC is based on the bipartite graph composed of VCLs, we can use the model of bipartite graph to formalize the LGLC. In fact, the LGLC problem can be transformed into the *minimum weighted vertex cover* (MWVC) problem of a bipartite graph. Given a weighted bipartite graph $G = (U \cup V, E)$ with a weight function $W : U \cup V \to \mathbb{R}^+$, where U, V and E represent left vertices, right vertices, and edges, the MWVC problem is to find a subset $V' \subseteq U \cup V$ such that for any $e = \langle u, v \rangle \in E$, at least one of u or v is contained in V' and $\sum_{v \in V'} W(v)$ is minimized.

We first describe the VCLs by the time-varying graph (TVG)[1] [27]. Let $V_L \cup V_S$ be the vertex set of a graph and the VCLs be the time-varying edges of the graph, then we can built a time-varying graph G_0 as the following:

$$G_0 = (V_L \cup V_S, E, \omega, \rho, \mathcal{T}),\ \ \rho : E \times \mathcal{T} \to \{0, 1\};$$
$$\omega : (V_L \cup V_S) \times \mathcal{T} \to \mathbb{R}^+, \tag{3}$$

where ρ is called *presence* function [28] which indicates whether a given edge is available at a given time, and the weight function ω corresponds to the VCL consumption in Definition 4. As the VCL consumption in different timeslots may be different, ω is also time-varying, which is different from the conventional TVG. An example can be seen in Fig. 4

If we regard all the ICC nodes (such as "$l \vdash t$" and "$s \vdash t$") in Formula (1) as the "selected" vertex subset V' in G_0, and regard the resource consumption of the VCLs as the vertex weight function, the constraint in Formula (2) actually means that all edges in G_0 should be covered by V'. The LGLC problem is essentially the timed MWVC problem of G_0: finding a series of ICC nodes with their own timeslots, to make all the vertices in G_0 be CC nodes.

[1] A time-varying graph $G = (V, E)$ is a dynamic graph where every edge has a lifetime, and the edge is available only at a given time.

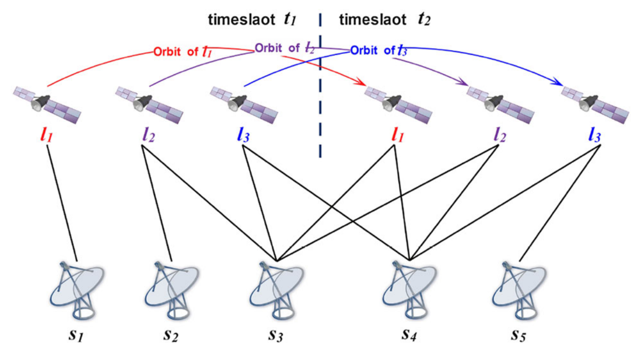

Fig. 4 The TVG representing the VCLs in different timeslots. There are three LEO satellites (l_1, l_2, l_3) and five ground stations (s_1, s_2, s_3, s_4, s_5). As the satellites moves by their respective orbits, 11 VCLs are established: five VCLs in timeslot t_1 and six VCLs in timeslot t_2, respectively

The introduction of time makes the MWVC problem more complex, so we use a unifying TVG (UTVG) model [27] to represent the LEO-Ground links to tune the effects brought by time. The UTVG decomposes a vertex into a series of time status, and every time status is regarded as a *virtual vertex*. By this means, the original time-varying edges can be reviewed as the static edges between the virtual vertices, and the UTVG can be treated like a static graph. In this paper, we take the ground surface as the reference where the ground stations are considered to be static and only the LEO satellites are dynamic. Then status of a satellite in a timeslot is seen as a ***LEO satellite-footprint***, and the TVG G_0 in Formula (3) can be transformed into a UTVG G_T as the following:

$$G_T = (U_L \cup V_S, E, \omega_T),$$
$$U_L = V_L \times \mathcal{T}\ \omega_T : U_L \cup V_S \to \mathbb{R}^+, \tag{4}$$

where U_L is called ***the set of LEO satellite-footprints***. Therefore, ***the controlled endpoint is essentially a LEO satellite-footprint or a ground station.***

According to the physical meaning, a proposition can be stated as the following:

Proposition 1 *As both OHLs and CTLs are the time-varying links related with timeslots,*

- *an OHL is essentially a link between a LEO satellite-footprint and a ground station;*
- *a CTL is essentially a link between a GEO satellite and a LEO satellite-footprint (or ground station).*

Correspondingly, the scenario in Fig. 4 can be represented by a UTVG, as shown in Fig. 5.

Remark 4 Note that we do not add any link between LEO satellite-footprints in the UTVG, so the UTVG here is a

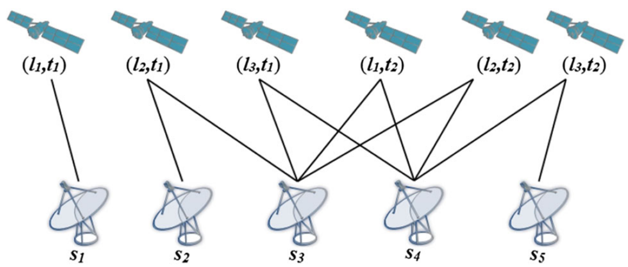

Fig. 5 The UTVG representing the time-varying VCLs. The time-varying status of every satellite in Fig. 5 is regarded as a static *LEO satellite-footprint* such as (l_i, t_j), where $i = 1, 2, \ldots, 5$ and $j = 1, 2$. The VCLs in t_1, t_2 are mapped onto the static edges between the LEO satellite-footprints and the stations in the UTVG

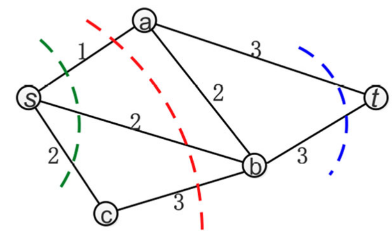

Fig. 6 Three *s*-*t* cuts of a graph. The *numbers* beside the edges signify the weights of the edges. The *dashed line* in *blue* represents a cut with weight equal to 6(3 + 3), which is $\{\langle s, a\rangle, \langle s, b\rangle, \langle s, c\rangle\}$. The *dashed line* in *red* represents a cut with weight equal to 6(1 + 2 + 3), which is $\{\langle s, a\rangle, \langle s, b\rangle, \langle c, b\rangle\}$. The *dashed line* in *green* represents the minimum cut with weight equal to 5(1 + 2 + 2), which is $\{\langle a, t\rangle, \langle b, t\rangle\}$ (Color figure online)

bipartite network. The foundation is that we consider in this paper *the satellites in different timeslots, even the same satellite, should have different GCI.* In our work, all the controlled endpoints (LEO satellites and ground stations) in the same timeslot should quickly get GCI, so a piece of GCI should as far as possible have the same structure and there is no necessary to cover different timeslots in the same GCI.

Now we can establish the formalized model of ***UTVG-based LGLC*** : Given the weighted bipartite UTVG $G_T = (U_L \cup V_S, E, \omega_T)$, where ω_T corresponds to the VCL consumption in Definition 4, the LGLC problem is to find a subset of controlled endpoints, $V' \subseteq U_L \cup V_S$, such that for an arbitrary $e = \langle u, v\rangle \in E$, at least one of u or v is contained in V' and $\sum_{v \in V'} \omega_T(v)$ is minimized.

4 Methodology of fast multicast

To get the optimal solution of the fast multicast in SDSN, based on the model proposed in Sect. 3, we translate the LGLC problem into the minimum cut problem in graph. The optimal solution can be obtained in polynomial time.

4.1 Minimum cut problem

Definition 6 *Cut in Graph* [29]. Given a graph $G = (V, E)$, a cut $C = (S, T)$ is a partition of V into two subsets S and T. The *cut-set* of a cut $C = (S, T)$ is the set of edges that have one endpoint in S and the other endpoint in T, denoted by $\{(u, v) \in E \big| u \in S, v \in T\}$. If s and t are specified vertices of the graph G, then an **s-t cut** is a cut in which s belongs to the set S and t belongs to the set T.

Definition 7 *Minimum Cut* [29]. In an undirected weighted graph, the weight of a cut is defined by the sum of the weights of the edges crossing the cut, and the minimum cut of the graph is a cut that has the minimum weight.

Figure 6 displays an instance of *s*-*t* cuts of a undirected weighted graph.

In fact, the minimum cut problem in an arbitrary undirected weighted graph can be solved by the Stoer-Wagner algorithm in polynomial time. Therefore, if we can transform the LGLC problem into the minimum cut problem in undirected weighted graph, we can get the optimum solution to the LGLC problem.

4.2 From LGLC to minimum cut

The LGLC problem can be transformed into the minimum cut problem. Given a bipartite UTVG $G_T = (U_L \cup V_S, E, \omega)$, the transformation is performed by the following steps:

– First, add a *source* vertex f_s and a *target* vertex s_t, and then the new vertex set is constructed as $V' = \{f_s\} \cup U_L \cup V_S \cup \{s_t\}$.
– Second, establish $|U_L|$ edges between f_s and all the left vertices in U_L, and $|V_S|$ edges between s_t and all the right vertices in V_S, respectively. Then a new edge set is constructed as $E' = E \cup \{\langle f_s, u\rangle | u \in U_L\} \cup \{\langle v, s_t\rangle | s_t \in V_S\}$.
– Third, construct an edge weight function $\omega'_T : E' \to \mathbb{R}^+$, as the following equation:

$$\omega'_T(x, y) = \begin{cases} \omega_T(y), \text{ for } x = f_s \wedge y \in U_L. \\ \infty, \text{ for } x \in U_L \wedge y \in V_S. \\ \omega_T(x), \text{ for } y = s_t \wedge x \in V_S. \end{cases} \quad (5)$$

– Finally, a weighted undirected graph $G'_T = (V', E', \omega'_T)$ is constructed.

Notice that in this transformation, G is a graph with *weighted vertices*, however G' is a graph with *weighted edges*. In G', the weight of every edge between the added vertex (f_s of s_t) and the original vertex (in U_L or V_S) is set the weight of the original vertex; the weights of the original edges (in E) are all set infinity (∞).

Remark 5 As shown in Fig. 7b, the weights of the original edges are all supposed to be infinity (∞). Note that the weight

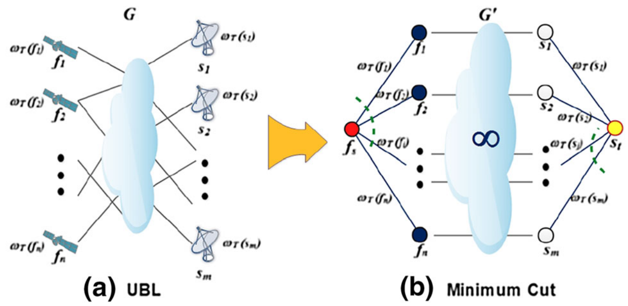

Fig. 7 The transformation from LGLC to Minimum Cut. The figure **a** displays a bipartite graph G which consists of n LEO satellite-footprints $(f_1, f_2, \ldots, f_n)$ and m ground stations $(s_1, s_2, \ldots, s_m)$, and the VCLs between them. The weights of vertices in G are listed beside the vertices. The figure **b** displays the graph G' which has two more vertices (the source vertex f_s in *red* and the target vertex s_t in *yellow*) than G. In G', the weights of $\langle f_s, f_i \rangle$ and $\langle s_j, s_t \rangle$ are set $\omega_T(f_i)$ and $\omega_T(s_j)$, respectively; the weight of $\langle f_i, s_j \rangle (i = 1, 2 \ldots, n; j = 1, 2, \ldots, m)$ is supposed to be ∞. For the minimum cut problem of G', as all the edges with weight ∞ cannot be selected, the minimum cut must be composed of the minimum weighted edges such as $\langle f_s, f_i \rangle$ and $\langle s_j, s_t \rangle$. Comparing G' with G, we can find that the minimum cut of G' corresponds to the minimum weighted vertex cover of G, as marked by *green dashed lines* in (**b**) (Color figure online)

of ∞ cannot be configured really in a connected graph. However, we can substitute a sufficiently large value for ∞. For example, in Fig. 7b, the weights of the original edges can be set to $w_m = \sum_{i=1}^{n} \omega_T(f_i) + \sum_{j=1}^{m} \omega_T(s_j)$. In this situation, G' is still a connected graph. As each $\omega_T(f_i)$ or $\omega_T(s_j)$ must be less than w_m, all the edges with weight w_m cannot be selected to compose the minimum cut.

By the transformation, selecting a set of vertices with the minimum weights in G is equivalent to selecting a set of edges with the minimum weights in G'. Note that the latter is essentially the minimum cut problem of G'. An example is shown in Fig. 7. In conclusion, the LGLC problem in this paper can be equivalently transformed into the minimum cut problem of a undirected graph.

4.3 Calculation of minimum cut

The Stoer-Wagner algorithm is a recursive algorithm to solve the minimum cut problem in undirected weighted graphs [30]. The essential idea of this algorithm is to shrink the graph by merging the most intensive vertices, until the graph only contains two combined vertex sets. After each shrinking, the weight of the merged cut would be stored in a list. Finally, the minimum weight cut in the list will be the minimum of the graph.

In this paper, we straightly use the Stoer-Wagner algorithm to solve the LGLC problem by the transformation discussed in Sect. 4.2. About the details of the Stoer-Wagner algorithm, please read literature [30]. According to the Stoer-Wagner algorithm, the computation complexity of solving the LGLC problem is $O_{LGLC} \sim O\big(|E|(|U_L| + |V_S|) + (|U_L| + |V_S|)^2 log(|U_L| + |V_S|)\big)$.

5 Evaluation metrics

Since the objective of LGLC is to find the lightest controlled endpoints to quickly spread GCI in SDSN, the effect of LGLC should be evaluated and the corresponding metrics need to be established.

Notice that there are several important polices in our work:

- *once the controlled endpoints are selected, the corresponding CTLs and OHLs are also selected*;
- *the transmission speed of CTL is much lower than that of OHL because the altitude of GEO is much higher than that of LEO*;
- *the transmission speeds of all the links (CTLs, OHLs, ISLs and IGLs) in SDSN are determined by the physical parameters of application scenarios but not by LGLC*.

Based on these ideas, for a UTVG $G_T = (U_L \cup V_S, E, \omega_T)$ as formalized in Formula (4), we explore several evaluation indices for the effect of LGLC.

5.1 Evaluation metrics of OHLs

As discussed in Sect. 2.2, once the controlled endpoints receive the GCI from GEO satellites, the dispatch of GCI mainly depends on the performance of OHLs. So the resource consumption of OHLs should be evaluated.

According to Definition 4 and Remark 3, the resource consumption of OHLs in this work is practically expressed by through the VCL consumption. Furthermore, according to Definition 5, Formulas (3) and (4), the VCL consumption is denoted by the vertex weight of UTVG. In the final analysis, the OHL consumption does correspond to the solution to LGLC.

Because LGLC has been expressed via bipartite network and can be solved as the minimum cut problem in polynomial time, the optimum solution of LGLC is essentially the minimum OHL consumption.

Remark 6 As the optimum solution of LGLC is equivalent to the solution of minimum cut problem, and the correctness has been proved mathematically [29,30], in the following contents, we will not designedly evaluate the OHL consumption any more.

5.2 Evaluation metrics of segments

As the delay of GCI mainly depends on GEO satellites and controlled endpoints, we propose the metrics to identify the extent of the delay.

Definition 8 *Segment Burden Rate(s)*. For a CTL $\langle g, u\rangle$ between a controlling endpoint (GEO satellite) $g \in V_G$ and a controlled endpoint (LEO satellite-footprint or ground station) $u \in U_L \cup V_S$, the *burden rates* of g and u are defined as the following:

$$Q_1(g,u) = \frac{T_E^{(g,u)}}{T_S^{(g,u)} + T_E^{(g,u)} + T_D^{(g,u)}},$$
$$Q_2(g,u) = \frac{T_D^{(g,u)}}{T_S^{(g,u)} + T_E^{(g,u)} + T_D^{(g,u)}} \tag{6}$$

where $T_S^{(g,u)}$ is the transmission time of a piece of GCI over the CTL $\langle g, u\rangle$; $T_D^{(g,u)}$ and $T_E^{(g,u)}$ are the process time of the GCI over the controlling endpoint g and the controlled endpoint u of CTL $\langle g, u\rangle$, respectively. $Q_1(g,u)$ is called the *burden rate of controlling endpoint*; $Q_2(g,u)$ is called the *burden rate of controlled endpoint*.

Remark 7 For a controlling endpoint or controlled endpoint, the segment burden rate physically means the extent of that a piece GCI delay on it before entering the OHLs. Note that we here ignore the influence of OHL, because the transmission time of a piece GCI over CTL is much more than that over OHL.

Remark 8 In Formula (6), $T_S^{(g,u)}$ is determined only by the physical parameters of application scenarios but independent of LGLC. Oppositely, $T_E^{(g,u)}$ and $T_D^{(g,u)}$ are affected by different multicast strategies, where the different selections of controlled endpoints bring GCI data in different complexities. Specially, when *unicast* is used, GEO satellites need to process all the dispatched GCI in CTLs but controlled endpoints only receive GCI, and $T_D^{(g,u)}$ can be considered to be very little but $T_E^{(g,u)}$ is great. Similarly, when *broadcast* is used, GEO satellites only send GCI but controlled endpoints need to analyze the contents of all the GCI data received, and $T_E^{(g,u)}$ can be considered to be very little but $T_D^{(g,u)}$ is great.

Definition 9 *Global Burden Rate(s)*. The *global burden rates* are defined as the following:

$$Q_I = \frac{1}{|V_G|} \sum_{u \in U_L \cup V_S}^{g \in V_G} Q_1(g,u),$$
$$Q_{II} = \frac{1}{|U_L \cup V_S|} \sum_{u \in U_L \cup V_S}^{g \in V_G} Q_2(g,u). \tag{7}$$

Remark 9 The global burden rate is actually the average of the burden rates of controlling endpoints or controlling endpoints in an SDSN. Its physical meaning is the extent of that GCI delay on GEO satellites or controlled endpoints before they enter OHLs. The higher Q_I and Q_{II} means that GCI needs more time to reach OHLs and the construction of SDSN is delayed more.

Remark 10 In this paper, our work is not subject to any specific strategy of multiple access such as FDMA, TDMA, SDMA and CDMA etc. No matter which strategy is used, a basic policy is followed: the more information of multiple access is included, the more complex a piece of GCI is, and the more process time on controlled endpoint is needed.

It can be concluded that Q_I and Q_{II} mirror the extent of that the controlling endpoint (GEO satellite) and the controlled endpoint (LEO satellite and ground station) of CTL delay the dispatches of GCI, respectively; the lower Q_I and Q_{II} correspond to the faster multicast.

5.3 Evaluation metrics of CTLs

Besides finding the lightest controlled endpoints to quickly spread GCI, a by-product of LGLC is that the selection of different controlled endpoints may affect the load balancing between different CTLs. Although the transmission speed of a sole CTL does not depend on LGLC, the different assignment of CTLs does affect the transmission performance of CTLs. Therefore, we propose a fairness index of CTLs to reflect this difference.

We first bring forward the concept of *CTL Burden Rate*.

Definition 10 *CTL Burden Rate*. For a CTL between the controlling endpoint $g \in V_G$ and the controlled endpoint $u \in U_L \cup V_S$, the *CTL burden rate* of $\langle g, u\rangle$ is defined as the following:

$$Q_c(g,u) = Q_1(g,u) + Q_2(g,u). \tag{8}$$

The *global CTL burden rate* is denoted by

$$Q_C(g,u) = \frac{1}{N} \sum_{u \in U_L \cup V_S}^{g \in V_G} Q_C(g,u), \tag{9}$$

where N is the number of CTLs.

Remark 11 $Q_C(g,u)$ is essentially the sum of burden rates of the pair of endpoints of CTL $\langle g, u\rangle$. It reflects the influence of the controlling endpoints and the controlled endpoints on the delay of GCI dispatching. In condition of determined transmission speed, the higher $Q_C(g,u)$ means that GCI is delayed more before entering the OHLs.

Based on Definition 10, the *CTL fairness* is defined.

Definition 11 *CTL Fairness.* For N CTLs between $|V_G|$ controlling endpoints and $|U_L \cup V_S|$ controlled endpoints of a SDSN in a period, the CTL fairness is denoted by

$$Q_F = \frac{1}{N}\left(\sum_{u\in U_L\cup V_S}^{g\in V_G} Q_c(g,u)\right)^2 \Bigg/ \sum_{u\in U_L\cup V_S}^{g\in V_G} Q_c(g,u)^2. \tag{10}$$

According to Formula (10), the greater difference of CTL burden rates corresponds to the lower Q_F. Specially, if all the CTL burden rates are equal to each other, there is $Q_F = 1$.

6 Experimental evaluations

6.1 Experimental methods

The simulation experiments are performed to evaluate the work. Two simulation tools are used: STK[2] and Matlab. The former is responsible for establishing the simulation scenario of SDSN; the latter is used to make the quantitative analyses.

Firstly, the LEO satellites, the ground stations and the GEO satellites are simulated in STK. The simulated Earth Observation scenario is composed of 66 LEO satellites and 40 ground stations, which can be recombined to generate many different virtual constellations. All the physical parameters, including the parameters of orbits, sensors, antenna and communication modes, etc., can be configured in STK. All the test periods of segments in this work are set to 1200 minutes. Secondly, based on the predesigned physical parameters of the segments, the corresponding links can be generated automatically in STK, and the a TVG is established. Thirdly, in order to transform the TVG into a UTVG, the trajectory of every LEO satellites needs to be divided into multiple *satellite-footprints*. This procedure can be implemented by analyzing the STK reports which provide record the states of the communication links in each *timeslot*. The ground stations, as they are considered to be static in the geocentric coordinate system, can be straightly regarded as the right vertices in UTVG. Lastly, the VCL consumption of every LEO satellite-footprint or ground station is quantified as the vertex weight of UTVG, by computing the transmission time of GCI over OHLs, ISLs and IGLs in STK.

With the established UTVG, the LGLC problem can be solved via the minimum cut of undirected weighted graph as explored in Sect. 4. Then, based on the selected controlled endpoints, the GCI transmission between the UTVG and the GEO satellites can be tested in Matlab programs. Lastly, the effect of LGLC is evaluated according to the metrics proposed in Sect. 5.

[2] Satellite Tool Kit STK: a physics-based software package from Analytical Graphics, Inc. that allows engineers and scientists to simulate complex space-ground networks.

Table 1 The parameters of simulated network in NS2

Elements	Numbers or semantics	Size of GCI
V_G	$\|V_G\| = 9$	162 KB
U_L	$\|U_L\| = 806$	
V_S	$\|V_S\| = 40$	
E(VCL)	$\|E\| = 281$	
$\omega_T(\cdot)$	$10 \sim 40$(ms), got in STK	

6.2 Experimental procedure

As discussed in the former Sections, the spread of GCI in SDSN is essentially the process that the controlling endpoints dispatch the GCI to the selected controlled endpoints in a UTVG. So the simulated network consists of two parts: a set of controlling endpoints, V_G, and a UTVG ,$(U_L \cup V_S, E, \omega_T)$. The main parameters are listed in Table 1, where the 66 LEO satellites in 1200 minutes are divided into 806 LEO satellite-footprints which constitute 281 VCLs with the 40 ground stations.

Moreover,to both simplify the work and highlight the difference of the strategies of multiple multicast, some rules are written in the simulation program of Matlab:

- R1 The size of every sole GCI packet involving only one controlled endpoint is 162KB[3], and the process time on a controlling endpoint or controlled endpoint is 5ms;
- R2 The process time increases 2ms for each additional control information of controlled endpoint.

These rules imply that the more controlled endpoints are involved in GCI, the more process time is needed.

In our experiments, we make ten groups of tests, and the experimental results are display in Fig. 8. The ith ($i = 1, 2, \ldots, 10$) group of tests consists of i *complete update operation(s)* [17], where every complete update operation corresponds to the reconfiguration of a virtual constellation, and the corresponding control information is dispatched to the controlled endpoints in the form of GCI to update all the LEO satellites and ground stations in SDSN. The four groups of metrics (Q_I, Q_{II}, Q_C, Q_F) proposed in Sect. 5 are computed for every group of tests.

For every metrics of every group of tests, we test four kinds of multicasts: the unicast, the broadcast, the random multicast and the LGLC-based multicast. The unicast, being a special case of multicast, dispatches the sole GCI

[3] The same value (162KB) has been used in the experiments of the literature [17]

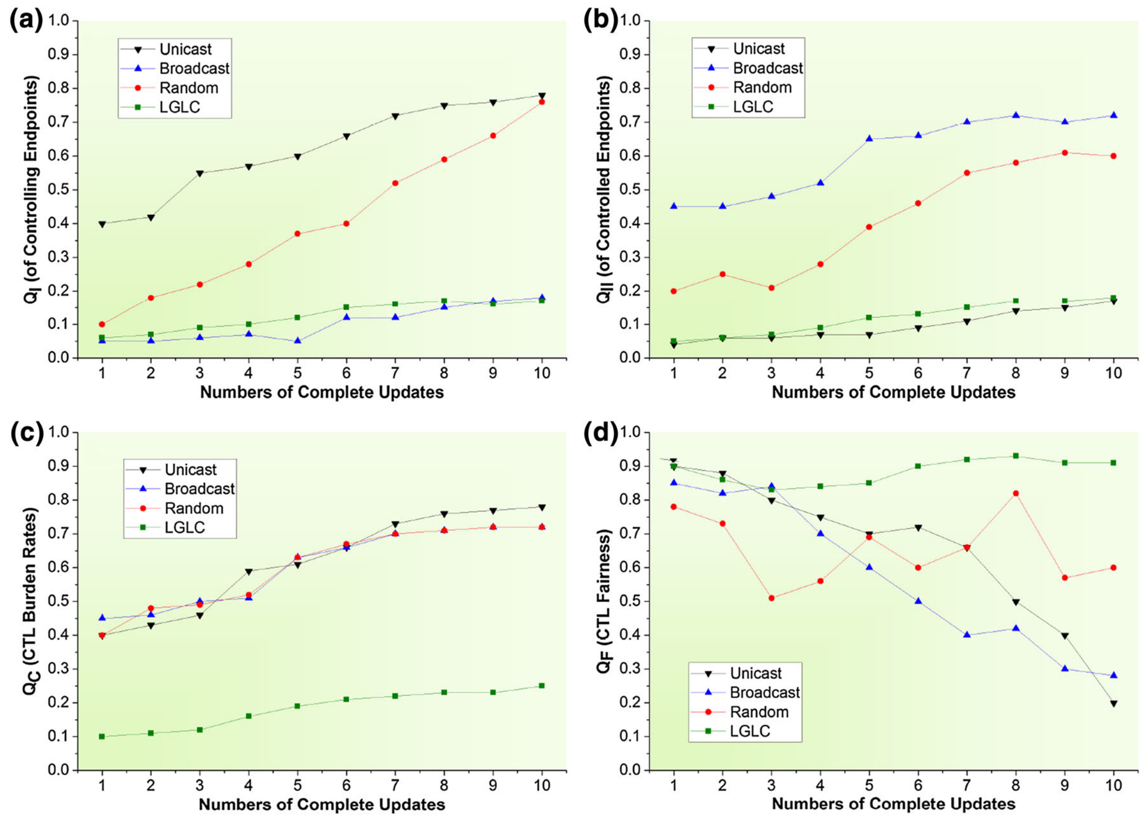

Fig. 8 The experimental results. Four groups of metrics (Q_I, Q_{II}, Q_C, Q_F) are computed based on every group of test. For the unicast, the broadcast and the LGLC-based multicast, the metrics values can be got directly by one specific test because their controlled endpoints and corresponding CTLs are determined. For the random multicast, as the selected endpoints are generated at random, we repeat 10 times for every group of tests, and compute the average values of metrics

packet for every LEO satellite-footprint and ground station. The broadcast, being another special case of multicast, dispatches the same combined GCI packet for all the LEO satellite-footprints and ground stations in SDSN. The random multicast dispatches the combined GCI for some randomly selected endpoints which covering all VCLs. The LGLC-based multicast dispatches the combined GCI for the selected optimum endpoints.

6.3 Experimental evaluation

Based on the experimental results in Fig. 8, the effect of LGLC can be evaluated.

- Q_Is of the LGLC-based multicast are markedly lower than those of the unicast and the random multicast, but close to Q_Is of the broadcast. This indicates that the LGLC-based multicast can save much process time of GCI on GEO satellites.
- Q_{II}s of the LGLC-based multicast, and are markedly lower than those of the broadcast and the random multicast, but close to Q_{II}s of the unicast. This indicates that the LGLC-based multicast can save much process time of GCI on LEO satellites and ground stations.
- Q_Cs of the LGLC-based multicast are much lower than those of another three cases. This indicates that the LGLC-based multicast can markedly improve the utilization of CTLs.
- Q_Fs of the LGLC-based multicast is overall better than that of another three cases. Specially for the multiple complete update operations, the LGLC-based multicast can provide better load balancing.
- The values of four metrics of the LGLC-based multicast vary smoother than those of another three cases. This indicates that the LGLC-based has the good robustness for different configuration requirements of SDSN.

7 Conclusion

Virtual constellation is an important source of obtaining EO big data, but the reconfiguration cost of virtual constellation is very costly. To reduce the reconfiguration costs, this paper proposes a LEO-ground links control-covering

(LGLC) model to address the fast lightweight reconfiguration of virtual constellation.

Based on the pattern of (software defined satellite network) SDSN where GEO satellites are responsible of the dispatch of control information, the LGLC model regards the reconfigurations of virtual constellations as a framework that consists of controlling endpoints (GEO satellites), controlled endpoints (LEO satellites and ground stations) and the virtual covering links (VCLs). Furthermore, a weighted unifying time-varying graph (UTVG) is established to mathematically describe LGLC. The goal of LGLC is to find the fewest controlled endpoints which can fast cover all the VCLs of UTVG, and to implement the fast lightweight reconfiguration of virtual constellation. In our work, the problem of LGLC is equivalent to the minimum cut problem of graph and can be solved in polynomial time. Therefore, according to the approach prosed, GEO satellites only need to multicast GCI to the most suitable but not all LEO satellites and ground stations, and then the GCI is spread quickly by one-hop links. Based on the evaluation metrics proposed, we perform the simulated experiments and evaluate the results. It can be concluded that the LGLC based approach can not only reduce the onboard burden of satellites and stations but also increase the resource utilization of communication links.

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