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Joint Placement of Controllers and Gateways in SDN-enabled 5G-satellite Integrated Network

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模拟退火算法解决基础问题，模拟退火与集群混合算法（SACA）解决联合优化问题

***Abstract*—Leveraging the concept of Software-Defined Network (SDN), the integration of terrestrial 5G and satellite networks brings us lots of benefits. The placement problem of controllers and satellite gateways is of fundamental importance for design of such SDN-enabled integrated network, especially for the network reliability and latency, since different placement schemes would produce various network performances. To the best of our knowledge, it is an entirely new problem. Toward this end, in this paper, we first explore the satellite gateway placement problem to obtain the minimum average latency. A simulated annealing based approximate solution, i.e, SAA, is developed for this problem, which is able to achieve a near-optimal latency. Based on the analysis of latency, we further investigate a more challenging problem, i.e., the joint placement of controllers and gateways, for the maximum network reliability while satisfying the latency constraint. A simulated annealing and clustering hybrid algorithm (SACA) is proposed to solve this problem. Extensive experiments based on real world online network topologies have been conducted and as validated by our numerical results, enumeration algorithms are able to produce optimal results but having extremely long running time, while SAA and SACA can achieve approximate optimal performances with much lower computational complexity.**

***Index Terms*—5G-satellite integrated network, controller placement, satellite gateway placement, joint placement.**

I. Introduction

There is a general tendency for traditional satellite communication and terrestrial 5G mobile system to evolve towards an integrated network, so as to meet the excessive consumer demand for wireless data access. Such network has many advantages in terms of coverage, congestion control and resilience. In particular, by deploying Relay Nodes (RNs) [1], it enables network operators to effectively extend their radio access network to rural [2] or environmentally harsh areas such as ocean and mountains where terrestrial network infrastructure may not be easily deployed [3]. Most importantly, with high throughput [4], the satellite can efficiently offload the terrestrial traffic to mitigate congestion in backhaul network, especially when the traffic amount exceeds the capacity of terrestrial links [5]. What's more, the integrated network is able to provide reliable wireless access service when terrestrial infrastructures are damaged in natural disasters [6]. In a word, the integration of satellite and terrestrial 5G system will provide a new network architecture to support various applications such as cloud computing, big data, and Internet of Things [7] in future wireless networks.

Although the integration of terrestrial 5G and satellite networks brings us many benefits, it also reveals lots of challenges. Firstly, how to determine the placement of terrestrial-satellite routing equipments, i.e., the so called *satellite gateways*, should be well accounted. Secondly, in the integrated network, usually there will be multiple available paths along which data traffic can be routed, when and how to select path while avoiding network congestion and obtaining the best resource utilization must be carefully considered. Thirdly, when the quality of satellite links becomes worsened under poor meteorological conditions [8], data flow should be transformed from one satellite gateway to another. How to devise a smart handover mechanism to guarantee the link quality is another challenge. In addition, the 5G-satellite integrated network is composed of different types of infrastructures, resulting in heterogeneous networks (HetNets) [9] [10], how to provide flexible and programmable management on these HetNets is also an important issue.

Note that these challenges can be well resolved by adopting Software-Defined Networking (SDN) [11]. Applying SDN into 5G-satellite integrated network makes it possible to manage the entire network through intelligent management and orchestration systems [12]. In SDN, the logical control entity (called the *controller*) is decoupled from the switch for a centralized control in the data plane. The SDN controller has an overview of the network so it is able to make decisions of global path selection according to the whole network states [13]. Based on the flow constraints and network performance indicators [14], the controller can easily decide when and how to execute the handover among satellite gateways. Left only data forwarding functionality, devices in HetNets need not to understand various protocols but merely to receive instructions from the controller, which paves the way to manage these devices with great flexibility and programmability.

It is observed from above discussions that, the controller plays an important role in SDN-enabled 5G-satellite integrated network. In order to ensure the switches or satellite to work properly, it is necessary to keep good connectivity between these nodes (switches or satellite) and controllers, otherwise they will receive/send outdated information from/to the controllers [15]. As we know that, most network components,

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such as terrestrial nodes and links as well as the satellite links in the integrated network, are prone to failing due to lots of factors [16] [17]. Therefore, in order to improve the reliability of the integrated network, it is of fundamental importance to determine the placement of controllers and satellite gateways. Generally, we need to take into account not only geographical locations but also the terrestrial topologies, when deciding the placement of controllers and satellite gateways.

Existing works on controller or gateway placement problem, although providing precious insights into performance optimization of reliability and latency, have one common limitation: all of them considered only terrestrial network. Because of the totally different network architecture as illustrated later, the available approaches in these works cannot be readily adopted for SDN-enabled 5G-satellite integrated network. To the best of our knowledge, we are the first to study the joint placement problem of controllers and satellite gateways in the SDN-enabled integrated network to maximize the communication reliability from terrestrial switches and satellite to the controllers. The main contributions of this paper are summarized as follows.

- Given the SDN-enabled 5G-satellite integrated network architecture, we present an entirely new problem of joint placement optimization for satellite gateways and controllers, which is very important for guiding the design and performance optimization of such integrated networks, and holds great promise for lots of application scenarios, such as deep space communication [18] and disaster resilient network.
- We first formally formulate the satellite gateway placement problem, with the objective of optimizing the average propagation latency from all terrestrial switches to the satellite. Then we define the problem of joint placement of controllers and gateways to obtain the maximum average reliability from terrestrial switches and satellite to the controllers given the latency constraint.
- A simulated annealing based algorithm, i.e, SAA, is proposed to address the satellite gateway placement problem. With much lower computational complexity of $O(k \cdot n)$ in each iteration, SAA is able to achieve the near-optimal latency performance compared to the OEA (optimal enumeration algorithm), which gives the optimal solution but with very high computational complexity of $O(k \cdot n \cdot C_n^k)$. We further develop another simulated annealing and clustering hybrid solution, i.e., SACA, for the joint placement problem. SACA can obtain the near optimal reliability with much smaller running time $O(n^2)$ in each iteration than OEAJ (optimal enumeration algorithm for joint placement problem), which is able to achieve the maximum reliability but with very high computational complexity of $O((k + n) \cdot m \cdot C_n^k \cdot C_n^m)$. In above descriptions, n, k, and m denote the number of terrestrial switches, number of satellite gateways, and number of controllers, respectively, while C_n^k and C_n^m represent the combinations.
- Extensive online real world topology based experiments have been conducted to evaluate the performances of our proposed algorithms. Experimental results show that for all topologies and failure probability settings, SAA and SACA can give the performance very close to the OEA and OEAJ, respectively, while taking very small running time.

The rest of this paper is organized as follows: Section II introduces the related works in recent years. Section III presents the system model. In Section IV we first formulate the problem of satellite gateway placement, then propose two detailed algorithms, OEA and SAA. Section V describes the joint placement problem, and two solutions, i.e., OEAJ and SACA, are devised for this problem. We present extensive numerical results in Section VI, and finally conclude the whole paper in Section VII.

II. Related Works

In the 5G-satellite integrated network, most data traffic from terrestrial nodes to the satellite must travel through satellite gateways, therefore, the satellite gateway placement problem should be considered at first. So far, such problem in the integrated network almost remains untouched. Existing works in this line mostly focused on gateway placement in wireless mesh networks [19]–[21] and sensor networks [22] [23]. The work that is mostly close to ours is [23], in which the authors proposed a DLINMAP (dynamic linear programming technique for multidimensional analysis of preferences) algorithm for sink selection to optimize the packet loss rate, average packet delay, and energy consumption, so as to enable sensor nodes access to the satellite backbone in the satellite-based sensor networks.

To achieve the best network performance in SDN, plenty of ink has been poured on the controller placement problem. Up to now, we can find that the studies on this problem generally exploit approaches to find out the best locations in a network to place controllers in order to get the optimal pre-defined objective value. We broadly classify the related solutions according to objectives into three main categories: minimizing latency [24]–[27], maximizing reliability [28]–[32], and minimizing deployment cost and energy consumption [33]–[36]. Especially, based on the target to maximize the communication reliability, variety of methods were proposed to fulfill their objectives. In [28], the authors presented a novel metric, called expected percentage of control path loss, to characterize the reliability of SDN control networks, and adopted simulated annealing to increase the reliability by placing appropriate controllers in the network. Maryam Tanha *et al.* [29] proposed a resilient control plane design and formulation by having physically distributed and redundant controllers. In [30], the authors used a mathematical model for the capacitated controller placement, which planed ahead for the failures to avoid a drastic increase in the worst case latency and disconnections between the switches and their reference controllers. A partition and selection approach to controller placement for improving the reliability in SDN was proposed in [31]. David Hock *et al.* [32] introduced a Pareto-based optimal controller placement reliability framework and used the Internet2 OS3E topology to evaluate the proposed mechanisms.

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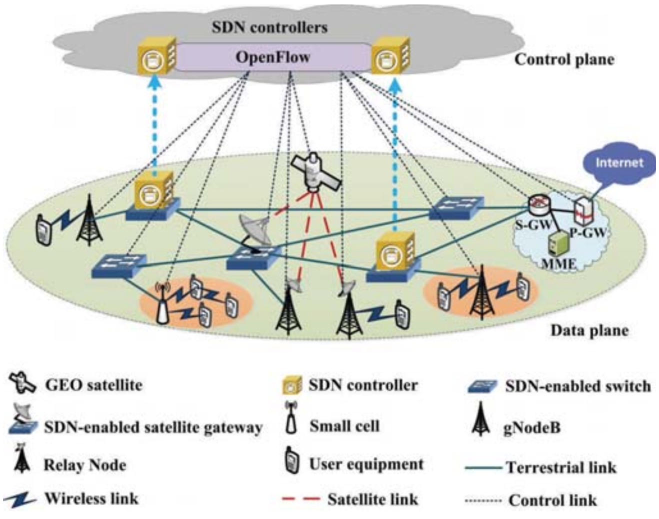

Fig. 1. An architecture for SDN-enabled 5G-satellite integrated network.

The available research works only focused on the independent placement problem of either controllers or gateways in terrestrial network. In such cases, the problem just needs to consider one object (controller or gateway) to place. Note that the SDN-enabled nodes in the integrated network include both terrestrial switches and satellites, control instructions the controllers send to satellites have to travel through the satellite gateways. Thus, how to place controllers must consider the placement of satellite gateways simultaneously. That is, it is a multi-object placement problem in the integrated network, which is significantly different from the single object placement in the terrestrial network. Therefore, the algorithms proposed in previous works cannot be applicable to the joint placement problem in our work. In light of this, we consider an integrated architecture for SDN-enabled 5G-satellite network in this paper, and explore the joint placement problem of controllers and satellite gateways to achieve the optimal performance of the whole integrated network.

III. System Model

In this section, we first give an architecture for SDN-enabled 5G-satellite integrated network and then elaborate the satellite gateway placement problem as well as the joint placement problem.

A. An Architecture for SDN-enabled 5G-satellite Integrated Network

In this paper, we mainly consider an SDN-enabled integrated network architecture for 5G-satellite communication. As depicted in Figure 1, the architecture is composed of two logical parts, i.e., the data plane and control plane. In the data plane, user equipments connect to the 5G network through gNBs (i.e., gNodeB, 5G NodeB) and RNs, and the terrestrial 5G network mainly relies upon fiber to establish connections among the SDN-enabled nodes within the backhaul as well as the Radio Access Network (RAN, e.g., gNBs, small cells, etc.) and core network. The geostationary orbit (GEO) satellite with high throughput is set as the complementary part of the 5G network in the architecture, and the satellite communicates with terrestrial nodes via satellite gateways and RNs. In the control plane, there are numbers of SDN controllers which are hosted on the physical nodes in the data plane, providing centralized control and management functions to both RAN and backhaul, as well as core network.

Given a fully SDN-enabled integrated network architecture, since we are interested in optimizing the joint placement of satellite gateways and controllers to guarantee the communication reliability of the paths from terrestrial switches and satellite to controllers, to simplify the analysis, the core network and RAN are not considered in our current network model.

B. Satellite Gateway Placement

In the SDN-enabled 5G-satellite integrated network architecture, we first consider the traffic transmission process from each terrestrial switch to the satellite through satellite gateways. It is necessary for each terrestrial switch to communicate with the satellite taking the least time. The latency between terrestrial switches and satellite is an important factor affecting the performance of the integrated network. The latency is mainly composed of two components: propagation latency and nodes (switches and satellite gateways) forwarding latency. The propagation latency is mainly determined by the distance between switches and satellite, and the forwarding latency is primarily affected by loads of nodes. Since the satellite-terrestrial distance is a constant (i.e., 35786 km [6]) and all data traffic delivery between terrestrial switches and satellite must travel through the gateways, the latency between switches and satellite gateways is especially critical. We assume that in the terrestrial network the propagation latency is dominated and neglect the forwarding latency. Therefore, where the satellite gateways should be located in the terrestrial network so as to minimize the average propagation latency of the integrated network is worth further studying. As for other issues like how many satellite gateways should be placed and how much traffic needs to be transmitted to the satellite from each switch, are left as our future work.

In this context, the latency mainly refers to propagation latency, and the latency of the path from terrestrial switch u to the satellite s, via satellite gateway g, is defined as L_{us}^{g}. The average latency, L_{ave}, from all terrestrial switches in $\mathbf{V}_T$ to the satellite s, is defined as

$$L_{ave} = \frac{1}{n} \sum_{u \in \mathbf{V}_T} L_{us}^{g}, \quad g \in \mathbf{W}. \tag{1}$$

In (1), $\mathbf{V}_T$ and $\mathbf{W}$ represent the set of terrestrial switches, set of satellite gateways, respectively, and n denotes the number of terrestrial switches in $\mathbf{V}_T$.

C. Joint Placement of Controllers and Satellite Gateways

The major function of SDN controllers in SDN-enabled 5G-satellite integrated network is making overall routing decisions, executing smart traffic offloading and gateway diversity. We assume that SDN is enabled in the satellite system and

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the satellite is turned into SDN switch which receives control instructions coming from the controllers located on the ground. It is noted that, either nodes or links failure may disconnect the control and data planes, so that prevent the switches or satellite from receiving instructions from the controllers and lead severe packet loss and performance degradation. Therefore, to improve the SDN network reliability is of great significance. Due to the impact of geographical locations, different placements of controllers may result in totally different performances of network reliability and different placements of satellite gateways may give various latencies.

We define the reliability of the path from each terrestrial switch u to controller c as R_{uc}, and the reliability of the path from the satellite s to controller c via gateway g as R^g_{sc}. The average reliability of all terrestrial switches and the satellite to the controllers, R_{ave}, can be defined as

$$R_{ave} = \frac{1}{n+k}\Big(\sum_{u\in\mathbf{V}_T} R_{uc} + \sum_{s} R^g_{sc}\Big), \quad c \in \mathbf{S}, g \in \mathbf{W}. \tag{2}$$

Here, n and k denote the number of terrestrial switches and number of satellite gateways, respectively, $\mathbf{S}$ represents the set of controllers.

Suppose each terrestrial switch's location can be a candidate site to place a controller or gateway, our goal is to place appropriate number of controllers and gateways into optimal locations to achieve the maximum R_{ave} of the integrated network based on the latency constraint.

IV. Satellite Gateway Placement for Latency Minimization

A. Problem Formulation

The SDN-enabled 5G-satellite integrated network can be represented by an undirected graph $G(\mathbf{V},\mathbf{E})$, where $\mathbf{V}$ is the set of nodes (switches and satellite), and $\mathbf{E}$ is the set of physical links between nodes, link weights represent propagation latencies. The detailed notations and definitions used in this paper are summarized in Table I.

TABLE I
Notations and Definitions

Notation	Definition
$G(\mathbf{V},\mathbf{E})$	Physical network with node set $\mathbf{V}$ and link set $\mathbf{E}$, $\mathbf{V} = \mathbf{V}_T \bigcup \{s\}$
$\mathbf{V}_T$	set of terrestrial switch nodes
$\mathbf{W}$	set of satellite gateways
$\mathbf{S}$	set of SDN controllers
u	a switch node in $\mathbf{V}_T$
s	satellite node
g	a satellite gateway in $\mathbf{W}$
c	a controller in $\mathbf{S}$
k	number of satellite gateways
m	number of SDN controllers
P_v	failure probability of terrestrial node
P_e	failure probability of terrestrial link
$P_{e_{sg}}$	failure probability of satellite link from s to g
L^g_{us}	latency from u to s via g
L_{ug}	latency from u to g
L_{gs}	latency from g to s
L_{max}	maximum latency the terrestrial network can tolerate
R_{uc}	reliability of the path from u to c
R^g_{sc}	reliability of the path from s to c via g

Given the set of terrestrial nodes $\mathbf{V}_T \subset \mathbf{V}$, and the number of satellite gateways k to be deployed, we aim at finding out a subset of k switches $\mathbf{W} = \{g_1, g_2, g_3, ..., g_k\} \subseteq \mathbf{V}_T$, so as to minimize the average latency when placing k satellite gateways at $\{g_1, g_2, g_3, ..., g_k\}$.

For the switch $u \in \mathbf{V}_T$, we need to calculate L^g_{us}. Let L_{ug} denote the latency from terrestrial switch u to gateway $g \in \mathbf{W}$ and L_{gs} the latency from g to satellite s, the calculation formula of L^g_{us} can be determined as

$$L^g_{us} = L_{ug} + L_{gs}. \tag{3}$$

Based on the above notations, the satellite gateway placement problem can be formally defined as follows.

Satellite Gateway Placement Problem (SGPP): Given the set of terrestrial switches $\mathbf{V}_T$, satellite s, as well as k satellite gateways for deployment, we need to decide an optimal placement of satellite gateways $\mathbf{W} = \{g_1, g_2, g_3, ..., g_k\} \subseteq \mathbf{V}_T$ so as to minimize the average latency of the integrated network

$$\min \frac{1}{n} \sum_{u\in\mathbf{V}_T} L^g_{us}, \quad g \in \mathbf{W}, \tag{4}$$

where n denotes the number of nodes in $\mathbf{V}_T$.

As discussed in Section III, L_{gs} is a constant, thus (4) is mainly to minimize L_{ug}. Therefore, the SGPP is simplified as

$$\min \frac{1}{n} \sum_{u\in\mathbf{V}_T} L_{ug}, \quad g \in \mathbf{W}. \tag{5}$$

B. An Optimal Enumeration Algorithm

To solve the satellite gateway placement problem, the most intuitive method is to enumerate all possible combinations of k satellite gateways from n nodes in $\mathbf{V}_T$, and then to choose an optimal combination that minimizes the average latency from the switch nodes to the gateways. The details of this optimal enumeration algorithm (OEA), are described in Algorithm 1.

C. A Simulated Annealing Based Approximation Algorithm

Simulated Annealing (SA) [37] is a probabilistic technique based on the annealing process of metals. It starts with a high temperature that is slowly lowered until the solid reaches its stable state. Algorithm 2, i.e., SAA, describes the method proposed to solve the satellite gateway placement problem based on the SA technique. At first, an initial set of satellite gateway $\mathbf{W}_{opt}$ is randomly selected as the best solution, and the average latency L_{min} is computed. Then at every iteration of the while-loop, a new neighbor solution $\mathbf{W}_{new}$ is generated to obtain the new average latency L_{new}. The new solution will be accepted if it is better than the old one, i.e., $L_{new} \le L_{min}$. Otherwise, the acceptance of $\mathbf{W}_{new}$ will be allowed with the acceptance probability $P(\Delta) = e^{-\frac{\Delta}{T}}$, where $\Delta = L_{new} - L_{min}$, and T denotes the current temperature.

As described in Algorithm 2, SAA accepts the new placement of satellite gateways as the currently optimal solution if it

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Algorithm 1 an optimal enumeration algorithm (OEA).

Input: $G(\mathbf{V}, \mathbf{E})$, k
Output: $\mathbf{W}_{opt}$-the optimal placement of k satellite gateways, L_{min}-the minimum average latency

```
Initialize n = |V_T|, L_min = +∞, S_sg = ∅
enumerate all combinations of k gateways from V_T, and record into the set S_sg
for all W_i ⊂ S_sg do
    for each u ∈ V_T do
        for each g ∈ W_i do
            compute L_ug
        end for
        select L_u as the minimum L_ug
    end for
    compute the average latency L_ave
    compute W_opt and L_min according to L_ave
end for
return W_opt, L_min
```

Algorithm 2 a simulated annealing based algorithm (SAA).

Input: $G(\mathbf{V}, \mathbf{E})$, k
Output: $\mathbf{W}_{opt}$, L_{min}

```
Initialize T = T_0-the initial temperature, T_final-the terminate temperature, α-the annealing coefficient
select randomly k nodes from V_T as the initial set of gateways W_opt
compute the average latency L_min
while T > T_final do
    W_new = W_opt
    generate the new set of gateways W_new
    compute the average latency L_new
    Δ = L_new − L_min
    generate a random number δ ∈ (0, 1)
    if Δ ≤ 0 or e^(−Δ/T) > δ then
        W_opt = W_new
        L_min = L_new
    end if
    T = T · α
end while
return W_opt, L_min
```

has better result. In addition, SAA allows the current solution to be worsened, and considers an acceptance probability that allows escaping from the local optimal problem. Therefore, SAA is able to obtain a near optimal solution to the satellite gateway placement problem in 5G-satellite integrated network.

D. Analysis And Discussions

OEA in Algorithm 1 is very simple and effective, but it has a very high computational complexity since OEA has to enumerate all combinations of k gateways from n nodes in $\mathbf{V}_T$ to find the overall minimum average latency, i.e., L_{min}. It can be easily proved that the computational complexity of OEA in Algorithm 1 is $O(k \cdot n \cdot C_n^k)$.

Compared to OEA, SAA has a bigger advantage on computational efficiency. From the description of SAA in Algorithm 2, one can readily come to the conclusion that each iteration of the while-loop in Algorithm 2 can be computed in $O(k \cdot n)$ time.

V. Joint Placement of Controllers and Satellite Gateways for Reliability Maximization

A. Problem Formulation

Once the satellite gateway placement problem is formulated, the average latency of the integrated network will be determined. Given the set of terrestrial nodes $\mathbf{V}_T \subset \mathbf{V}$, let $P_v, P_e, P_{e_{sg}}$ denote the failure probability of terrestrial node u, terrestrial link e, and satellite link e_{sg} between satellite s and gateway g, respectively. Given the number of SDN controllers m to be placed, we aim at finding out a sub set of m switches $\mathbf{S} = \{c_1, c_2, c_3, ..., c_m\} \subseteq \mathbf{V}_T$, in order to maximize the average reliability of the integrated network when deploying m controllers at $\{c_1, c_2, c_3, ..., c_m\}$ with the constraint of latency L_{max}.

In SDN-enabled 5G-satellite integrated network, we need to calculate the communication reliability of two different paths, i.e., R_{uc}, and R_{sc}^g. Based on previous research works [24] [28], we only consider the shortest path from u or s to c. Let $V_{u\to c}$ denote the set of nodes and $E_{u\to c}$ the set of links on the terrestrial path from $u \in \mathbf{V}_T$ to $c \in \mathbf{S}$, R_{uc} can be calculated in

$$R_{uc} = \prod_{e \in E_{u\to c}} (1 - P_e) \prod_{v \in V_{u\to c} \backslash u} (1 - P_v). \tag{6}$$

Similarly, let $V_{s\to c}$ denote the set of nodes and $E_{s\to c}$ the set of links on the path from s to c via $g \in \mathbf{W}$. The calculation formula of R_{sc}^g can be determined as

$$R_{sc}^g = (1 - P_{e_{sg}}) \prod_{e \in E_{s\to c}} (1 - P_e) \prod_{v \in V_{s\to c} \backslash s} (1 - P_v). \tag{7}$$

Based on the above notations, the joint placement problem can be formally defined as follows.

Joint Placement Problem of Controllers and Satellite Gateways(JPPCS): Given the set of terrestrial nodes $\mathbf{V}_T$, satellite s, m controllers and k satellite gateways for deployment, we need to decide an optimal placement of controllers $\mathbf{S} = \{c_1, c_2, c_3, ..., c_m\} \subseteq \mathbf{V}_T$, and an optimal placement of gateways $\mathbf{W} = \{g_1, g_2, g_3, ..., g_k\} \subseteq \mathbf{V}_T$, so as to maximize the average reliability of the SDN-enabled integrated network while satisfying the latency constraint.

$$\max \quad \frac{1}{(n+k)}\Big(\sum_{u \in \mathbf{V}_T} R_{uc} + \sum_{s} R_{sc}^g\Big), \quad c \in \mathbf{S}, g \in \mathbf{W} \tag{8}$$

$$\text{s.t.} \quad \frac{1}{n} \sum_{u \in \mathbf{V}_T} L_{ug} \le L_{max}, \quad g \in \mathbf{W}. \tag{9}$$

In (8) and (9), n and k denote the number of nodes in $\mathbf{V}_T$, number of satellite gateways in $\mathbf{W}$, respectively. L_{max} is the constraint of latency, i.e., the maximum average latency that the terrestrial network can tolerate.

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B. An Optimal Enumeration Algorithm

Similar to SGPP described in Section IV, we first consider the optimal enumeration method (OEAJ) to solve the joint placement problem. As elaborated in Algorithm 3, all optional combinations of k satellite gateways and m controllers from n terrestrial switches are enumerated. Then the optimal combinations of both gateways and controllers, which maximize the average reliability of the integrated network with the latency constraint, are chosen.

Algorithm 3 an optimal enumeration algorithm for JPPCS (OEAJ).

Input: $G(\mathbf{V}, \mathbf{E})$, L_{max}, k, m
Output: R_{max}-the maximum reliability of the integrated network, $\mathbf{W}_{opt}$-the optimal placement of k satellite gateways, $\mathbf{S}_{opt}$-the optimal placement of m controllers

Initialize $n = |\mathbf{V}_T|$, $R_{max} = 0$, $\mathbf{S}_{sg} = \emptyset$, $\mathbf{S}_{con} = \emptyset$
enumerate all combinations of k gateways and all combinations of m controllers from n nodes, and record into the set $\mathbf{S}_{sg}$, $\mathbf{S}_{con}$, respectively
for all $\mathbf{W}_i \subset \mathbf{S}_{sg}$ **do**
  compute the average latency L_{ave}
  if $L_{ave} \leq L_{max}$ **then**
    $R_{\mathbf{W}_i} = 0$
    for all $\mathbf{S}_j \subset \mathbf{S}_{con}$ **do**
      for each $u \in \mathbf{V}_T$ **do**
        for each $c \in \mathbf{S}_j$ **do**
          compute R_{uc}
        end for
        select R_u as the maximum R_{uc}
      end for
      for each $g \in \mathbf{W}_i$ **do**
        for each $c \in \mathbf{S}_i$ **do**
          compute R_{sc}^g
        end for
        select R_g as the maximum R_{sc}^g
      end for
      compute the average reliability R_{ave}
      compute $R_{\mathbf{W}_i}$ and $\mathbf{S}_{opt}$ according to R_{ave}
    end for
    compute R_{max} and $\mathbf{W}_{opt}$ according to $R_{\mathbf{W}_i}$
  end if
end for
return $\mathbf{W}_{opt}$, $\mathbf{S}_{opt}$, R_{max}

C. A Simulated Annealing and Clustering Hybrid Solution

It is noted that, the satellite gateway placement affects not only the reliability R_{sc}^g but also the latency L_{ug}. Thus, to solve the joint placement problem, we should first decide the placement of gateways, then that of controllers. Based on this, a simulated annealing and clustering hybrid algorithm (SACA) is proposed. As described in Algorithm 4, the simulated annealing algorithm is used to generate a set of satellite gateways and compute the average latency. The cluster based approximation approach (CAA) is adopted as a procedure in SACA to obtain a near optimal solution of the controller placement, based on the given set of satellite gateways.

Algorithm 4 a simulated annealing and clustering hybrid algorithm (SACA).

Input: $G(\mathbf{V}, \mathbf{E})$, L_{max}, k, m
Output: R_{max}, $\mathbf{W}_{opt}$, $\mathbf{S}_{opt}$

Initialize $T = T_0$, T_{final}, α
generate randomly the initial set of gateways $\mathbf{W}_{opt}$
compute the average reliability R_{max} and the set of controllers $\mathbf{S}_{opt}$ in Procedure 1
while $T > T_{final}$ **do**
  generate a new set of gateways $\mathbf{W}_{new}$
  compute the average latency L_{ave}
  if $L_{ave} \leq L_{max}$ **then**
    compute the average reliability R_{new} and the set of controllers $\mathbf{S}_{new}$ in Procedure 1
    $\Delta = R_{new} - R_{max}$
    generate a random number $\delta \in (0, 1)$
    if $\Delta \geq 0$ OR $e^{\frac{\Delta}{T}} > \delta$ **then**
      $\mathbf{W}_{opt} = \mathbf{W}_{new}$
      $R_{max} = R_{new}$
      $\mathbf{S}_{opt} = \mathbf{S}_{new}$
    end if
  end if
  $T = T \cdot \alpha$
end while
return $\mathbf{W}_{opt}$, $\mathbf{S}_{opt}$, R_{max}

In Procedure CAA, given a set of satellite gateways $\mathbf{W}_{new}$, let R_{tot} denote the sum of the following two parts: the reliability from each terrestrial node u to others, and the reliability from satellite s to u via satellite gateway g in $\mathbf{W}_{new}$. Firstly, we select m nodes with the corresponding maximum values of R_{tot} as the initial set of controllers, $\mathbf{S}_{opt}$. According to the maximum reliability from each node to the controllers in $\mathbf{S}_{opt}$, we divide these n nodes into m clusters $\mathbb{C}=\{\mathbf{C}_1, \mathbf{C}_2, ..., \mathbf{C}_m\}$. Then R_i, the maximum sum of reliability of each node to others in $\mathbf{C}_i$ is computed and the optimal controller location in each cluster is decided. We define R_T as the maximum sum of reliability from terrestrial nodes to controllers, which can be calculated in

$$R_T = \sum_{i=1}^{m} R_i.$$

Then calculate R_s, the maximum sum of reliability from satellite s to controllers via gateways. Finally, the maximum average reliability of the whole integrated network based on the satellite gateway placement $\mathbf{W}_{new}$ is computed in:

$$R_{ave} = \frac{1}{n+k}(R_T + R_s),$$

where n, k denotes the number of terrestrial nodes and numbers of satellite gateways, respectively. The details of CAA are presented in Procedure 1.

As discussed in Section IV-C, the simulated annealing algorithm can give a near-optimal solution to the satellite

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Procedure 1 a cluster based approximate approach (CAA)

Input: $G(\mathbf{V}, \mathbf{E})$, $\mathbf{W}_{new}$, m
Output: $\mathbf{S}_{opt}$, R_{ave}
1: **Initialize** $n = |\mathbf{V}_T|$, $\mathbf{S}_{opt} = \emptyset$, $R_{max} = 0$, $R_T = 0$, $R_s = 0$, $\mathbf{C} = \emptyset$, $\mathbf{S}_u = \emptyset$
2: **for** each $u \in \mathbf{V}_T$ **do**
3: R_{tot}=0
4: **for** each $v \in \mathbf{V}_T$ **do**
5: $R_{tot} = R_{tot} + R_{uv}$
6: **end for**
7: compute R^g_{su}, the reliability from satellite s to u via $g \in \mathbf{W}_{new}$
8: $R_{tot} = R_{tot} + R^g_{su}$
9: $\mathbf{S}_u = \mathbf{S}_u \bigcup \{R_{tot}\}$
10: **end for**
11: sort $\mathbf{S}_u$ in a descending order
12: select the first m values in $\mathbf{S}_u$ and the corresponding m nodes, $\mathbf{S}_{opt} = \mathbf{S}_{opt} \bigcup \{m \text{ nodes}\}$
13: record the m nodes into $\{\mathbf{C}_1, \mathbf{C}_2, ..., \mathbf{C}_m\}$ respectively
14: **for** each $u \in (\mathbf{V}_T - \mathbf{S}_{opt})$ **do**
15: **for** each $c \in \mathbf{S}_{opt}$ **do**
16: compute R_{uc}
17: **end for**
18: select the index i of c in $\mathbf{S}_{opt}$ with the maximum R_{uc}, $\mathbf{C}_i = \mathbf{C}_i \bigcup \{u\}$, $\mathbf{V}_T = \mathbf{V}_T \setminus u$
19: **end for**
20: $\mathbf{S}_{opt} = \emptyset$
21: **for** $i = 1$ to m **do**
22: **for** each $u \in \mathbf{C}_i$ **do**
23: $R_{tot} = 0$
24: **for** each $v \in \mathbf{C}_i$ **do**
25: $R_{tot} = R_{tot} + R_{uv}$
26: **end for**
27: select R_i as the maximum R_{tot}, and the corresponding node u
28: **end for**
29: compute R_T
30: $\mathbf{S}_{opt} = \mathbf{S}_{opt} \bigcup \{u\}$
31: **end for**
32: compute R_s
33: compute R_{ave}
34: **return** $\mathbf{S}_{opt}$, R_{ave}

gateway placement problem. At each iteration of the while-loop in SACA, we use Procedure 1 to get the approximate optimal placement of controllers. As for the CAA in Procedure 1, we choose the first m maximum reliability values of each node to others, and select the corresponding m nodes as the initial controllers, then divide the n terrestrial nodes into m clusters. For the m nodes, we first make global optimal choices, and then select the optimal controller location again in each cluster so as to get a near-optimal placement scheme of the m controllers. Therefore, SACA in Algorithm 4 can give an approximate optimal solution to the joint placement problem in SDN-enabled 5G-satellite integrated network.

D. Analysis And Discussions

It is clearly that OEAJ in Algorithm 3 is very effective. It can find an optimal solution to the joint placement problem in SDN-enabled 5G-satellite integrated network. But it has an extremely high computational complexity since OEAJ has to enumerate all combinations of k gateways and m controllers from n nodes so as to find the overall maximum average reliability, i.e., R_{max}. More details on the computational complexity of OEAJ are discussed as follows.

Theorem 1: The computational complexity of OEAJ in Algorithm 3 is $O((k+n) \cdot m \cdot C^k_n \cdot C^m_n)$, where n, k, and m denote the number of terrestrial nodes, number of satellite gateways, number of controllers, respectively.

Proof: The OEAJ in Algorithm 3 mainly contains three parts, i.e., enumerating all combinations of k gateways and all combinations of m controllers from n nodes in step 2, computing $R_{\mathbf{W}_i}$ and $\mathbf{S}_{opt}$ based the combinations of controllers in steps 7-22, and computing R_{max} and $\mathbf{W}_{opt}$ based the combinations of satellite gateways in steps 4-24. In particular, the running time of step 6 to step 24 is $O(C^k_n \cdot C^m_n)$. There are n nodes to be selected in step 8 and m controllers in step 9, k gateways in step 14 and also m controllers in step 15, thus the time complexity of calculating R_{ave} for each controller placement solution S_i is $O(m \cdot n + k \cdot m) = O((k + n) \cdot m)$. So we can get the conclusion that the entire running time of OEAJ in Algorithm 3 is $O((k + n) \cdot m \cdot C^k_n \cdot C^m_n)$. ■

Due to its high computational complexity, OEAJ can only run with a very small number of nodes and is impractical in practice with a large one in the SDN-enabled integrated network. We propose OEAJ in this paper just to present a benchmark for the performance evaluation of our SACA solution.

Compared to OEAJ, SACA has a bigger advantage on computational efficiency. In particular, the following conclusion can be easily proved for SACA.

Theorem 2: Each iteration of the while-loop in SACA described in Algorithm 4 can be computed in $O(n^2)$ time, where n denotes the number of terrestrial nodes.

Proof: In Algorithm 4, step 6, which uses Procedure 1 to compute the maximum average reliability and the set of controllers, has the most computational complexity in each iteration of the while-loop. Thus, to prove this conclusion, we only need to analyze the running time of Procedure 1. Procedure 1 mainly contains five parts, i.e., step 2 to step 10 using for calculating the sum of reliability, step 11 using for sorting the n values in S_u, steps 14-19 using for dividing the n nodes into m clusters, step 21 to step 31 using for computing the maximum reliability in each cluster and step 32 using for computing the maximum sum of reliability from satellite to controllers. Specifically, for steps 2-10, outer for-loop runs for n times and inner one $n + k$ times, so the double for-loops run $n \cdot (n + k)$ times. It takes $\frac{n \cdot (n-1)}{2}$ times to perform the sorting procedure. For step 14 to step 19, the running time is $O(m \cdot (n - m))$, for step 21-31 is $O(\frac{n^2}{m})$, and for step 32 is $O(k \cdot m)$. In brief, the time complexity of CAA in Procedure 1 can be calculated by adding them up, i.e., $O(n \cdot (n + k) + \frac{n \cdot (n-1)}{2} + m \cdot (n - m) + \frac{n^2}{m} + k \cdot m) = O(n^2)$. Therefore, each

TABLE II
TOPOLOGY SETTINGS

Topology	Number of nodes	Number of links
Nsfnet	13	15
Agis	25	30
OS3E	34	41
Chinanet	42	66

TABLE III
FAILURE PROBABILITY SETTINGS

	P_v terrestrial nodes	P_e terrestrial links	P_{esg} satellite links
Case 1	[0, 0.05]	[0, 0.02]	[0, 0.02]
Case 2	[0, 0.06]	[0, 0.04]	[0, 0.03]
Case 3	[0, 0.07]	[0, 0.06]	[0, 0.04]
Case 4	[0, 0.08]	[0, 0.08]	[0, 0.05]

iteration of the while-loop in Algorithm 4 can be computed in $O(n^2)$ time. ■

VI. NUMERICAL RESULTS

Besides the four algorithms proposed in Section IV and Section V, i.e., OEA, SAA, OEAJ and SACA, we also adopt two random placement algorithms with the lowest computational complexity in our experiments, named RANDS and RANDJ, for satellite gateway placement and joint placement problem, respectively.

A. Experimental Settings

Without loss of generality, we took the real world online network topologies from the Topology Zoo [38] for implementing SDN-enabled 5G-satellite communication infrastructures. In particular, Table II lists four different topologies we considered. Regarding the failure probability of switches, terrestrial and satellite links for the joint placement problem discussed in Section V, we considered four different cases as summarized in Table III. For the random placement algorithms, we repeated the random selection process 1000 times and took the average value. All experiments were performed in Matlab R2016a running on a PC with double 3.30GHz CPUs, 8.00GB RAM, and Windows 7 OS.

B. Satellite Gateway Placement for Latency Minimization

As stated in Section II, there have been several algorithms proposed to solve the gateway placement problem in terrestrial network, Table IV lists the computational complexity of those algorithms and our proposed solutions. In Table IV, n, k, and t denote the number of network nodes, number of gateways, and the number of iterations, respectively. To provide comparisons between our proposed solutions and available algorithms, in addition to OEA and SAA as well as RANDS, we also adopt a well-known clustering algorithm, k-median, in our experiments.

We use Figure 2 and Figure 3 to demonstrate the experimental results of satellite gateways placement problem. Figure 2(a) depicts the comparison results of overall average latency among OEA, SAA, k-median and RANDS, where

TABLE IV
COMPUTATIONAL COMPLEXITY OF GATEWAY PLACEMENT ALGORITHMS

Algorithm	Reference	Computational complexity
Polynomial time near-optimal algorithm	[19]	$O(n^2)$
k-center	[20]	$O(n^3)$
k-median	[21]	$O(t \cdot (k \cdot n + \frac{n^2}{k}))$
Integer linear programming	[22]	$O(n^2)$
SAA	this paper	$O(t \cdot k \cdot n)$

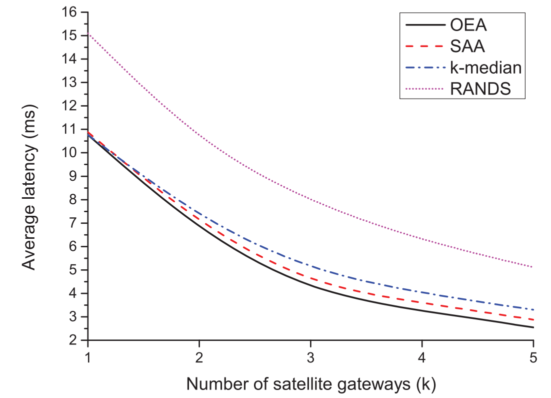
the X-axis denotes the number of satellite gateways, i.e., k, and the Y-axis is the calculated minimum average latency. As illustrated in Figure 2(a), the network latency decreases monotonically with the increasing number of gateways k due to that more satellite gateways can reduce the least hops of the path from each terrestrial node to the satellite. It is clearly that OEA could get the optimal solution. With k increasing from 1 to 5, the gap between OEA and SAA is small, that is, SAA can obtain a near-optimal solution compared to OEA, and it has better performance than k-median. Figure 2(b) presents the comparison of the running time among these algorithms. From Figure 2(b), one can observe that OEA has much longer running time than SAA and k-median, and the computational complexity of SAA is lower than that of k-median.

In order to give further validation that SAA is able to give a near-optimal solution to the satellite gateway placement problem in different network scales, for each topology listed in Table II, we place three satellite gateways to compare the overall minimum average latency and running time among these four algorithms. From Figure 3(a), we can see that SAA can obtain a near-optimal solution compared to OEA and it has better performance than k-median for all the four different topologies. Moreover, RANDS has a bad performance whether the number of the topology nodes and links is large or small. Figure 3(b) shows that though OEA and k-median have smaller running time than SAA does in the small scale network topology (Nsfnet), with the number of nodes and links increasing, the running time of both OEA and k-median becomes larger than that of SAA, and OEA has extremely longer running time.

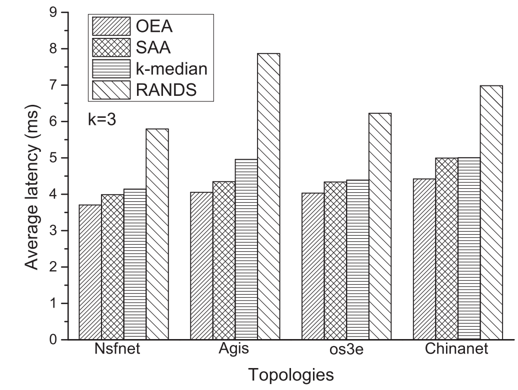
From above experiments, we can see that although OEA gives an optimal solution to SGPP, it is unacceptable in practice due to its exponential computational complexity. Rather, although SAA can only give near optimal solutions, it has very higher computational efficiency than OEA, and thus it provides workable solutions to the satellite gateway placement problem in 5G-satellite integrated network.

C. Joint Placement for Reliability Maximization with Latency Constraint

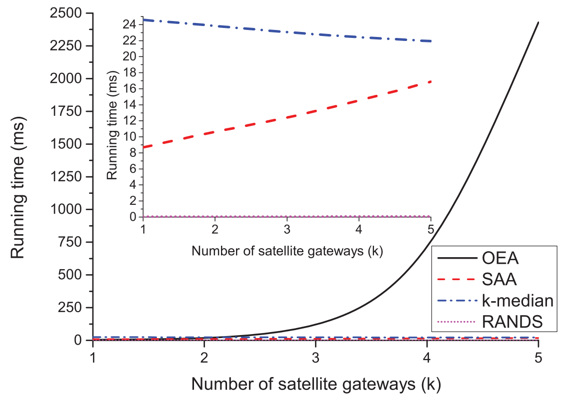
In the following, we make some comparisons between OEAJ, SACA and RANDJ to show the experiment results of the joint placement problem. Since existing algorithms cannot be readily applicable to such a problem, in order to validate the performance of our proposed solutions, we replace Procedure 1 with a modified k-median approach in SACA to design a new algorithm and name it as SAKM. Here, the Agis Topology is



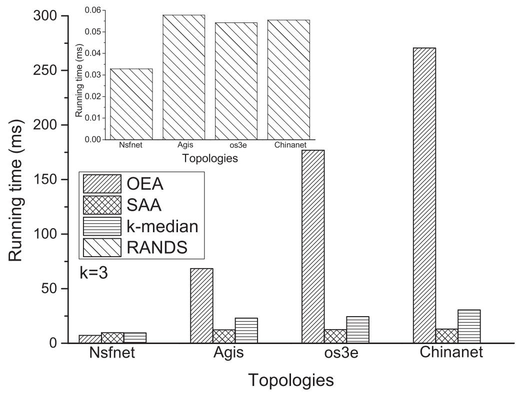
(a) Comparisons of the overall network average latency.



(a) Comparisons of the overall network average latency .



(b) Comparisons of the overall running time.



(b) Comparisons of the overall running time.

Fig. 2. Illustration of experimental results of network average latency and running time in Agis Topology.

Fig. 3. Comparisons of network average latency and running time of four topologies in Table II.

used in this experiment, and Case 1 in Table III is selected as the failure probability setting, the number of satellite gateways, k, is set as 3.

Figure 4 illustrates the comparison results of the maximum average reliability and running time among OEAJ, SACA, SAKM, and RANDJ. As depicted in Figure 4(a), with the latency constraint L_{max} = 10 ms, SACA and SAKM can give an approximate solution to OEAJ, which can achieve an optimal one, and RANDJ gets the worst performance. What's more, SACA has better performance than SAKM. From Figure 4(a), we also observe that, the reliability presents a monotone increasing tendency with the number of controllers growing. Obviously, increasing the number of controllers is a direct method to improve the whole network reliability. The reason is that, if each terrestrial node acts as a controller, the hops between switch and controller will reduce to zero so as to avoid the failure of physical links and get a maximum reliability. From the comparison of computational complexity among these four algorithms in Figure 4(b), one can see that, SACA has better computational efficiency than SAKM, with the m growing, the running time of OEAJ becomes excessively longer while that of SACA and SAKM remain almost no change. We can obtain the conclusion that SACA is indeed able to give a near optimal performance and has an efficient computational complexity.

To further evaluate the performance of OEAJ, SACA, SAKM, and RANDJ, we execute these algorithms in different topologies and failure probability settings with $k = 2$ and $m = 2$. As shown in Figure 5(a), with the latency constraints, for all the four different topologies, the average reliability of SACA is very close to the optimal performance of OEAJ and is even higher than that of SAKM, and RANDJ has a bad performance. Figure 5(b) shows that the network reliability decreases as the failure probability increases since there is more possibility for nodes or physical links in unreliable state in the network. Furthermore, SACA can give a more near-optimal solution than SAKM for all the four cases .

To identify how the latency constraint affects the maximum reliability of the integrated network, we place two satellite gateways and two controllers into the Agis Topology to compare the performances among OEAJ, SACA, SAKM and RANDJ. In this simulation, we set the network components failure probabilities to the same values as Case 1 in Table III. In particular, the latency constraint varies from 6 ms to 20

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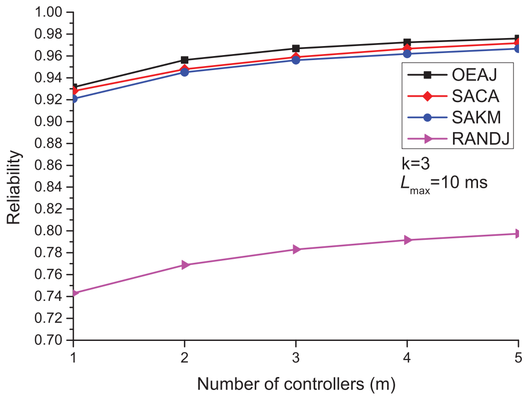
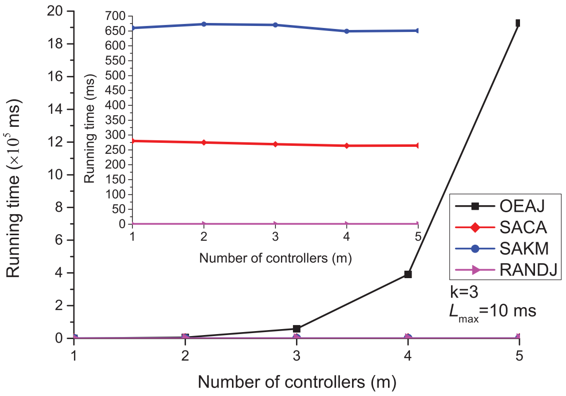
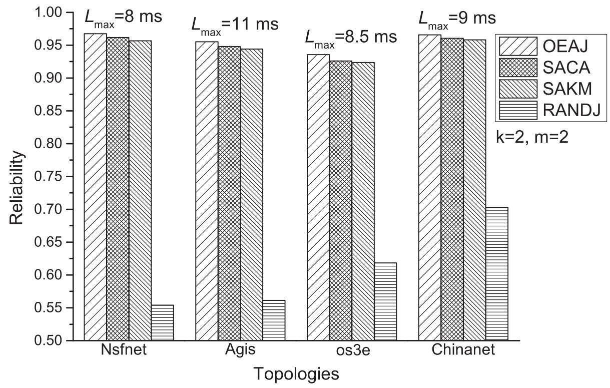


(a) Comparisons of the overall network average reliability .

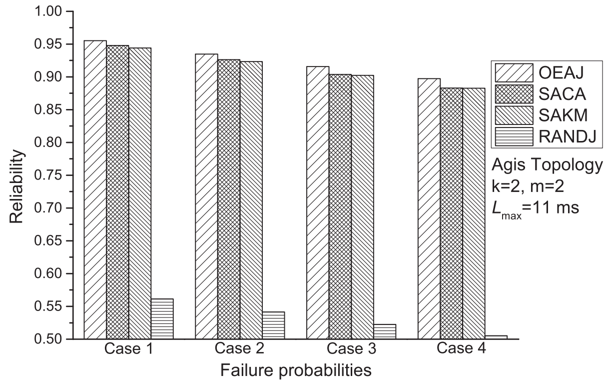


(b) Comparisons of the overall running time.

Fig. 4. Comparisons of network average reliability and running time with the latency constraint in Agis Topology.



(a) Comparisons of four topologies in Table II.



(b) Comparisons of four failure probability cases in Table III.

Fig. 5. Illustration of experimental results of average network reliability with the latency constraint in different settings of network topology and failure probability.

ms with the increment of 0.5 ms. Figure 6 illustrates the comparison results of the maximum average reliability with the latency constraints among these four algorithms. As depicted in Figure 6, when the latency constraint L_{max} is less than the minimum value obtained from the OEA solution, all the four algorithms give the reliability of zero. With the L_{max} becoming larger than the minimum value, especially when $L_{max} \geq 7.5$ ms, OEAJ and SACA as well as SAKM can give their maximum performances. While RANDJ is unable to obtain its best solution until L_{max}>16 ms.

D. Reliability Maximization with Minimum Latency

In general, the optimization problem in SDN-enabled 5G-satellite integrated network requires tradeoffs between performance metrics. Specifically, we are interested in finding the tradeoff between reliability and latency in the integrated network. The experiments are executed using SAA to get the near optimal placement solution of the satellite gateways and the minimum average latency. Based on this satellite gateway placement, we use CAA to obtain the near optimal reliability of the integrated network. Figure 7 shows the relationship between the maximum reliability and minimum latency of the

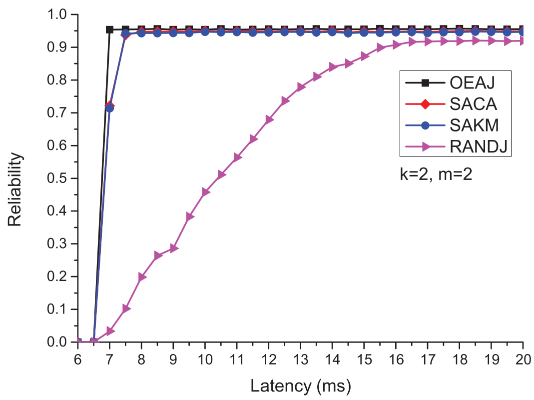


Fig. 6. Illustration of experimental results of maximum average network reliability with different latency constraints in Agis Topology.

network for the four different topologies in Table II. Here the number of controllers is set as 5 and that of satellite gateways varies from 1 to 5, and the failure probability is selected as

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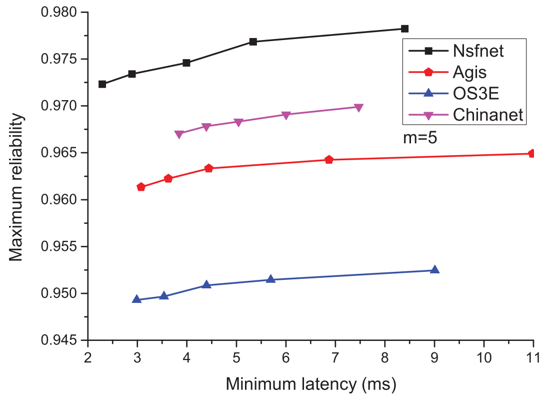

Fig. 7. Illustration of relationship between maximum reliability and minimum latency for four topologies in Table II.

case 1 in Table III.

From Figure 7, one can easily know that when the network latency increases, the reliability follows. It is almost impossible to improve reliability while reducing latency simultaneously. A natural question is how to make tradeoff between these metrics. To answer this question, we should consider the actual application scenarios of the integrated network. For example, in a time sensitive circumstance, we should give priority to the latency minimization and have to lose a certain reliability, and vice versa.

VII. Conclusion

In this paper, we have investigated the joint placement problem of controllers and satellite gateways for network reliability maximization in SDN-enabled 5G-satellite integrated network. We first discussed how to place satellite gateways to minimize the average latency from terrestrial nodes to the satellite and proposed SAA as solution to solve this problem. Then we developed SACA for the joint placement problem so as to maximize the reliability of whole network with latency constraint. Four different real world online topologies and four different failure probability settings were adopted for our experiments. Experimental results corroborated that SAA and SACA can obtain near-optimal performances compared to enumeration algorithms with much lower computational complexity.

Notice that toward the joint placement problem, we considered a relatively simple scenario where only average propagation latency and reliability were optimized, which neglected an important issue of traffic distribution. Therefore, as part of our future works, we plan to further study the traffic distribution and traffic offloading problems in the SDN-enabled 5G-satellite integrated network, where traffic flows with different QoS requirements should be routed to different terrestrial or satellite links according to their actual bandwidths. Besides, to explore whether there are new algorithms to solve such a joint placement problem, is also one of our future directions.

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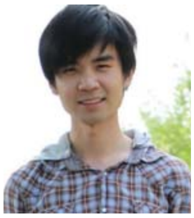

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