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Bandwidth Allocation With Utility Maximization in the Hybrid Segment Routing Network

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ABSTRACT Segment routing (SR) is a new network paradigm to optimize network performance. Through leveraging source routing, SR is able to achieve more fine-grained control of data flow in the SR domain. However, it is difficult to introduce large-scale full SR network into existing traditional network due to the economic constraints and immature operation technology. Thus, incrementally deploying SR nodes into an existing network is preferred, which forms the hybrid IP/SR scenario. In the hybrid network, with SR enabled devices, the routing path of flow can be dynamically adjusted. Network utility is an important factor to reflect the user's satisfaction with the allocated bandwidth. In this paper, we propose a bandwidth allocation algorithm to maximize network utility in hybrid IP/SR network and thus improve customer's satisfaction. The simulation results show that the bandwidth allocation algorithm proposed is able to improve the utility of network significantly, and the utility of network will increase with the number of SR nodes deployed in the network.

INDEX TERMS Segment routing, hybrid network, utility maximization.

I. INTRODUCTION

This conventional routing protocol Interior Gateway Protocol (IGP), which uses fixed single static routing metric and shortest path algorithm, is likely to cause congestion on critical links. Some traffic engineering measures such as Multi-Protocol Label Switching (MPLS) were introduced to solve the problem in traditional IP network. MPLS can explicitly route flows end-to-end. However, the signaling protocols Label Distribution Protocol (LDP) and Resource Reservation Protocol-Traffic Engineering (RSVP-TE) used in control plane of MPLS are complicated and suffer lack of scalability. Software Define Network (SDN) [1] is a new network paradigm, which decouples the control plane and data plane. Taking advantage of SDN, traffic engineering can be implemented in a centralized way. However, in SDN network, the control granularity of OpenFlow [2] is too small. To transmit a traffic flow, every switch on the routing path needs to store flow state in its ternary content addressable memory (TCAM) [3]. Because TCAM has limit resource, when the number of flows is large, the switch may not have memory to store flow state.

Recently, Segment routing (SR) [4] is proposed to deal with above problem. SR has tremendous advantages in future network transformation and traffic engineering for the following reasons. Firstly, SR leverages source routing paradigm, which steers a packet routing in the network through injecting a series of segments in packet header at edge router. Inner router only needs to forward the packet according to the segment list in packet header without storing the state information of every flow. The only thing controller needs to do is to calculate the routing path and send instructions to the source node instead of programming each flow on routers along the path. This feature of SR solves the scalability problem of SDN. Secondly, SR architecture can be applied to MPLS or IPv6 data plane through upgrading existing infrastructure software, which means this technology can be rapidly introduced into the existing network without causing disruption. Its ease of deployment is a significant advantage over other SDN technologies. In order to deploy SR on a large scale, the same problems of deploying SDN has to be considered [5]. Firstly, operators hope that the deployment of SR will not affect the existing network functions. Secondly, SR/SDN technology is not very mature. The reliability and stability of hardware and software need to be verified when SR nodes are deployed on a large scale. Thirdly, the budgets and operating costs of ISP is limited. So, upgrading a subset IP node to SR node is a suitable way to balance network performance and overheads.

Based on the above analysis, hybrid IP/SR network is a better transitional scenario. In hybrid IP/SR network scenario, SR nodes and IP nodes coexist. In IP domain, the data packets

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are forwarded by Open Shortest Path First (OSPF) routing protocol. In SR domain, the packets are routed by the control of SR controller. In this scenario, how to allocate the bandwidth to the flows in the network is a problem. Utility is an important factor to reflect the user's satisfaction with the allocated bandwidth. Therefore, it is important to study utility based bandwidth allocation algorithm for hybrid IP/SR network scenario. So far, most of the research work focus on full-SR scenario [6]–[8]. In [9], a TE approach is proposed with the goal of minimizing maximum link utilization in the hybrid scenario. However, this paper doesn't consider network utility as the key factor. As far as we are concerned, there is no related research work focusing on the problem of bandwidth allocation based on utility in the hybrid IP/SR network scenario.

In this paper, a utility-optimized network bandwidth allocation algorithm is proposed in the hybrid IP/SR scenario, which considers the coexistence of IP nodes and SR nodes. The main contribution of this paper are two folds. Firstly, to the best of our knowledge, this is the first solution for bandwidth allocation with optimal utility in hybrid IP/SR networks. Secondly, a novel algorithm is also proposed to solve the network utility maximization model. Extensive simulations have been done to evaluate the performance of proposed algorithm, which show that the proposed algorithm is able to achieve better performance in terms of utility.

The rest of the paper is organized as follows: Section II describes the related works. Section III describes hybrid IP/SR scenario. Problem formulation and some definitions are given in Section IV. In section V, we propose an algorithm to solve the problem. In section VI, the experiments are conducted to evaluate network performance on different network topologies. In section VII, a conclusion is given with a summary.

II. RELATED WORK

Traffic engineering (TE) based on SR or SDN is a thriving topic. TE is to design routing algorithm to improve network performance, such as throughput or maximum link utilization. So far, most of researches mainly focus on full-SR scenario. In [6], Carpa *et al.* propose a routing algorithm to improve energy efficient of network. In [7], Lee and Sheu propose a routing algorithm based on SR in SDN network, which can balance the traffic load. In [8], Bhatia *et al.* propose the online and offline routing algorithm to minimize the maximum link utilization. However, there are few studies on hybrid IP/SR scenario, in which SR nodes and IP nodes coexist.

Nowadays, some researches study incremental deployment scheme to deploy SDN nodes in legacy network, which is called hybrid IP/SDN network. Some works propose routing algorithm to improve hybrid IP/SDN network performance [10] and [11]. However, the routing problem between hybrid IP/SR network and hybrid IP/SDN network is different because the routing paradigm of SDN and SR is different. The SDN nodes are isolated and they need not compose a domain, however, SR nodes need to compose a domain to route packets. Therefore, the routing algorithm in hybrid IP/SDN network cannot be used in hybrid IP/SR network.

In this paper, the network utility is taken as the key factor for algorithm design. Network utility can be viewed as a measure of the Quality of Service (QoS) performance [12], customer satisfaction [13] and fairness allocation [14]–[16] based on the allocated bandwidth. The theory of network utility maximization is to fairly distribute the bandwidth resources in the network by algorithms, so that individual users are satisfied and the overall utility of the network is maximized. In the case of limited network resources, the theory of network utility maximization can be used to improve resource utilization. Previous bandwidth allocation based on utility models mainly focus on traditional IP network.

All in all, the bandwidth allocation based on utility in the hybrid IP/SR network scenario was not fully researched in past studies.

III. HYBRID IP/SR NETWORK SCENARIO

When a part of the IP nodes in legacy network are upgrading by SR nodes, the coexistence of IP nodes and SR nodes forms a hybrid IP/SR network. Since SR node can explicitly determine the routing path of the flow in the network, thus, to better utilize the network resources, the routing path is re-determined once the traffic reaches the SR domain ingress node. Different users have different bandwidth requirements. Network utility can be used to reflect customers' satisfaction with bandwidth allocation. In the hybrid IP/SR network, the SR controller can allocate bandwidth more efficiently according to the utilization of link and the bandwidth requirement of the customers. Therefore, compared with legacy network, optimizing the path planning and bandwidth allocation in the hybrid network can improve the network utility and the customers' satisfaction.

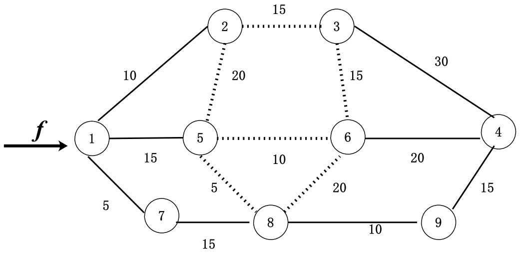

FIGURE 1. An example of flow forwarding behavior in hybrid network.

Next, we will give an example of how to forward and allocate bandwidth to a flow in the hybrid IP/SR network. The network topology, which consists of the SR node and traditional IP node is shown in Fig.1. There are 9 nodes, in which the node 5,2,3,6 and 8 are SR nodes and are controlled by the SR controller. These nodes form a SR domain. The links in this domain are represented by dotted lines. The node 1,7,9 and 4 are traditional IP nodes, which only support traditional OSPF routing protocol. The solid lines between these nodes represent the traditional IP link. The number for each link indicates the link capacity, and the cost of each link is the reciprocal of bandwidth. Next, we will give a detailed description of forwarding process and bandwidth allocation of flow f in the network. We assume that node 1 is the source node, and node 4 is the destination node of flow f.

The source node (node 1) of flow f is a traditional IP node, and it calculates the forwarding path of flow f using OSPF routing protocol. The next hop of the shortest path is node 5. Node 5 is a SR node, which can insert SR index in the header of packet to indicate the forwarding path of the packet. Thus, for flow f, there are 8 optional paths, which are shown in Table 1. The possible allocated bandwidth of each path for this flow is also shown.

TABLE 1. **The optional path of flow *f*.**

Optional paths	Path	Bandwidth
p_1	$1 \to 5 \to 6 \to 4$	10
p_2	$1 \to 5 \to 2 \to 3 \to 4$	15
p_3	$1 \to 5 \to 2 \to 3 \to 6 \to 4$	15
p_4	$1 \to 5 \to 8 \to 9 \to 4$	5
p_5	$1 \to 5 \to 8 \to 6 \to 4$	5
p_6	$1 \to 5 \to 6 \to 3 \to 4$	10
p_7	$1 \to 5 \to 6 \to 8 \to 9 \to 4$	10
p_8	$1 \to 5 \to 2 \to 3 \to 6 \to 8 \to 9 \to 4$	10

If the packets of the flow are transmitted over different paths, the cost of re-ordered and the latency of the flow will increase. Hence, in this paper, only single-path flow is considered. As the allocated bandwidth increases, the utility will increase as well. In this case, path p_2 and path p_3 are more suitable since the possible bandwidth of them is larger than that of other paths. Then the cost of these two paths will be calculated. As indicated above, link cost is the reciprocal of the bandwidth, the cost of the path is calculated by the equation $Cost_p = \sum_{(i \in p)} 1/B_i$, where i is the link in the path p and B_i is the bandwidth of the link i, so the cost for path p_2 is $1/15 + 1/20 + 1/15 + 1/30 = 13/60$ and the cost for the path p_3 is $1/15 + 1/20 + 1/15 + 1/15 + 1/20 = 3/10$. The cost of path p_2 is less than path p_3, therefore, the path p_2 will be selected by SR controller.

This example shows one simple case with only one flow in the network. However, in the actual network scenario, there are many flows with different source and destination nodes and bandwidth demands. In this paper, the motivation is to design a novel scheme to efficiently select path and allocate bandwidth in the hybrid IP/SR network scenario so that the overall utility of the network can be improved.

IV. THE PROPOSED SCHEME

The goal of this paper is to optimize the utility of network through path planning and bandwidth allocation. The hybrid IP/SR network scenario is considered, in which SR node and IP node are coexisting. There are two main issues to consider for the proposed scheme. The first one addresses how to select the routing path for the flows in the network. The second one addresses how to select the path and allocate the reasonable bandwidth for the selected path. In the following, some basic definitions will be listed firstly, and then the detailed description for the mathematic model of proposed scheme will be given.

In this paper, the hybrid IP/SR network topology is modeled as a graph $G = (V, E)$, where V is the set of nodes in the network, and E is the set of links in the network. B_e indicates the capacity of the link e, where $e \in E$. s indicates the source node of the traffic flow, and d indicates the destination node. Table 2 are the parameters and variables used in this paper.

TABLE 2. **Description of symbols.**

Symbols	Description
V, E	Node and link set in the network
$U_f(x)$	Utility function for flow f with allocated bandwidth x
$b(p)$	The allocated bandwidth of path p
b_f^p	The allocated bandwidth of flow f on path p
AP_f	The allowable path set for flow f
P	The allowable path set in the network
F	The flow set in the network
B_e	The bandwidth capacity of link e
Z_e^p	Boolean indicating whether link e belongs to path p
Y_f^p	Boolean indicating whether path p is used to forwarded flow f
E_f	The essential bandwidth of flow f
a_f	The parameter of flow f in utility function
H_p	Number of hops in path p
FP_f	The feasible path set of flow f
C_f	The minimum path cost of flow f
φ_e	The link cost of link e

Boolean parameter Y_f^p indicates whether the path p is used for flow f, its definition is:

$$\forall p, f : Y_f^p = \begin{cases} 0, & b_f^p = 0 \\ 1, & b_f^p > 0 \end{cases} \tag{1}$$

The problem can be divided into two parts. One is to search the allowable path set, because the SR domain has routing rule, in the hybrid IP/SR network, we should design the strategy to calculate path that follow the rule of SR domain. Another part is to allocate the path and bandwidth to flows. Next, we will introduce these two parts respectively.

A. ALLOWABLE PATH SEARCH

For each flow in hybrid IP/SR network, if the shortest path of the flow does not pass through the SR domain, the flow has only one shortest path calculated by the traditional routing protocol OSPF, otherwise, the available paths for data transmission include the lowest cost path calculated by the traditional routing protocol OSPF and the paths which pass through the SR domain. That is, if the node along the shortest path of a flow is upgraded to support SR, the routing path in SR domain can be re-determined. The path planned by SR domain ingress node should only include SR nodes.

Next we will give an example to explain how to select the feasible path. Fig.2 is a hybrid IP/SR network, in which the node 2, 3, 5 and 6 are SR nodes controlled by the

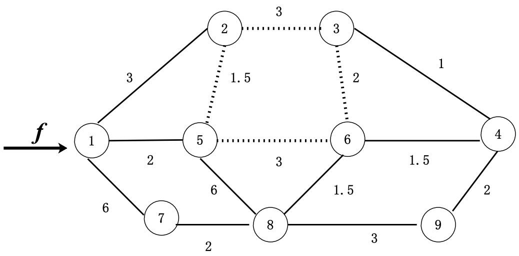

FIGURE 2. An example of feasible path selection.

SR controller. These nodes form a SR domain. The links in this domain are represented by dotted lines. The node 1, 4, 7, 8 and 9 are traditional IP nodes, which only support traditional OSPF routing protocol. The solid lines between these nodes represent the traditional IP link. The number on the links indicates the link cost of the link. The source node and destination node of flow f is node 1 and node 4. According to the link cost, we can calculate the OSPF shortest path that is $\{1 \rightarrow 5 \rightarrow 6 \rightarrow 4\}$. Node 5 is SR node, so when the data packets reach node 5, node 5 can explicitly plan the routing path of the flow. However, node 5 can only select SR node as the next hop rather than IP node. For example, path $\{1 \rightarrow 5 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 4\}$ is a feasible path. However path $\{1 \rightarrow 5 \rightarrow 8 \rightarrow 6 \rightarrow 3 \rightarrow 4\}$ is not feasible path, because the next hop of node 5, i.e. node 8, is a IP node. Only SR node can recognize the Segment List in the packet header, so when the data packets reach to the SR domain, the packets should be route in SR domain and then leave the SR domain. When the packets leave the SR domain, the packets won't enter the SR domain again. In other words, the packets cannot shuttle in and out of SR domain. The feasible path selection should follow above rules.

Additionally, in a large-scale SR network, the number of feasible paths may be very large. Thus, the complexity of the path planning and bandwidth allocation will increase if all feasible paths are considered, which makes it difficult to obtain a good scheme for path planning and bandwidth allocation. Therefore, the SR controller is required to select a set of paths from the feasible paths, which is called the allowable path set. The allowable path set is defined as follows:

$$AP_{ij} = \left\{p | H_p \leq H_{sp} + \mu\right\} \tag{2}$$

where H_{sp} is the number of hops of the shortest path from node i to node j. Compare to shortest path, large hop count means that the packet header carries longer SR header, which will increase the consumption of the network. In addition, more paths taken into consideration will increase the complexity of the calculation of controller. So, we introduce parameters μ to select the allowable paths from all feasible paths. For example, when $\mu = 2$, the maximum number hop of allowable paths is the shortest path hop number plus 2. The allowable path selection algorithm is shown as follows. We firstly use Deep First Search(DFS) find all feasible paths of flow f, and then filtrate the allowable path according to above restricted constraints.

Algorithm 1 Allowable Path Set Selection

```
Input: $G = (V, E)$, $F$
for each $f \in F$ do
    $SP_f = Dijkstra\_shortest\_path(s, d)$
    $FP_f = DFS(s, d)$
end for
if $SP_f$ not contain SR node then
    Add $SP_f$ to $AP_f$
else
    for each $p \in FP_f$ do
        if $p$ violate the rule of SR domain then
            continue
        else if hop count of $p$ out of range then
            continue
        else if the part of $p$ in IP domain is not the shortest path then
            continue
        else
            Add $p$ to $AP_f$
        end if
    end for
end if
Output: $AP_f$
```

B. PATH PLANNING AND BANDWIDTH ALLOCATION

After calculating the allowable path set of flow, we should allocate route path from allowable path set and allocate bandwidth for flows. The problem of path planning and bandwidth allocation in a hybrid IP/SR network is a problem of maximizing network utility that must obey some constraints (e.g., link capacity). Network utility refers to the degree of satisfaction of users with the network resources or services. Utility function can be regarded as the level of satisfaction of a user as a function of resource allocation. In this paper, resource refers to bandwidth. That is, utility function is a quantitative relationship between the utility and the allocated bandwidth. The satisfaction of users will increase with the increase of allocated bandwidth. In this paper, it is assumed that the utility function of each flow is continuously increasing and strictly concave logarithmic function[17]. Hence, utility function can be defined as $U_f(x) = a_f log(x + 1)$, where x is the allocated bandwidth for flow f, $U_f(x)$ is the utility of flow f with the bandwidth x, and a_f is the coefficient that randonmly generated between 1 and 10. Based on the above definition, the optimization model of utility is described as follows.

$$max \sum_{f \in F} a_f log\left(\sum_{p \in AP_f} b_f^p + 1\right) \tag{3}$$

$$s.t. \sum_{p \in P} b_f^p Z_e^p \leq B_e, \quad e \in E \tag{4a}$$

$$b_f^p \geq 0, \quad \forall p \in AP_f, \ f \in F \tag{4b}$$

$$\sum_{p \in AP_f} Y_f^p = 1, \quad \forall f \in F \tag{4c}$$

The goal of the optimization model is to maximize the overall utility of the network. The equation (4a) is used to ensure that the total amount of traffic on the link is less than its capacity. The equation (4b) is used to ensure that the bandwidth allocated on the allowable path of the flow is non-negative. The equation (4c) ensures that only one path can be allocated the flow.

We propose an algorithm to solve the optimization model of utility. The algorithm can be divided into 2 parts. One is to calculate the transmission rate for each flow, i.e., bandwidth. Another part is to update the weight of links that is the link cost according to the transmission rate of flows.

In this paper, the iterative method is used to calculate the transmission rate of the flow to gain the approximate optimal value. Firstly, according to the objective function and its constraints, we give the corresponding Lagrangian function. Secondly, we use the Karush-Kuhn-Tucker (KKT) method to find the optimal solution. And then the subgradient algorithm is used to allocate bandwidth for the flow. The definition of Lagrangian function as follows.

$$\begin{aligned} L\left(x, \lambda, \varphi, \xi, \mu\right) = &\sum_{f\in F} a_f log(\sum_{p\in AP_f} b_f^p + 1) \\ &- \sum_{e\in E} \varepsilon_e (\sum_{p\in P} x_f^p Z_e^p - B_e) \\ &+ \sum_{f\in F}\sum_{p\in AP_f} \varphi_{f,p} b_f^p \end{aligned} \tag{5}$$

where $\varepsilon = [\varepsilon_1, \ldots, \varepsilon_E]^T$ and $\varphi = \left[\varphi_{1,1}, \ldots, \varphi_{1,p_1}, \ldots, \varphi_{F,p_F}\right]^T$. ε and φ are *Lagrangian* multipliers, and they are all non-negative. In the Lagrangian function, ε_e and φ_f and are belong to ε and φ. The price of the path p can be defined as: $C_p = \sum_{e\in E} \varepsilon_e Z_e^p$. The bandwidth allocated to flow f is: $X_f = \sum_{p\in AP_f} b_f^p$.

The optimal solution needs to meet the following KTT conditions:

$$U_f'(X_f) + \varphi_{f,p} - C_p = 0 \tag{6a}$$

$$\varepsilon_e(X^e - B_e) = 0 \tag{6b}$$

$$\varphi_{f,p} x_f^p = 0 \tag{6c}$$

$$\varepsilon_e, \varphi_{f,p} \geq 0 \tag{6d}$$

According to above functions, it can be concluded that the path of flow f is the path with the lowest cost. The minimum cost of the path of the flow f is defined as $C_f = \min_{p\in AP_f} C_p$. The optimal allocated bandwidth of the flow f is:

$$X_f^* = \sum_{p\in P} b_f^*(p) Y_f^p = U_f^{'-1}(C_f) = \frac{1}{C_f(t)ln10}, \quad \forall f \in F \tag{7}$$

The objective function of optimization model is not strictly concave, thus, the *first-order* Lagrangian algorithm will oscillate. The subgradient algorithm is considered to overcome this problem. It decomposes the original algorithm into the problems of flow control and routing. The problem of flow control is used to determine the data rate of the flow, and the problem of routing is used to determine how to choose the best path for a flow. The path allocated to flow f is the lowest cost path. Based on the above analysis, the *first−order* Lagrangian function is following:

$$X_f(t+1) = U_f^{'-1}(C^f(t)) = \frac{1}{C_f(t)ln10} \tag{8}$$

where $C_f(t)$ is the cost of the shortest path of flow f within the iteration step t.

After calculating the allocated bandwidth for each flow, the weight of links that is the link cost should be updated according to the allocated bandwidth of flows.The weight of link should be updated using the subgradient algorithm after the allocated bandwidth X^e is calculated. The X^e can be represented as:$X^e = \sum_f \sum_{p\in AP_f} Z_e^p b_f^p$. The formula of link cost update is given as follows:

$$\varphi_e(t+1) = \left[\varphi_e(t) + r(X^e(t) - B_e)\right]^+ \tag{9}$$

where r is learning rate. If the allocated bandwidth is greater than the link capacity, its weight will grow, and vice versa. Therefore, the weight of the overload path will increase so that these paths may not be used for subsequent assignments of path. The algorithm 2 summarizes the update process of link weights.

Algorithm 2 Path Planning and Bandwidth Allocation

```
for each $f \in F$ do
    Calculate the admissible path set $AP_f$
    Calculate the cost of each path in $AP_f$ and find the lowest cost $C_f$ and the shortest path is $SP_f$
    Calculate the allocated bandwidth using above equation we propose
    Update the allocated bandwidth $b_f^p$
    Update the link weight
    Get the occupied bandwidth of all paths that contain link $e$
    Calculate the link utilization of link $e$
    Update link weight using above Eq.9
    Broadcast the new link weight to all nodes and SR controller
end for
```

Based on the above analysis, we propose the path planning and bandwidth allocation algorithm. As described in algorithm 2, the ingress node of the SR domain communicates with the SR controller firstly to seek the allowable path of the flow f and the shortest path with the smallest link weight. And then, the SR controller updates the weight of the link after calculating the data rate of the flow. Finally, after a certain number of iterations, the iteration is terminated when the algorithm gets close to convergence.

As a summary, Fig.3 shows a flow diagram of the algorithms we propose.

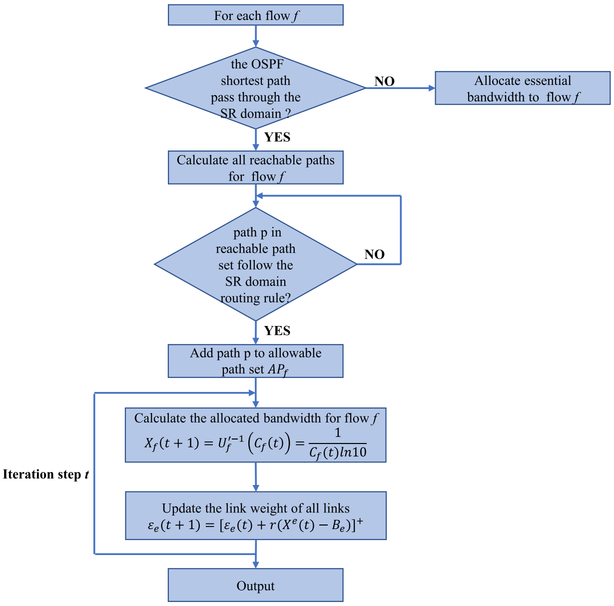

FIGURE 3. Flow diagram of the algorithms.

V. EXPERIMENTS AND EVALUATION

In this section, several experiments have been done to verify the utility maximization algorithm proposed in this paper.

A. EXPERIMENT DESIGN

We use the workstation with the Intel Core i5 Microprocessor and 8GB RAM. Three network topologies with various nodes and numbers of links are selected from SNDlib. SNDlib provides the library of test cases of telecommunication network. Assuming that all links in the network topology is bidirectional, the bandwidth of each link is generated randomly, and the weight of the link is the reciprocal of bandwidth. The traffic matrix in each experiment is generated randomly. The traffic matrix includes the flows' source node, destination node and bandwidth demand. Three network topologies in this experiment are: Atlanta Topology, Nobel-Germany Topology, and Geant Topology. Atlanta Topology consists of 15 nodes and 22 links. Nobel-Germany Topology consists of 17 nodes and 26 links. Geant Topology consists of 22 nodes and 36 links.

Simulation experiments will be conducted from different perspectives to verify the efficiency of the utility maximization algorithm in the hybrid IP/SR network. Firstly, a case study with a small-scale network topology is done to analyze and verify the algorithm. And then, comparing with other algorithm, we do experiments in different scale of network topologies.

B. CASE STUDY

Firstly, the simulation experiment is done with Atlanta topology. As Fig.4 shows, the 50% of the network nodes is upgraded to the SR node. The links within the SR domain are represented by dotted line.

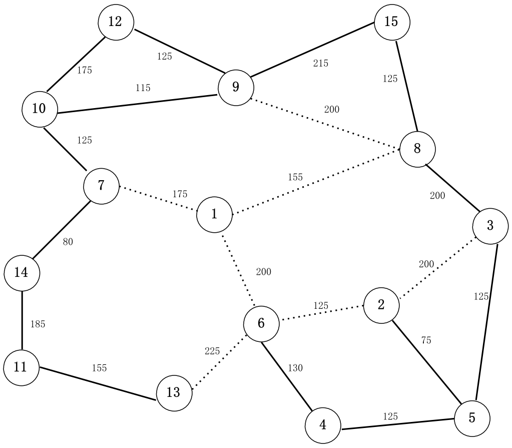

FIGURE 4. Hybrid IP/SR Atlanta topology.

TABLE 3. The information of the five flows.

flow	Source	Destination	a_f
f_1	10	13	4
f_2	4	12	6
f_3	6	10	3
f_4	4	14	4
f_5	7	5	2

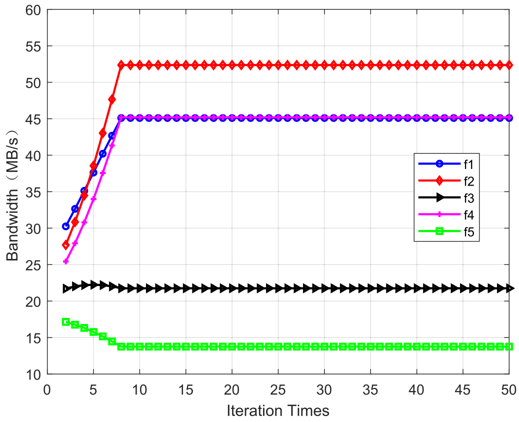

FIGURE 5. The allocated bandwidth of these five flows.

The SR controller dynamically adjusts the path of the flow passing through the SR domain through calling the routing algorithm proposed in this paper. The utility function used by this experiment is $U_f = a_f log(x+1)$. The information of these five flows f_1, f_2, f_3, f_4 and f_5 is shown in Table 3. All flows in this experiment are non-split, and traffic demand of each flow and the coefficient of utility function a_f are generated randomly.

Fig.5 shows the bandwidth allocation of 5 flows. As the number of iterations increases, the allocated bandwidth of flow f_1, f_2 and f_4 increases, while the allocated bandwidth of flow f_4 and f_5 decreases. To improve the overall utility of network, the SR controller will add the allocated bandwidth to some flows because of the fixed overall bandwidth, which means that the allocated bandwidth of other flows will bring down. The algorithm we propose can only adjust the bandwidth of the flow passing through the SR domain. In this experiment, all selected 5 paths pass through the SR domain, so the allocated bandwidth will be changed once the path of each flow is adjusted. The utility of network will not change with the increasing number of iterations if the flow doesn't pass through the SR domain.

Fig.6 shows the overall utility of network. The overall utility of network grows as the number of iterations increases initially. And then, when the algorithm comes to converge, the overall utility of network maintains a stable state.

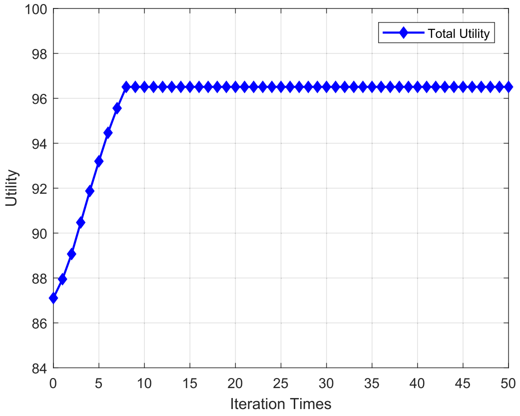

FIGURE 6. Total utility of the hybrid IP/SR network.

TABLE 4. The information of three topology.

Topology	node	link	Flow number
Atlanta	15	22	20
Nobel-Germany	17	26	25
Geant	22	36	30

C. MAXIMUM UTILITY EVALUATION

Three topologies are selected in this experiment. The bandwidth of link and the traffic matrix in the network topology is generated randomly, and the weight of the link is the reciprocal of bandwidth. Table 4 shows the topology information and the number of the flow in the traffic matrix used in simulation experiment.

Different node selection results will cause different network performance in traffic routing, so SR node selection needs a certain strategy to improve the network performance. If we select different IP nodes to upgrade to SR nodes, the path in the allowable path set will have different result. Then, the network will be different. In this paper, we use the node selection algorithm (IDNS Algorithm) proposed in paper [18]. We compare the IDNS Algorithm with random node selection in Altanata topology. Fig.7 is the experiment result. The results show that the IDNS algorithm is better than random node selection. In the later experiments, the SR nodes are selected by IDNS algorithm.

At present, there are few studies in the hybrid IP/SR network scenario. Besides, there are no studies work on routing algorithm based on network utility in hybrid IP/SR scenario or pure SR network scenarios. In order to verify the effectiveness of the algorithm proposed, the compared experiment shifts SRLB routing algorithm [7] which proposed in pure SR scenario to hybrid scenario, that is, in the hybrid scenario, use OSPF algorithm in IP domain, and use the pure SR network routing algorithm in SR domain, and both of two algorithms are independent. The routing algorithm proposed in this paper is to use OSPF algorithm for path planning in IP domain, and the path planning and bandwidth allocation algorithm in SR domain is designed based on the link state in IP domain.

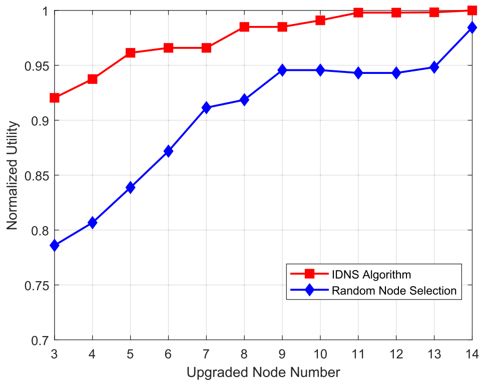

FIGURE 7. Compare with random node selection.

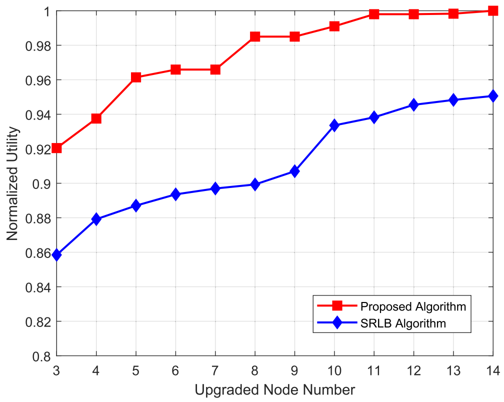

FIGURE 8. Utility of hybrid IP/SR Atlanta topology.

Because SR nodes need to form a SR domain, the minimum number of SR nodes is 3. This paper considers the hybrid IP/SR network scenario, so the maximum number of SR nodes in the network is the number of topological nodes minus one. Every time, the experiment adds one SR node in the network until the network becomes a pure SR network.

Fig.8, Fig.9 and Fig.10 are the simulation results of three topologies. The X-axis is the number of SR nodes in the network, and the Y-axis is the normalized utility. In this experiment, normalized utility is used as the factor to evaluate the performance. In this case, flow set is fixed and number of nodes selected changes. Therefore, normalized utility can be defined as $\frac{U(x(F,n))}{U(x(F,N))}$, where $x(F, n)$ refers to the allocated bandwidth of the F flow sets when n SR nodes are selected to deploy with SR. $U(x(F, N)$ corresponds to the case with maximized utility, in which the network is fully deployed with SR to transmit F flows. The ratio is less than one.

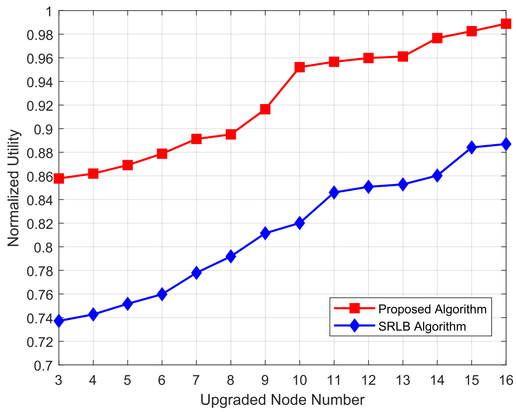

FIGURE 9. **Utility of hybrid IP/SR Nobel-Germany topology.**

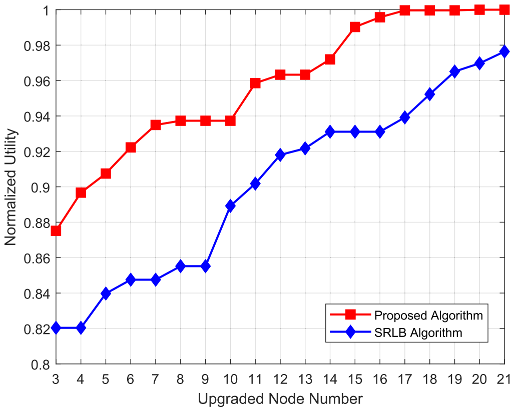

FIGURE 10. **Utility of hybrid IP/SR geant topology.**

The simulation results show that the overall utility of network promoted with the increase of the number of SR nodes. This is because the total number of adjustable flows within domain increases. The bandwidth is reallocated by modifying the path of flows through algorithm. And it can be seen from the figure that the growth rate of the overall utility of network will slow down when the number of nodes deployed in the network exceeds 50%. Compared with the SRLB algorithm, the simulation results show that the algorithm we propose is better. Because only introducing the routing algorithm in SR domain can't consider the link state in IP domain. The SRLB algorithm can only adjust the traffic flow in SR domain according to the network state in SR domain, so the calculated routing path is not optimal. The algorithm we propose considers the link state in IP domain and SR domain synthetically when we plan the routing path of flows, so the result of the algorithm we propose is better than that of SRLB algorithm.

D. COMPARE TO OSPF ALGORITHM

In this experiment, the algorithm proposed in this paper is also compared with the traditional OSPF routing algorithm to verify our algorithm's performance. We select 8 nodes from Atlanta topology to form a SR domain, and then do the experiment in this hybrid IP/SR network. We have done 15 contrast experiments, and the traffic matrix of each experiment is generated randomly. The experimental result is shown in Fig.11, in which X-axis indicates number of experiments, and Y-axis indicates the normalized utility of network. In this case, the number of nodes selected to deploy with SR is fixed and flow set will change for each number of experiments. Therefore, the normalized utility function can be defined as $\frac{U(x(F,n))}{U(x(F',n))}$. $U(x(F', n)$ corresponds to the case with maximized utility, in which selected n nodes of network is deployed with SR to transmit F' flows. The ratio is also less than one. As Fig.11 shows, a varying number of flows are chosen in each test, the utility is various. When the flow number is increased/decreased, the allocated bandwidth becomes large/small. Then the total utility, which indicates the degree of user's satisfaction with the allocated bandwidth, has same variation trend in both algorithms. Compared with OSPF algorithm, our algorithm shows better performance due to dynamically adjusting the routing path of flows.

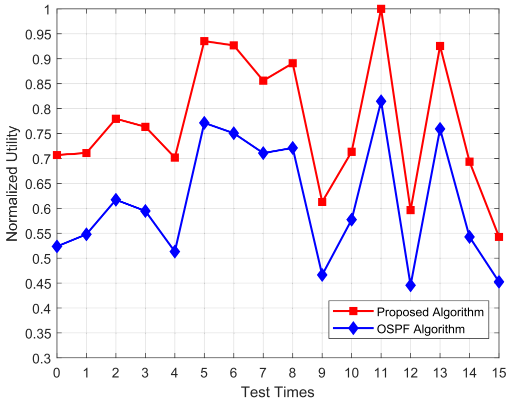

FIGURE 11. **Comparative experiment with OSPF.**

VI. CONCLUSION

In this paper, we considered the hybrid scenario, in which the SR device and the traditional IP device coexist forming a hybrid IP/SR network. It's a transition period from legacy network to the SR-based network. The hybrid IP/SR network can adjust the routing path of the flow in the network by calling the centralized control function of the SR controller to improve the utility of the network sources. Bandwidth allocation is used to enhance the utility of network in the hybrid network by taking advantage of SR. This paper proposes the optimization model with taking the network utility maximization as the optimization goal in the hybrid IP/SR network. In order to solve this model, a novel algorithm is proposed. The simulation results show that, compared with the simple routing algorithms combination (OSPF+SRLB) which uses SRLB algorithm in SR domain and uses OSPF algorithm in IP domain, the algorithm we propose can improve the utility of network significantly. Additionally, with the increase of the number of SR nodes in SR domain, the utility of network will increase.

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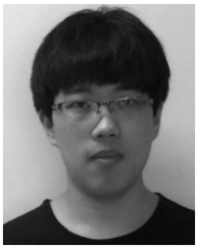

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