tp-MA: Orchestrating Three Populations Memetic Algorithm for VNF Deployment in 5G Network

Hejun Xuan, Shiwei Wei, Xuelin Zhao, Yahui Xue, Lanlan Qiao, and Yanling Li

Abstract—**Virtual network function (VNF) is the key issue and can provide various network services and is widely deployed in 5G communication. Routing and VNF deployment for the VNF service chain (VNF-SC) is a very important and well-known NP-hard problem. For this problem, if determining the number and locations of data centers is additionally considered, it will be more complexity. In this paper, we investigate a network planning problem by determining all these factors, i.e, by determining not only the optimal routing and the optimal VNF deployment for VNF-SCs, but also the optimal number and locations of data centers. To achieve this purpose, a three objectives optimization model, which minimizes capital expenditure, the maximum index of used frequency slots and the number of deployed VNFs on all data centers, is estimated. To solve this model efficiency, we integrate three objectives into one objective by using a weighted sum strategy. Then, a high-performance memetic algorithm with three populations (tp-MA), which includes well-designed crossover, mutation, and local search operators, is proposed. To demonstrate reasonable of the model and high performance of the designed algorithm, a series of experiments are conducted in several different experimental scenes. Experimental results indicate that the effectiveness of the proposed model and the efficiency of the proposed algorithm.**

Index Terms—**5G Network, Datacenter Placement, Multi-objective Optimization, Memetic Algorithm**

I. INTRODUCTION

IN recent years, service providers are facing the problem to deploying some new network services flexibly and effectively. To realize this, researchers developed the network function virtualization (NFV) to satisfy various demands of users [1], [2]. NFV utilizes virtualization technology to decouple network functions from dedicated hardware into virtual network functions so that these functions can run as software images on commodity hardware as well as custom-built hardware [3], [4], [5]. With NFV technology, traditional hardware-based network appliances are replaced by software-based virtual network functions (VNFs), and VNFs can be realized on the datacenters (i.e., VNF service chain, VNF-SC) [6], [7], [8]. The deployment of new network services can be easily realized by routing data traffic through a series of VNFs on datacenters [9], [10], [11]. In general, VNF-SC has many advantages, such as high bandwidth capacity and low power consumption [12], [13], [14]. So, VNF-SC is especially beneficial. However, it is difficult and challenging to use the VNF-SCs.

Some researches have been done on network planning problems using the VNF-SCs, which mainly focused on the VNF-SC routing and VNF deployment problem[15], [16]. However, there are some challenges to serve VNF-SCs. The widely investigate problems are VNF-SC routing and VNF deployment To optimize the cost of the VNF deployment, an integer linear programming model is first established, and then three heuristic algorithms are proposed to solve the integer linear programming model effectively [17]. An efficient algorithm, which is based on the back-to-back strategy, is designed for the sake of minimizing the total cost of the energy consumption and the revenue loss due to QoS degradation [18]. Besides, a heuristic-based algorithm, which is divided into two sub-algorithms: one-hop optimal traffic scheduling problem and VNF chain composition problem is proposed to solve the mixed-integer linear programming model effectively. Marouen, et al. [19] proposed an algorithm based on the eigendecomposition for the VNF deployment in EONs for the sake of respecting user's requirements and maximizing provider's revenue. A strategy, which is based on graph partitioning game theory, is proposed to improve the overall allocation performance of deploying service chains satisfying server affinity, collocation, and latency constraints [20]. Shohreh et al. [21] formulated the problem of VNF placement as an integer linear programming model and proposes a cost-efficient centrality-based VNF Placement algorithm for the sake of finding the optimal number of VNFs along with their locations with the provider cost is minimized. In two domain EONs, literature [22] proposed an integer linear programming model and designed two time-efficient heuristics algorithms to minimize the total resource cost of VNF provisioning. A systematic method to elastically tune the proper link and server usage of each demand based on network conditions and demand properties is proposed, and the importance of the relation between the link and server usage in VNF placement and path selection problem is investigated [23]. To minimize the spectrum and the switch port usage, an integer linear programming model is established to solve the resource allocation problem in intra-DC EONs [24]. These studies investigate the routing and VNF deployment problem for VNF-SC. However, they have not investigated the DC placement problem. In general, the location of DC affects on the efficiency of routing and VNF deployment for VNF-SC. So, not only are routing and VNF

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Hejun Xuan, Xuelin Zhao, Yahui Xue, and Lanlan Qiao are with the school of Computer and Information Technology, Xinyang Normal University, Henan Xinyang, China, 464000 e-mail: xuanhejun0896@126.com.

Shiwei Wei are with the School of Computer and Technology, Guilin University of Aerospace Technology, Guilin, China, 541000.

Yanling Li is with Henan Key Lab. of Analysis and Application of Education Big Data, Xinyang Normal University, Henan Xinyang, China, 464000.

deployment for VNF-SC investigated, but also DC placement problem is investigated.

In this paper, we investigate a network planning problem in EONs by considering all these factors, i.e., we should determine not only the optimal routing and VNF deployment scheme for VNF-SC, but also the optimal number and location of data centers. To handle this problem, we first set up a three objectives optimization model. Then, these three objectives are integrated into one by using a weighted sum method. The major contributions of this study are summarized as follows:

- Not only the optimal routing and VNF deployment for VNF-SCs, but also the optimal scheme of data centers placement is investigated.
- A multi-objective optimization model, which minimizes the number of placed data centers, the maximum index of used frequency slots and the number of deployed VNFs on all data centers, is established.
- We design an effective three population memetic algorithm (tp-MA) with a novel encoding scheme and tailor-made crossover, mutation and local search operators to solve the proposed model.

The rest of this paper is organized as follows. Section II describes the problem formulation, and establishes the optimization model. To solve the optimization model effectively, we propose a memetic algorithm with tailor-made operators in section III. To evaluate the algorithm proposed, simulation experiments are conducted, and the experimental results are analyzed in Section IV. The paper is concluded with a summary in Section V.

II. PROBLEM DESCRIPTION AND MATHEMATICAL MODELING

A. Problem Description

We can use an undirected graph $V = (V, E)$ to denote a network, where $V = \{V_1, V_2, \cdots, V_{N_V}\}$ and N_V denotes the nodes set and the number of the nodes in the network, respectively. $E = \{l_{ij} | V_i, V_j \in V\}$ denotes the link set, and N_E denotes the number of links in the network. If $l_{ij} = l_{ji} = 1$, there is a link between V_i and V_j, otherwise, $l_{ij} = l_{ji} = 0$. Let $F = \{f_1, f_2, \cdots, f_{N_F}\}$ denote the set of available frequency slots (FSs) in each link, and N_F be the number of frequency slots. $VNF = \{VNF_1, VNF_2, \cdots, VNF_{N_{vnf}}\}$ denotes the VNF set that this network can be realized, and N_{vnf} is the number of VNFs. Now, given some data centers, we have to select the same number of nodes in EONs as the number of given data centers and connect these selected nodes to the given data centers. In general, each selected node uniquely connects to one data center and each data center also uniquely connects to one selected node. In this way, we can consider this node connected to a data center as a DC-node which has the all resources and functions of the data center without any cost.

$R = \{R_1, R_2, \cdots, R_k, \cdots, R_{N_R}\}$ denotes a set of VNF-SCs, where N_R is the number of VNF-SCs, and R_k is the k-th VNF-SC. R_k can be represented as $R_k = (s_k, d_k, B_k, VNF_k^I, VNF_k^D)$, where s_k and d_k are the source and destination node. $VNF_k^I = \{VNF_{k_1}^I, VNF_{k_2}^I, \cdots, VNF_{k_{N_k^I}}^I\}$ and $VNF_k^D = \{VNF_{k_1}^D, VNF_{k_2}^D, \cdots, VNF_{k_{N_k^D}}^D\}$. In VNF_k^I, all the required VNFs are independent and the order of these VNFs is flexible. However, all the required VNFs in VNF_k^D are dependent. That is to say, VNFs in VNF_k^D can not be arranged freely, they must be arranged in a special order. $B_k = (b_k^0, B_k^I, B_k^D)$, where b_k^0 is the number of frequency slots occupied by the initial data in R_k. $B_k^I = (b_{k_1}^I, b_{k_2}^I, \cdots, b_{k_{N_k^I}}^I)$ and $B_k^D = (b_{k_1}^D, b_{k_2}^D, \cdots, b_{k_{N_k^D}}^D)$ are the numbers of frequency slots of R_k required to send the given data. The changed data will continue to be sent to the next DC-node. Generally, let b_k^I or b_k^I denotes the number of frequency slots occupied by the changed data after $VNF_{k_t}^I$ or $VNF_{k_t}^D$ is realized. Each frequency slot has the same bandwidth C_{fs}, and the capacity of a frequency slot is $ML \times C_{fs}$, where ML is the bits per symbol in a specific modulation level. ML can be assigned as 1, 2, 3 and 4 for different modulation level of BPSK, QPSK, 8QAM and 16QAM. If the modulation level of connection request R_k is denoted by ML_k, the number of frequency slots b_k^0 of connection request R_k required can be calculated by

$$b_k^0 = \left\lceil \frac{B_k^I}{ML_k \times C_{fs}} \right\rceil . \tag{1}$$

where B_k^I denotes the number of frequency slots occupied by the initial data in R_k without modulation level considered.

Since these VNFs must be realized on data centers, the data center placement scheme should be determined. If the number of data center is smaller, it will reduce the performance of the network, otherwise, it will increase the capital expenditure. Also, the location of the data centers can also affect on the performance of the network, so the optimal data center placement scheme should be determined. To complete the VNF-SC, we have to do the following things: 1) select a path from the source node to the destination node to send the given data i.e., routing. 2) assign which DC-nodes in the path to realize which VNFs, i.e., VNF deployment. 2) assign the frequency slots in each link of the path for VNF-SC.

B. Mathematical Modeling

To achieve the some objectives, the optimal schemes of data center placement, routing, VNF deployment and frequency slots assignment should be determined. In this paper, the first objective is minimize the capital expenditure, that is to say, the should minimize the number of placed data centers. This objective can be expressed as

$$\min N_{DC} = \min \left\{ \sum_{i=1}^{N_V} x_i \right\} \tag{2}$$

where $x = (x_1, x_2, \cdots, x_i, \cdots, x_{N_V})$, and $x_i (i = 1, 2, \cdots, N_V)$ is boolean variable, $x_i = 1$ if and only if there is a data center connected to node V_i, otherwise, $x_i = 0$. Since we have $N_{DC} \leq N_V$, we can normalize N_{DC} by N_{DC}/N_V. Then we have $0 \leq N_{DC}/N_V \leq 1$ and the objective can be re-expressed as

$$\min f_1 = \min \left\{ \frac{1}{N_V} \sum_{i=1}^{N_V} x_i \right\} \tag{3}$$

The second objective is minimize the maximum index of the used frequency slots to serve all the VNF-SCs, that is to say, the should minimize the number of data centers. This objective can be expressed as

$$\min N_F^U = \min \left\{ \max_{l_{ij} \in E} n(F_{l_{ij}}) \right\} \tag{4}$$

where $n(F_{l_{ij}})$ is the maximum index of used frequency slots on link l_{ij} of R_k. Note that $N_F^U \leq N_F$. We can normalize N_F^U by N_F^U / N_F. Thus, we have $0 \leq N_F^U / N_F \leq 1$. So this objective can be expressed by

$$\min f_2 = \min \left\{ \frac{N_F^U}{N_F} \right\} \tag{5}$$

The third objective is minimize the number of deployed VNFs on all data centers. If λ_i denotes the number of deployed VNFs on node V_i, this objective is

$$\min N_{vnf}^I = \min \left\{ \sum_{i=1}^{N_V} x_i \lambda_i \right\} \tag{6}$$

Note that $\lambda_i \leq N_{vnf}$ and $N_{DC} \leq N_V$. We can normalize N_{vnf}^I by $N_{vnf}^I / (N_{vnf} \times N_V)$. Thus, we have $0 \leq N_{vnf}^I / (N_{vnf} \times N_V) \leq 1$. So this objective can be expressed by

$$\min f_3 = \min \left\{ \frac{N_{vnf}^I}{N_{vnf} \times N_V} \right\} \tag{7}$$

Now we integrate the three objectives into one to be minimized as follows

$$\min f = \min \left\{ \alpha \frac{N_F^U}{N_F} + \beta \frac{N_F^U}{N_F} + \gamma \frac{N_{vnf}^I}{N_{vnf} \times N_V} \right\} \tag{8}$$

where α, β and γ are three weights to adjust the importance of the three objectives, and we have $0 \leq \alpha, \gamma, \delta \leq 1$, $\alpha + \gamma + \delta = 1$. Since $0 \leq f_1, f_2, f_3 \leq 1$, thus, $0 \leq f \leq 1$. The objective should be made under some conditions. These conditions constitute the constraints of the problem as follows:

Constraint (a): The number of DC-nodes should be not be greater than the number of nodes in EONs and not less than n_{dc}. That is

$$n_{dc} \leq N_{DC} = \sum_{i=1}^{N_V} x_i \leq N_V, \tag{9}$$

Constraint (b): Each VNF service chain $R_k (\forall R_k \in R)$ must occupy one and only one path. That is,

$$\sum_{q=1}^{N_k^Q} \lambda_k^q = 1, \ \forall R_k \in R \tag{10}$$

where $Q_k = \{Q_k^1, Q_k^2, \cdots, Q_k^{N_k^Q}\}$ is the set of candidate paths for the VNF-SC R_k with N_k^Q being the number of candidate paths. λ_k^q is a boolean variable, and $\lambda_k^q = 1$ if and only if the path Q_k^q is occupied by R_k, otherwise, $\lambda_k^q = 0$.

Constraint (c): Each VNF of $R_k (\forall R_k \in R)$ required can only be deployed in one datacenter. We can express this constraint by

$$\sum_{v_i \in V_k^q} \psi_{kt}^i = 1, \ \forall VNF_{k_t} \in (VNF_k^I \cup VNF_k^D) \tag{11}$$

where ψ_{kt}^i is a boolean variable, $\psi_{kt}^i = 1$ if and only if the VNF_{k_t} is deployed in V_i, otherwise, $\psi_{kt}^i = 0$. V_k^q denotes the set of datacenters in path Q_k^q.

Constraint (d): VNFs on the datacenters, which connect to the nodes of each candidate paths in Q_k, can satisfy the specific order of the VNFs in VNF_k^D. That is

$$VNF_{k_a}^D \in \bigcup_{v_i \in V_k^q(b^D)} VNF_{v_i}, \ \forall \langle VNF_{k_a}^D, VNF_{k_b}^D \rangle \tag{12}$$

where $\langle VNF_{k_a}^D, VNF_{k_b}^D \rangle$ represents that $VNF_{k_a}^D$ should be implemented before $VNF_{k_b}^D$. $V_k^q(b^D)$ denotes the set of data centers in path Q_k^q (the order of data centers in $V_k^q(b^D)$ is the same as that of data centers appeared in path Q_k^q), and these data centers must be located in front of the data center that $VNF_{k_a}^D$ is deployed in.

Constraint (e): Assuming that l_{ij} and $l_{i'j'}$ are two different links on the path of $R_k (\forall R_k \in R)$ occupied, the index of the first frequency slot, which are assigned to R_k on l_{ij} and $l_{i'j'}$, must be identical. This can be given by

$$f_{ij}^k = f_{i'j'}^k, \ \forall r_k \in R \tag{13}$$

where f_{ij}^k and $f_{i'j'}^k$ are the index of the first frequency slot that R_k occupied on link l_{ij} and $l_{i'j'}$, respectively.

Constraint (f): We must assign consecutive frequency slots to $R_k (\forall R_k \in R)$. We can express this constraint by

$$\sum_{u=f_{ij}^k}^{f_{ij}^k + B_k + GF - 1} \phi_{k,ij}^{q,u} = B_k + GF, \ \forall r_k \in R \tag{14}$$

where $\phi_{k,ij}^{q,u}$ is a boolean variable. $\phi_{k,ij}^{q,u} = 1$ if and only if the u-th frequency slot on link l_{ij} of path Q_k^q is occupied by R_k, otherwise, $\phi_{k,ij}^{q,u} = 0$. GF is the number of guaranteed frequency slots.

Constraint (g): For any two VNF-SC R_k and $R_{k'}$ which occupy the same link l_{ij}, if the start frequency slot index of R_k is smaller than that of $R_{k'}$, this case is denoted by $R_k \prec r_{k'}$. Then these two VNF-SC should satisfy

$$f_{ij}^k + B_k + GF \leq f_{ij}^{k'}, \ \forall R_k \prec R_{k'} \tag{15}$$

Based on above objectives and constraints, we can set up a global constrained optimization model as follows:

$$\left\{ \begin{array}{l} \min f = \min \left\{ \alpha \frac{N_F^U}{N_F} + \beta \frac{N_F^U}{N_F} + \gamma \frac{N_{vnf}^I}{N_{vnf} \times N_V} \right\} \\ s.t. \\ (a) n_{dc} \leq N_{DC} = \sum\limits_{i=1}^{N_V} x_i \leq N_V; \\ (b) \sum\limits_{q=1}^{N_k^Q} \lambda_k^q = 1, \ \forall R_k \in R; \\ (c) \sum\limits_{v_i \in V_k^q} \psi_{kt}^i = 1, \ \forall VNF_{k_t} \in (VNF_k^I \cup VNF_k^D); \\ (d) VNF_{k_a}^D \in \bigcup_{v_i \in V_k^q(b^D)} VNF_{v_i}, \ \forall \langle VNF_{k_a}^D, VNF_{k_b}^D \rangle; \\ (e) f_{ij}^k = f_{i'j'}^k, \ \forall r_k \in R; \\ (f) \sum\limits_{u=f_{ij}^k}^{f_{ij}^k + B_k + GF - 1} \phi_{k,ij}^{q,u} = B_k + GF, \ \forall r_k \in R; \\ (g) f_{ij}^k + B_k + GF \leq f_{ij}^{k'}, \ \forall R_k \prec R_{k'}; \end{array} \right. \tag{16}$$

The problem of data center placement, routing, VNF deployment and spectrum assignment for VNF-SC in EONs is a hardest combinatorial optimization problems. The existing algorithms cannot be applied directly, and are necessary to make some improvements or revisions. To solve the global constrained optimization model established, we propose an efficient algorithm and denote it as tp-MA (three-population Memetic Algorithm).

III. Proposed tp-Memetic Algorithm

Memetic Algorithm have been proven to be an effective technique for many hard problems[25], [26]. However, it is not suitable to directly apply the algorithms mentioned above to the problems of VONs mapping in EONs, and it is necessary to make some improvements or revisions on them. In this section, we will describe the proposed tp-MA detailed, which includes encoding scheme, crossover operators, mutation operators and local search operators.

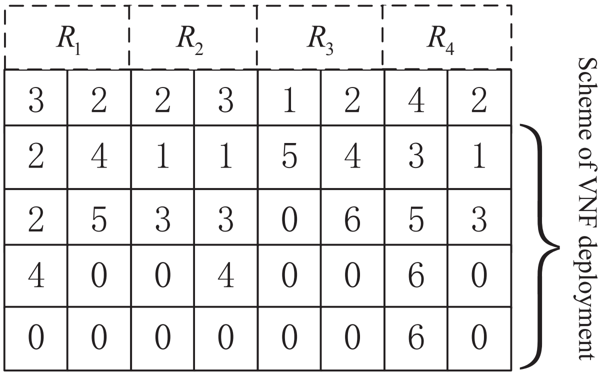
A. Encoding scheme

Note that there are four necessary steps to solve the problem: 1) determining the scheme of the data center placement; 2) routing; 3) VNF deployment; 4) spectrum assignment. It is much easier to assign spectra using first fit strategy [27] than using the method with encoding. Thus, we do not encode in the step of spectrum assignment. Therefore, it only needs to encode for the solutions in steps 1, steps 2, and steps 3. So it is necessary and reasonable to use three populations, i.e., data center placement population, routing population and VNF deployment population.

In data center placement population, each individual presents a data center placement scheme. We assume that $x = (x_1, x_2, \cdots, x_{N_V})$ is an individual in data center placement population. We have $x_i = 1 (1 \leq i \leq N_V)$ if and only if a data center connect to node v_i.

Similar to data center placement population, each individual in routing population presents a routing scheme. $Q_k = \{Q_k^1, Q_k^2, \cdots, Q_k^q, \cdots, Q_k^{N_k^Q}\}$ denotes the candidate paths set of VNF-SC R_k which is calculated by K-Dijkstra algorithm in advance, where N_k^Q is the number of the candidate paths and Q_k^q is the q-th path. We assume that $y = (y_1, y_2, \cdots, y_{N_R})$ is an individual in path selection population. $y_k = q$ if and only if R_k occupies the path Q_k^q.

Each individual in VNF deployment population presents a VNF deployment scheme for all the VNF-SC. We assume that $z = (z_1, z_2, \cdots, z_{N_R})$ is an individual in VNF deployment population, where z_k represent the VNFs in VNF_k^I and VNF_k^D deployment schemes of R_k, respectively. $N_D = max_{1 \leq k \leq N_R}\{N_k^I, N_k^D\}$. As shown in Fig.1, it denotes a VNF deployment scheme for a VNF-SC. The first column denotes the scheme of VNF deployment of dependent VNFs for R_1. Three VNFs are deployed on the V_2, V_2 and V_4. The second column denotes the scheme of VNF deployment of independent VNFs for R_1. These two VNFs are deployed on the V_4 and V_5. Similarly, the third and forth columns are the scheme of VNF deployment of VNFs for R_2.



R_1		R_2		R_3		R_4	
3	2	2	3	1	2	4	2
2	4	1	1	5	4	3	1
2	5	3	3	0	6	5	3
4	0	0	4	0	0	6	0
0	0	0	0	0	0	6	0

Fig. 1. An example of encoding scheme for VNF deployment

B. Crossover Operators

Since three different populations exist, three different crossover operators are presented to solve the optimization model effectively. Algorithm 1 is used to generate offspring for the datacenter placement individuals. Offspring for routing individuals are generated by Algorithm 2. Algorithm 3 is used to generate the new VNF dependent individuals. These three crossover operators have an advantage that the offsprings obtained by them are all the feasible solutions.

Algorithm 1: Crossover operator for datacenter placement individual

```
Input: Individual $x$ in datacenter placement population,
       minimum number of datacenters $n_{dc}$
Output: Offspring $x^c$ obtained by crossover operator
Two individuals $x'$ and $x''$ are selected randomly.
Let $A = x^T x'$ and $C = x''^T x'$,
    $x^A = diag(A)$,$x^C = diag(C)$;
for $k = 1, 2, \cdots, N_V$ do
    if $rand() \leq 0.5$ then
        $x_i^c = x_i^A \bigvee x_i^C$;
    else
        $x_i^c = x_i^A \bigwedge x_i^C$;
    end
end
if $diag((x^c)^T (x^c)) \leq n_{dc}$ then
    Let $n'_{dc} = \sum_{i=1}^{N_V} x_i^c$;
    An integer $n$ is generated randomly, and
        $n_{dc} \leq n \leq N_V$;
    $n' = n - n'_{dc}$;
    $Q$ denotes a indexes set that the elements are zeros
        in $x^c$;
    Generate a permutation of $Q$ randomly, and denote
        is as $Per$;
    $x^c_{Per(1:n')} = 1$;
end
```

C. Mutation Operators

Similar to the crossover operator, we also design three mutation operators to generate new individuals. Algorithm 4, which used to generate offspring, is the mutation operator for data center placement individuals. Offspring for routing individuals are generated by mutation operator in Algorithm 5. As shown in Algorithm 6, the mutation operator is used to generate the new VNF dependent individuals. These three mutation operators have an advantage that the offsprings obtained by them are all the feasible solutions.

Algorithm 2: Crossover operator for the routing individual

```
Input: Individual $y$ in routing population
Output: Offspring $y^c$ obtained by crossover operator
An individual $y' = (y'_1, y'_2, \cdots, y'_{N_T})$ is selected in the population;
Let $A = y^T y'$, and $C = diag(A)$
for $k = 1, 2, \cdots, N_R$ do
    $y_k^{'} = mod(C_k, N_k^Q) + 1$;
    if $f(x, y, z) \leq f(x, y', z)$ then
        $y_k^{'} = y_k$;
    end
end
```

Algorithm 3: Crossover operator for VNF deployment individual

```
Input: Individual $z$ in VNF deployment population
Output: Offspring $z^c$ obtained by crossover operator
Let $z^c = z$, An individual $z' = (z'_1, z'_2, \cdots, z'_{N_R})$ is selected in the population;
for $k = 1, 2, \cdots, N_R$ do
    $\eta$ is generated randomly, and $0 \leq \eta \leq 1$;
    if $\eta \leq 0.5$ then
        $z_k^c(:, 2 \times k) \leftrightarrow z_k^{'}(:, 2 \times k)$;
    else
        $z_k^c(:, 2 \times k + 1) \leftrightarrow z_k^{'}(:, 2 \times k + 1)$;
    end
    if $f(x, y, z) \leq f(x, y, z^c)$ then
        if $rand() \geq \exp(f(x, y, z) - f(x, y, z^c))$ then
            $z^c = z$;
        end
    end
end
```

Algorithm 4: Mutation operator for data center placement individual

```
Input: Individual $x$ in datacenter placement population
Output: Offspring $x^m$ obtained by mutation operator
for $i = 1, 2, \cdots, \lfloor N_V/2 \rfloor$ do
    $x'_i = x_{N_V - i}$;
end
An integer $p$ is generated randomly in $[1, N_V]$;
Let $A = x^T x'$, and $x^m = A(p, :)$;
if $\sum_{i=1}^{N_V} x_i^m < n_{dc}$ then
    Let $n_{dc}^{'} = \sum_{i=1}^{N_V} x_i^m$;
    An integer $n$ is generated in $[n_{dc}, N_V]$;
    $n' = n - n_{dc}^{'}$;
    $Q$ denotes a indexes set that the elements are zeros in $x^m$;
    Generate a permutation of $Q$ randomly, and denote is as $Per$;
    $x^m_{Per(1:n')} = 1$;
end
```

Algorithm 5: Mutation operator for routing individual

```
Input: Individual $y$ in routing population
Output: Offspring $y'$ obtained by mutation operator
for $k = 1, 2, \cdots, N_R$ do
    $y'_k = N_k^Q - y_k$;
end
Let $A = y^T y'$, and $C = diag(A)$
for $k = 1, 2, \cdots, N_R$ do
    $y'_k = mod(C_k, N_k^Q) + 1$;
end
```

Algorithm 6: Mutation operator for VNF deployment individual

```
Input: Individual $z$ in data center placement population
Output: Offspring $z'$ obtained by mutation operator
Let $z' = z$;
for $k = 1, 2, \cdots, N_R$ do
    $\eta$ is generated randomly, and $0 \leq \eta \leq 1$;
    if $\eta \leq 0.5$ then
        An integer $\mu$ is generated randomly, and $1 \leq \mu \leq N_k^D$;
        A node $\omega$, which satisfy the relationship of dependent in paths' set, is selected;
        $z_k^{'}(\mu, 2 \times k) \leftarrow w$;
    else
        An integer $\mu$ is generated randomly, and $1 \leq \mu \leq N_k^I$;
        A node $\omega$ is selected;
        $z_k^{'}(\mu, 2 \times k - 1) \leftarrow w$;
    end
    if $f(x, y, z) \leq f(x, y, z')$ then
        if $rand() \geq \exp(f(x, y, z) - f(x, y, z^c))$ then
            $z^c = z$;
        end
    end
end
```

D. Local Search Operator

Local search is an important operator in memetic algorithm, and it can help to get more precise solutions. In this paper, a local search operator, which can accelerate the convergence and enhance the searching ability of the proposed algorithm, is designed. Three local search operators for data center placement individual, routing individual and VNF deployment individual are shown in Algorithm 7, Algorithm 8 and Algorithm 9.

E. Fitness Function

Fitness function is an indicator which can evaluate the quality of individuals. In general, a fitness function is derived from the objective function of the programming model. We establish a global optimization model. So, we use formula (17) to define the fitness function to measure the quality of individuals. Since all the individuals are feasible solutions, the smaller the value of its fitness function is, the better the quality of the individual will be.

Algorithm 7: Local search operator for the data center placement individual

```
Input: Individual $x$ in datacenter placement population
Output: Offspring $x^l$ obtained by local search operator
$x^l = x$;
if $rand() \le 0.5$ then
    $N_{DC} = \sum_{i=1}^{N_V} x_i$;
    if $N_{DC} \le n_{dc}$ then
        $Q$ denotes an index set that the elements is 0 in $x$;
        Generate a permutation of $Q$, and denote is as $Per$;
        An integer $num$ is generated, and $1 \le num \le N_V - N_{DC}$, $x^l_{Per(1:num)} = 1$;
    else
        if $rand() \le 0.5$ then
            $Q$ denotes an index set that the element is 0 in $x$;
            Generate a permutation of $Q$, and denote is as $Per$;
            An integer $num$ is generated, and $1 \le num \le N_V - N_{DC}$, $x^l_{Per(1:num)} = 1$;
        else
            $Pos = [ind_1, ind_2, \cdots, ind_{N_{DC}}]$ denotes an index set that the element is 1 in $x$;
            Generate a permutation of $Pos$, and denote as $Per$;
            An integer $num$ is generated, and $1 \le num \le N_{DC} - n_{dc}$, $x^l_{Per(1:num)} = 0$;
        end
    end
else
    An integer $num$ is generated, and $1 \le num \le N_V$;
    for $i = 1, 2, \cdots, N_V$ do
        if $rand() \le 0.5$ then
            $x^l(mod(i + num, N_V) + 1) = x_i$;
        else
            $x^l(mod(i + N_V - num, N_V) + 1) = x_i$;
        end
    end
end
```

Algorithm 8: Local search for the routing individual

```
Input: Individual $y$ in routing population
Output: Offspring $y^l$ obtained by local search operator
$y^l = y$; $num = randint(N_V)$;
if $rand() \le 0.5$ then
    for $i = 1, 2, \cdots, N_R$ do
        $y^l(mod(i + num, N_V) + 1) = y_i$;
    end
else
    for $i = 1, 2, \cdots, N_R$ do
        $y^l(mod(i + N_V - num, N_V) + 1) = y_i$;
    end
end
```

Algorithm 9: Local search operator for VNF deployment

```
Input: Individual $z$ in the population
Output: Offspring $z^l$ obtained by mutation operator
Let $z^l = z$;
for $k = 1, 2, \cdots, N_R$ do
    $\eta$ is generated randomly, and $0 \le \eta \le 1$;
    if $\eta \le 0.5$ then
        An integer $\mu$ is generated randomly, and $1 \le \mu \le N_k^D$;
        A node $\omega$, which satisfy the relationship of dependent in paths' set, is selected;
        $z_k^l(\mu, 2 \times k) \leftarrow w$;
    else
        An integer $\mu, \nu$ is generated randomly, and $1 \le \mu \le N_k^I$;
        $z_k^l(\mu, 2 \times k - 1) \leftrightarrow z_k^l(\nu, 2 \times k - 1)$;
    end
    if $f(x, y, z) \le f(x, y, z^l)$ then
        if $rand() \ge \exp(f(x, y, z) - f(x, y, z^c))$ then
            $z^c = z$;
        end
    end
end
```

$$f(x,y,z) = \alpha\frac{N_F^U}{N_F} + \beta\frac{N_F^U}{N_F} + \gamma\frac{N_{vnf}^I}{N_{vnf} \times N_V} \tag{17}$$

IV. Experiments and Analysis

To demonstrate the effectiveness and efficiency of the proposed algorithm, several experiments are conducted, and the results are presented in this section. In section IV-A, the parameters used in the algorithms will be given. Experimental results are presented in section IV-B. Finally, the experimental analysis is given in section IV-C.

A. Parameters Setting

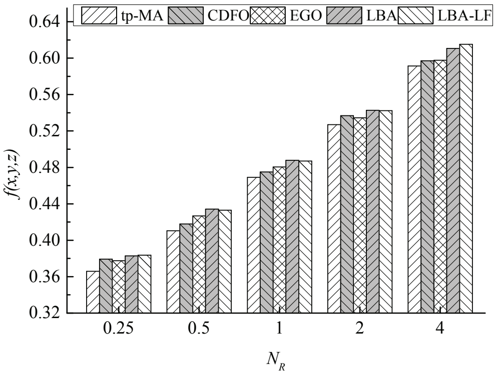
In the experiments, two widely used networks are used, i.e., NSFNET with 14 nodes and 21 links and US Backbone with 27 nodes and 44 links, respectively[28], [29]. We assume that each frequency slot is 12.5 GHz. There are N_{vnf} = 8 VNFs, and each VNF-SC has 1-5 VNFs to realize. Each VNF-SC requires frequency slots satisfy uniform distribution in [5, 10], and Each link has 1000 frequency slots, i.e., N_F = 1000. In proposed three populations memetic algorithm (we denote it as tp-MA), following parameters are chosen: population size $P_s = 100$, crossover probability $p_c = 0.8$, mutation probability $p_m = 0.1$, maximum iterations $G_{max} = 1000$, number of elites is 10.

B. Experimental Results

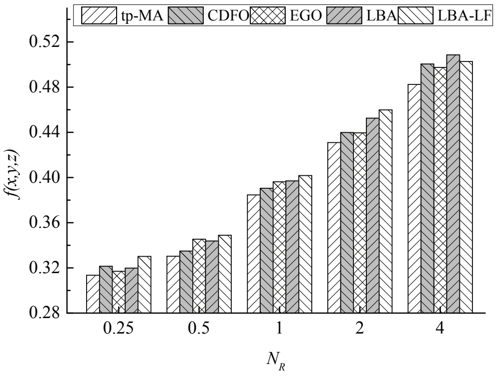
By our knowledge, there is no existing algorithm focusing on the problem of data center placement, we compare the proposed algorithm with the other two algorithms, which investigate path selection and VNF deployment for VNF-SC in EONs. The one is modified by the algorithm proposed in literature [7](briefly LBA), and the other one is LF-LBA, which includes the least fist strategy and LBA algorithm. In this way, we can make comparisons between the proposed algorithms and these two efficient algorithms. Besides, to demonstrate the proposed tp-MA can solve the global optimization model effectively, two recent algorithms, which denoted by CDFO[30] and EGO[31], are selected to compare with tp-MA.

To demonstrate the performance of proposed model and algorithm, we design two experimental scenes. In the first scene, we fixed the number of datacenter as $N_{DC} = N_V/3$ and $N_{DC} = 2N_V/3$, respectively. Fig.2 and Fig.3 show the results obtained in NSFNST topology and US Backbone topology when $\alpha = 0, \beta = 1, \gamma = 0$. Fig.4 and Fig.5 show the results obtained in NSFNST topology and US Backbone topology when $\alpha = \beta = 0, \gamma = 1$. Fig.6 and Fig.7 show the results obtained in NSFNST topology and US Backbone topology when $\alpha = \beta = \gamma = 1/3$. In each experiment, number of VNF-SCs are set as $N_R = \omega N_V(N_V - 1)$, and $\omega =$ 0.25, 0.5, 1, 2 and 4, respectively.

In the second experimental scene, the number of datacenters is not fixed, and the number of VNF-SCs are set as $N_R = \omega N_V(N_V - 1)$, where $\omega =$ 0.25, 0.5, 1, 2 and 4, respectively. Fig.8 shows the results obtained in NSFNST topology and US Backbone topology when $\alpha = 0, \beta = 1, \gamma = 0$. Fig.9 shows the results obtained in NSFNST topology and US Backbone topology when $\alpha = \beta = 0, \gamma = 1$. The results obtained in NSFNST topology and US Backbone topology when $\alpha = \beta = \gamma = 1/3$ are shown in Fig.10.

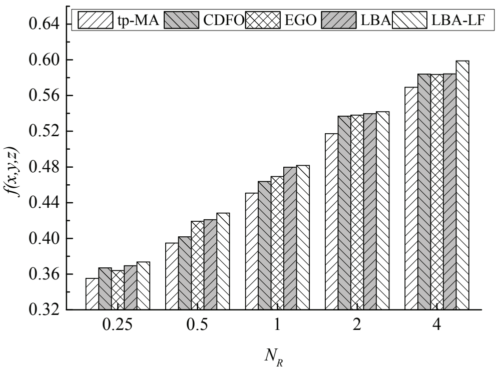


(a) $N_{DC} = N_V/3$

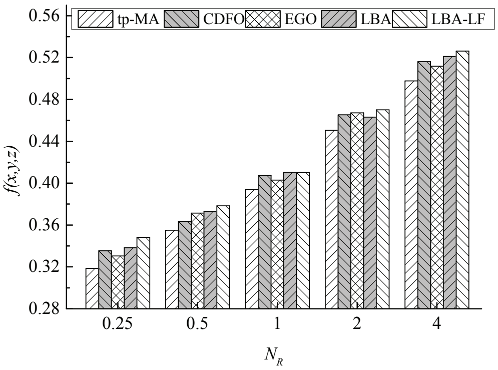


(b) $N_{DC} = 2N_V/3$

Fig. 2. Results obtained in NSFNET when $\alpha = 0, \beta = 1, \gamma = 0$.

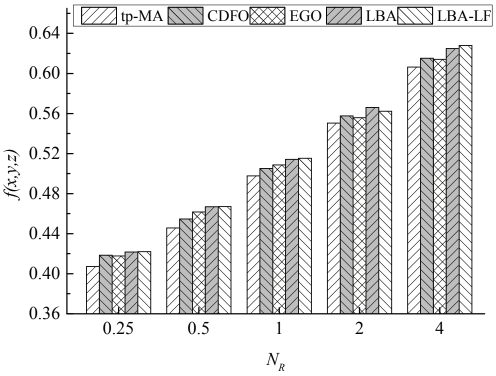


(a) $N_{DC} = N_V/3$

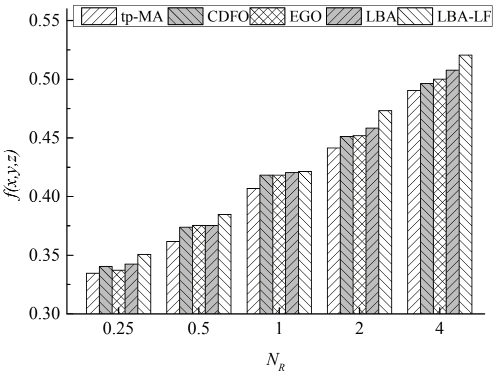


(b) $N_{DC} = 2N_V/3$

Fig. 3. Results obtained in US Backbone when $\alpha = 0, \beta = 1, \gamma = 0$.



(a) $N_{DC} = N_V/3$

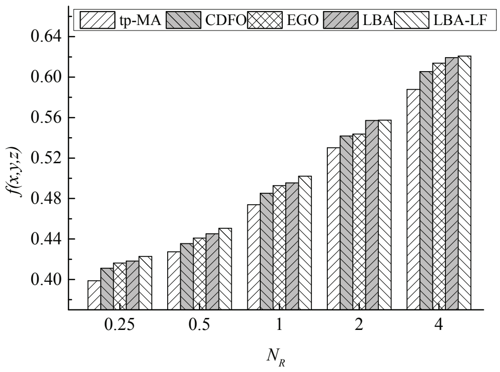


(b) $N_{DC} = 2N_V/3$

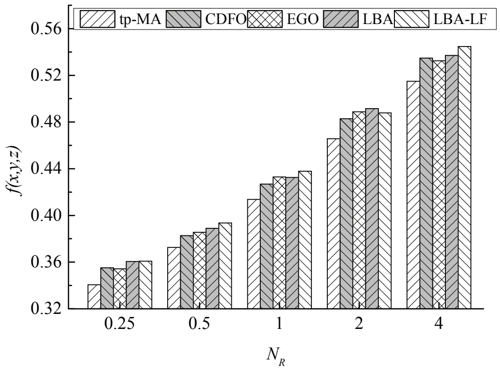
Fig. 4. Results obtained in NSFNET when $\alpha = \beta = 0, \gamma = 1$.

C. Experimental Analysis

In the first experimental scene, the experimental results obtained by the proposed algorithm (tp-MA) and four compared algorithms are shown in Fig.2 to Fig.7. The experimental results are shown in Fig.2 and Fig.3 in NSFNET and US BackBone when α, β and γ are selected as 0,

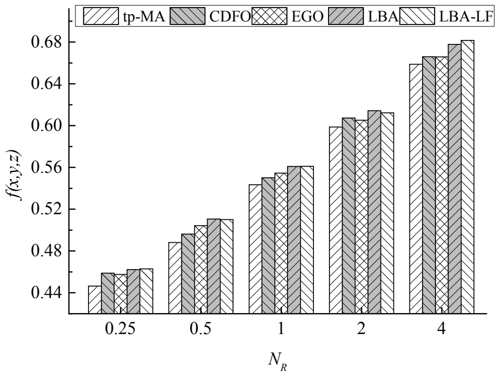


(a) $N_{DC} = N_V/3$

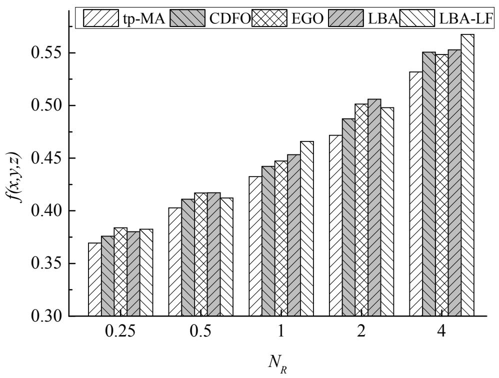


(b) $N_{DC} = 2N_V/3$

Fig. 5. Results obtained in US Backbone when $\alpha = \beta = 0, \gamma = 1$.

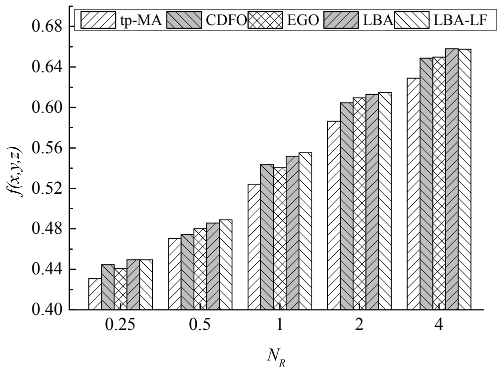


(a) $N_{DC} = N_V/3$

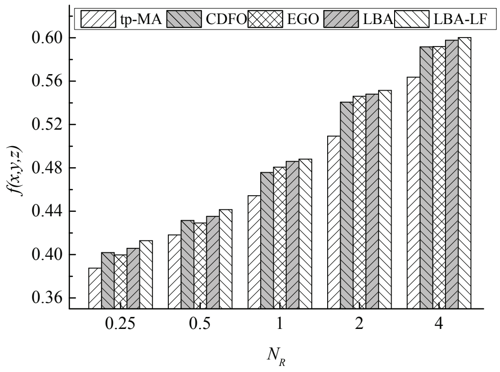


(b) $N_{DC} = 2N_V/3$

Fig. 6. Results obtained in NSFNET when $\alpha = \beta = \gamma = 1/3$.

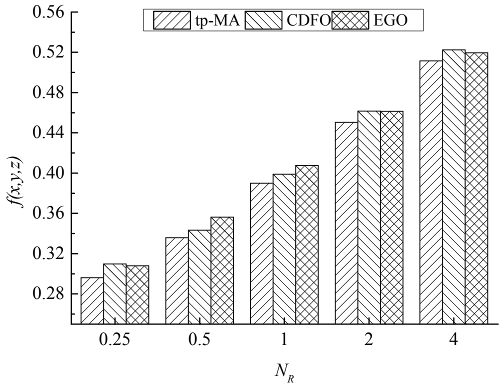


(a) $N_{DC} = N_V/3$

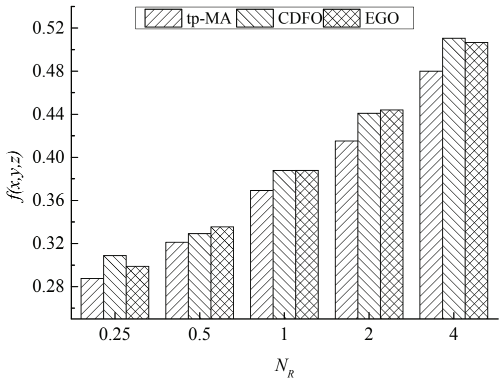


(b) $N_{DC} = 2N_V/3$

Fig. 7. Results obtained in US Backbone when $\alpha = \beta = \gamma = 1/3$.



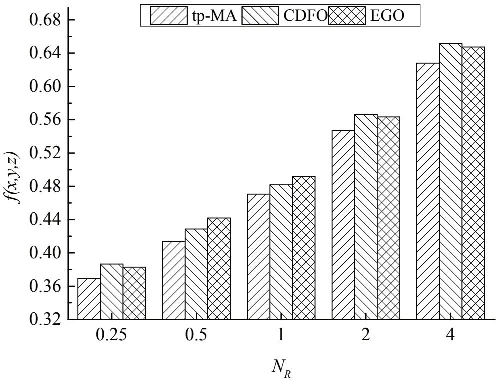
(a) Results obtained in NSFNET



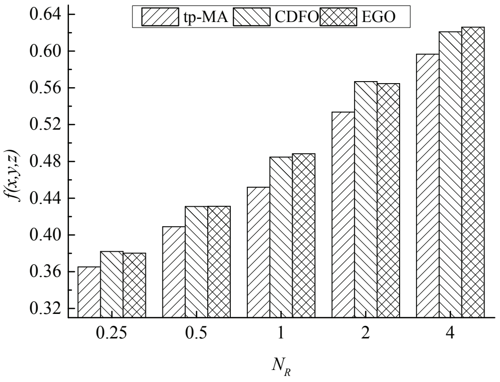
(b) Results obtained in US Backbone

Fig. 8. Results obtained when $\alpha = 0, \beta = 1, \gamma = 0$.

1 and 0, respectively. Thus, the objective function is to minimize the maximum index of used frequency slots. From the experimental results, we can see that the tp-MA can obtain better results than the four compared algorithms. The objective obtained by the tp-MA is 5.2%-6.8% less than those compared algorithms when the number of VNF-

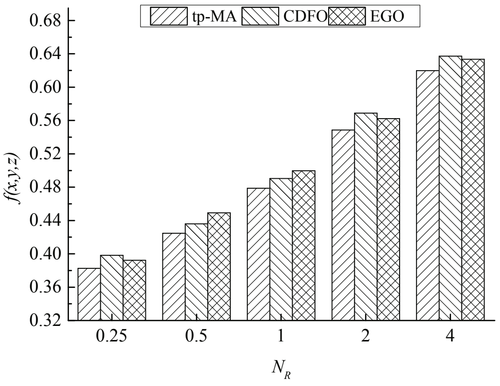


(a) Results obtained in NSFNET

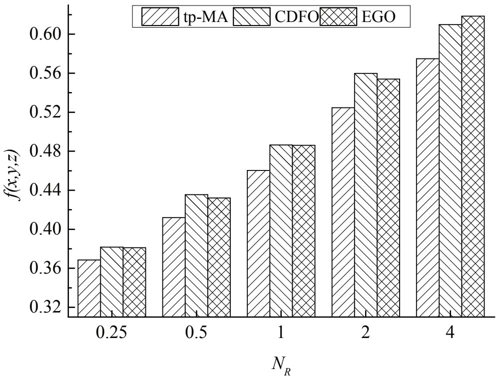


(b) Results obtained in US Backbone

Fig. 9. Results obtained when $\alpha = \beta = 0, \gamma = 1$.



(a) Results obtained in NSFNET



(b) Results obtained in US Backbone

Fig. 10. Results obtained when $\alpha = \beta = \gamma = 1/3$.

SCs is $0.25N_V(N_V - 1)$. When the number of VNF-SCs is $4N_V(N_V - 1)$, the objective obtained by the proposed algorithms is 10.5%-13.4% less than those obtained by compared algorithms. That is to say, the proposed algorithm can obtain a smaller maximum index of used frequency slots and save more frequency slots used than the four compared algorithms with the increase of the number of VNF-SCs. In general, the least first strategy can decrease the maximum index of used frequency slots. However, VNF dependency makes it disabled. So, LBA can obtain better results than LF-LBA in some cases, and LF-LBA is better than LBA in other scenarios. With the high-performance crossover, mutation and local search operator, tp-MA can find optimal data center placement, routing and VNF deployment schemes to serve all the VNF-SCs. So, tp-MA can obtain a better solution than the four compared algorithms. Also, when the number of data centers is $N_{DC} = 2N_V/3$, the value of objective function obtained is smaller than that obtained when the number of data centers is $N_{DC} = N_V/3$ for the same number of VNF-SCs. When the number of data centers is $N_V/3$, it will result that some links occupied by a large number of VNF-SCs became key links. So, the frequency slots used are imbalanced on different links. The VNF-SCs are deployed on different links balanced when the number of data centers is $2N_V/3$. So, the maximum index of used frequency slots and the number of frequency slots used are small.

Fig.4 and Fig.5 show the experimental results in NSFNET and US BackBone when α, β and γ are selected as 0, 0 and 1, respectively. Thus, the objective function is to minimize the number of deployed VNFs on all data centers. The objective obtained by the tp-MA is 2.7%-4.2% less than those obtained by compared algorithms when the number of VNF-SCs is $0.25N_V(N_V - 1)$. When the number of VNF-SCs is $4N_V(N_V - 1)$, the objective obtained by the proposed algorithms is 5.1%-6.9% less than those obtained by compared algorithms. That is to say, proposed algorithm tp-MA can obtain a smaller number of deployed VNFs on all data center and save the number of deployed VNFs on all datacenter than the four compared algorithms with the increase of the number of VNF-SCs. Also, when the number of data centers is $N_{DC} = 2N_V/3$, the value of objective function obtained is smaller than that obtained when the number of data centers is $N_{DC} = N_V/3$ for the same number of VNF-SCs.

The experimental results are shown in Fig.6 and Fig.7 in NSFNET and US BackBone when α, β and γ are all selected as 1/3. Thus, the objective function is to minimize the number of placed datacenters, the maximum index of used frequency slots and the number of deployed VNFs on all datacenters. Similarly, we can see that the tp-MA can obtain better results than the four compared algorithms. The objective obtained by the tp-MA is 4.0%-7.1% less than those obtained by algorithms LBA and LF-LBA, respectively when the number of VNF-SCs is $0.25N_V(N_V - 1)$. When the number of VNF-SCs is $4N_V(N_V - 1)$, the objective obtained by the proposed algorithms is 8.7%-14.2% less than those obtained by algorithms LBA and LF-LBA, respectively. The proposed algorithm tp-MA can obtain a smaller number of placed datacenters, the maximum index of used frequency slots and the number of deployed VNFs on all datacenters. Besides, it can decrease the number of placed datacenters, the maximum index of used frequency slots and the number of deployed VNFs on all datacenters than the four compared algorithms with the increase of the number of VNF-SCs. Also, when the number of data centers is $N_{DC} = 2N_V/3$, the value of objective function obtained is smaller than that obtained when the number of data centers is $N_{DC} = N_V/3$ for the same number of VNF-SCs.

V. CONCLUSION

In this paper, we investigate a resource allocation problem by considering all these factors, i.e., we should determine not only the optimal routing and VNF deployment scheme for VNF-SC, but also the optimal number and location of data centers. To minimize the number of placed data centers, the maximum index of used frequency slots and the number of deployed VNFs on all data centers, we first set up a three objectives optimization model. Then, three objectives are integrated into one objective by using a weighted sum method. To solve the model efficiency, a high performance three populations memetic algorithm, which includes well-designed crossover, mutation, and local search operators, is proposed. To demonstrate reasonable of the model and high performance of the designed algorithm, a series of experiments are conducted with several different scenes. Experimental results demonstrate that the proposed algorithm has a higher performance than the compared algorithms.

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