Computer and Information Science; Vol. 8, No. 1; 2015
ISSN 1913-8989 E-ISSN 1913-8997
Published by Canadian Center of Science and Education

Non-Real-Time Network Traffic in Software-Defined Networking: A Link Bandwidth Prediction-Based Algorithm

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Received: November 3, 2014 Accepted: November 17, 2014 Online Published: January 28, 2015
doi:10.5539/cis.v8n1p54 URL: http://dx.doi.org/10.5539/cis.v8n1p54

The research is financed by 973 project (2011CB706901) and Huawei Technology Co. Ltd.

Abstract

Network traffic control is the process of managing, prioritizing, controlling or reducing the network traffic by the network scheduler. High utilization of link bandwidth is very significant for network control and maintenance in Software-Defined Networking (SDN). When we get the accurate link bandwidth predictions for *T* time periods of the future in a specific network topology, the residual link bandwidth could be determined by the link bandwidth capacity and corresponding prediction values. Given the non-real-time request pairs, this process can be transformed into a multi-commodity flow model. But the traditional multi-commodity model has not introduced the time dimension. In this paper, the model associated with the time dimension is to complete the transmission of the non-real-time network traffic. However, in consideration of the large scale of the problem, a heuristic algorithm on the basis of greedy strategy is proposed to schedule the non-real-time network traffic properly. The experiments show that the heuristic algorithm is superior to global optimization in computing speed and the single path resulting from heuristic algorithm occupies fewer links in the network topology for the non-real-time network traffic.

Keywords: SDN, network control, network traffic prediction, multi-commodity model

1. Introduction

As the number of Internet users and all kinds of network services grows rapidly, many new problems are led by the drastic data flows of the internet (K. Hao, Z. Jin & P. Hao, 2012). The main problem is the network congestion which seriously affects the packet transmission rate and the network operating quality (Bing, Lu & Long, 2008). Although network congestion might be have many causes such as limited storage space for node, bad construction of the network topology or the trouble of the routing method etc., the core reason is that bandwidth capacity and the device processing ability provided by network could not satisfy the requirements while the growth of application traffic is approximately unlimited. In the network, "queue management" is the main approach to solve the congestion control problem and Mohammad M. H. Y (2010) proposed a fuzzy active queue management for internet congestion control. Random Early Detection (RED) (Floyd & Jacobson, 1993) is a very popular and important algorithm of the active queue management and all variants of the algorithms based RED are proposed such as Stabilized RED (Ott, Lakshman & Wong, 1999), Dynamics of Random Early Detection (Lin & Morris, 1997) and Adaptive RED (Floyd, Gummadi & Shenker, 2001). But active queue management algorithm exist many shortcomings especially in the detection phase (Papadimitriou, Welzl, Scharf & Briscoe, 2011). Another approach for network control is TCP congestion control. Research by Dassouki, Debar, Safa and Hijazi (2013) proposed a mechanism which is capable of detecting congestions by monitoring passively an aggregation link. Moreover, the increases of the network scale enhance the complexity so that the design for more effective network congestion control strategy is confronted with great challenge.

In order to better fulfill the development of network requirements, a new configuration model of network called Software-Defined Networking (SDN) is proposed in recent years. SDN is an emerging architecture purporting to be dynamic, manageable, cost-effective, and adaptable, seeking to be suitable for the high-bandwidth, dynamic nature of today's applications. SDN architectures decouple network control and forwarding functions, enabling network control to become directly programmable and the underlying infrastructure to be abstracted from applications and network services, which can treat the network as logical or virtual entity (Open Networking Foundation [ONF], 2013). SDN introduces new possibilities for changing business needs which are more convenient and flexible to control the network traffic (McKeown et al., 2008).

Whereas the goal of the SDN is global optimization of the network, it is obvious that network traffic control is still an important issue in the network management with the sustained expanding of network scale and emergence of lots of real-time service request. In addition, with the rapid development of datacenters, large amounts of non-real-time network traffic should be transmitted or communicated between the datacenters, such as data backup traffic and content synchronization traffic (Jia & Wang, 2013). The optimization of the network link transmission efficiency could meet the traffic demands and attaining a low congestion as well as high-efficient utilization of network resources (Huerta, Hesselbach & Fabregat, 2006).

Recognizing the distinctions of the real-time and non-real-time network traffic (Wijnants & Lamotte, 2008) in the process of transmission, different types of network traffic utilize different transmission modes inspired by the particular characteristics of the traffic. In the network, each link has a bandwidth capacity and parts of the bandwidth are occupied by the real-time network traffic. In general, real-time users' traffic fluctuates over time. Therefore, based on the change trend of real-time traffic predicted by network traffic prediction algorithm, we could control non-real-time network traffic to transmit at the time when there is a relatively small amount of real-time traffic in the network. Based on the above analysis, we can take full advantage of the idle bandwidth resources to complete the transmission of non-real-time network traffic while the real-time user's action will not be affected. Because of the not too strict time limitation, the links are not occupied too much in transmitting nor-real-time network traffic. To solve the issue, a heuristic algorithm on the basis of greedy strategy is proposed to schedule the non-real-time network traffic properly.

The rest of the paper is organized as follows. Section 2 analyzes the predictability of the real-time network traffic. In section 3, we depict the mathematical model of the problem as well as the corresponding proposed algorithm. And in section 4 our experimental results are presented. Finally, we draw a conclusion in section 5.

2. Real-Time Network Predictions

Real-time network prediction is an important issue in the network management. As the importance and the extensive potential applications of network traffic prediction in SDN, a lot of network traffic prediction models or algorithms have been investigated by researchers.

In 1993, Ethernet LAN traffic was demonstrated to have statistically self-similar (Leland, Taqqu, Willinger & Wilson, 1993). Network traffic is essentially a stochastic time series. Many prediction models have been created for decades with the development of the time series analysis. The time series model proposed by Box-Jenkins (Box, Jenkins & Reinsel, 2013) supplied a solution for the linear stationary process by Auto-Regressive (AR), Moving Average (MA) and the combination of Auto-Regressive and Moving Average (ARMA). Recently, as the fast development in Artificial Intelligence, many intelligent algorithms, such as Wavelet Analysis, Artificial Neural Networks (Kantz & Schreiber, 2004), and Support Vector Machine (SVM) are widely used in forecasting (Cristianini & Shawe-Taylor, 2000). Besides, many hybrid algorithms integrate the advantages of various algorithms to attain better prediction effect.

As the real-time network traffic consists of the group behavior of the users, real-time network traffic will appear some regularity. Thus we can design the proper model to predict the real-time network traffic changes in the future. In this paper, we assume that we could accurately predict the future T time interval network traffic of every link and distribute the non-real-time network traffic to the residual network. This kind of strategies that transmit the non-real-time network traffic can take full advantage of the idle link bandwidth, and decrease the cost of the network transmission.

3. Model Descriptions and Algorithm

In this section, firstly we depict the problem with the directed acyclic graph and give the mathematical model of the problem. Then according to the characteristic of the problem a routing selection algorithm on the basis of link capacity of the bandwidth is proposed in part 3.2.

3.1 Mathematical Model

In the process of transmitting the real-time service, we assume the SDN topology of the network is a directed acyclic graph $G=(V, E, c, w)$, where V denotes the set of vertices, E denotes the set of edges or links, $c(e)$ denotes the link bandwidth of the edge e and $w(e)$ represents the cost of every link for transmission. Because the network traffic of each link is obtained by periodic sampling, a maximum number T is given as the non-real-time network traffic will be transmitted in T periods of the future. The purpose of non-real-time traffic control is to optimize the transmission path with the time and link bandwidth limit, where every time period represented by Δt is identified as unite of time, i.e., $\Delta t=1$.

Suppose the kth request pair is $r_k=(s_k, t_k, d_k)$ and denotes its flow function by f_{kp} at the pth time period, where $p=1, 2...T$ and $k=1, 2, ...n$. We denote the real-time network traffic by $X_p(e)$ for $e\in E$ in time period p. Then the link bandwidth which could be used for non-real-time network traffic transmission is:

$$c_p(e)=c(e)- X_p(e),\ e\in E, p=1, 2...T.$$

When given the specific network and the number of time period, a mathematical model based on multi-commodity problem with time window constraint is described as follows:

$$\min \sum_{p=1}^{T}\sum_{e\in E} w(e)\left(\sum_{k=1}^{n} f_{kp}(e)\right) \tag{P}$$

s.t.

$$\sum_{k=1}^{n} f_{kp}(e) \le c_p(e), \quad \text{for } e\in E \text{ and } 1\le p\le T \tag{1}$$

$$\sum_{p=1}^{T}\sum_{(s_k,y)\in E} f_{kp}(s_k,y) = \sum_{p=1}^{T}\sum_{(x,t_k)\in E} f_{kp}(x,t_k) = d_k,\ \ 1\le k\le n \tag{2}$$

$$\sum_{p=1}^{T}\sum_{(x,s_k)\in E} f_{kp}(x,s_k) = \sum_{p=1}^{T}\sum_{(t_k,y)\in E} f_{kp}(t_k,y) = 0,\ \ 1\le k\le n \tag{3}$$

$$\sum_{(u,v)\in E} f_{kp}(u,v) = \sum_{(v,u)\in E} f_{kp}(v,u), \ \text{ for } u\in V/\{s_k,t_k\}, 1\le p\le T, 1\le k\le n \tag{4}$$

$$f_{kp}(e)\ge 0, \quad \text{for } e\in E, 1\le k\le n, 1\le p\le T \tag{5}$$

The objective function expresses the total cost of the traffic transmission. Constraint (1) implies that the total flow of a link e should not exceed the capacity $c_p(e)$. Constraints (2) ~ (4) indicate that for every network node the traffic must satisfy the flow conservation. Constraint (5) assures the non-negativity of the variables.

3.2 Algorithm Description

Problem (P) is a multi-commodity model essentially with time dimension which augments the complexity of the computation to solve a linear programming, although many accurate algorithms could get optimal solution. In order to meet the transmission requirements of non-real-time network traffic rapidly and make full use of the link bandwidth, we design a heuristic routing selection algorithm on the basis of link capacity to get a non-real-time network traffic scheme according to the characteristics of the problem. In the heuristic algorithm, we introduce the concept of priority associated with the demand d_k of require r_k ($k=1,...,n$). Given a priority function denoted by $prio(\cdot)$, for all $d_i>d_j$, $prio(r_i) > prio(r_j)$ if and only if require r_i is first transmitted in the algorithm (breaking ties arbitrarily).

For any link $e\in E$ in G, given that $X_p(e)$ denotes the bandwidth already used in the link e and the residual bandwidth of link e denotes by $c_p(e)=c(e)- X_p(e)$ in the pth time interval. Therefore, the residual network is defined $G_p=(V, E, c_p, w)$ but with the bandwidth capacity $c_p(e)$. The major steps of the proposed heuristic algorithm are illustrated below:

Step 1. Suppose the historical network traffic time series of each link $e\in E$ have been collected and then calculate the predicted value $X_p(e)$ of time period from $p=1$ to T.

Step 2. For any $e\in E$ in G, according to the predicted value $X_p(e)$ of each link in the forecasting period p, it is convenient to obtain the residual bandwidth of each link. Intuitively the residual bandwidth of each link is depicted as:

$$c_p(e)=c(e)- X_p(e), p=1,...,T.$$

Step 3. Now the residual network $G_p=(V, E, c_p, w)$ ($p=1,...,T$) covers the whole process of the network transmission in the T time periods. And in every time period p, employing the path selection algorithm the non-real-time network traffic will be distributed on each link of the topology G_p.

In the T time periods, Without loss of generality, we assume that if $i<j$, $prio(r_i) > prio(r_j)$. Under the definition of priority the specific network traffic loading process is as follows:

Step 3.0 Initialization of $i=0$. Define $c_{ip}(e)$ ($i=1,2,\dots,n$) as the residual bandwidth which is about to transmit the require r_i at the$p$th ($p=1,\dots,T$) time period for $e\in E$.

Step 3.1 Set $i=i+1$ and $p=0$.

(1) Set $p=p+1$, the residual bandwidth is $c_{ip}(e)$ right now. Then calculate the routing path of request r_i according to the procedure **(∗)**, and denote d_{ip} as the maximal traffic in the routing path;

(2) Set $d_i=d_i-d_{ip}$,

If $d_i\leq 0$ and $p\leq T$, then succeed to transmit request r_i, go to step 3.2;

If $d_i>0$ and $p<T$, go to step (1);

If $d_i>0$ and $p\geq T$, then cannot complete the transmission of request r_i within the T time periods and abandon the request r_i from the transmission queue. Then set $d_{ip}=0$ and go to step 3.2.

Step 3.2 If $i=n$, then stop. Otherwise, for all $p=1,\dots,T$ and $e\in E$:

$$c_{(i+1)p} = c_{ip}(e) - d_{ip},$$

Go to step 3.1.

Procedure (∗) Routing Selecting Algorithm

Input: The directed graph G with capacity constraint *cap*;

The source node s and the terminal node t.

Output: The flow and path from s to t.

```
Step 1 Let $label(s)=\infty$, $label(v)=0 (v\neq s)$, $maxcap=0$;
    Let Q is a First-in First-Out queue of candidate vertices, push s to Q;
Step 2 while Q is not empty
        $u$=pop Q;
        temp=find($cap(u,:)>0$);
        for each vertex $v$ in temp
            if $label(v)<\min\{label(u), cap(u,v)\}$
                $label(v)=\min\{label(u),cap(u,v)\}$
            end if
            if $v$ is not in Q
                push $v$ into Q
            end if
        end for
    end while
Step 3 traverse from the $t$ to the $s$ to get the path;
    $Maxcap=label(t)$.
```

4. Experiments and Results

4.1 Experiments Simulation

In this part, the Internet2 network topology is given to demonstrate the validity and high-efficiency of the proposed algorithm by the simulation results. The Internet2 backbone network has nine main nodes and also denotes it by $G=(V, E, c, w)$ where the w is determined by the transmission distance. The values of w are illustrated in table 1. In the experiments, the number of time period T is set to 8 and the request pair number is two; i.e. $r_1=(s_1, t_1, d_1)=(1, 5, 2200)$ and $r_2=(s_2, t_2, d_2)=(3, 7, 2000)$. In order to simplify the description of the process, the time interval Δt is consider as the unit of the time as before, i.e., $\Delta t=1$ in this paper.

Table 1. The values of *w* of each Link

w	v1	v2	v3	v4	v5	v6	v7	v8	v9
v1	0	0	0	0	0	0	1.342	0.913	0
v2	0	0	1	0.905	1.045	0	0	0	0.69
v3	0	1	0	0.278	0	0	0	0	0
v4	0	0.905	0.278	0	0.7	0	0	0	0
v5	0	1.045	0	0.7	0	1.385	0	0	0
v6	0	0	0	0	1.385	0	1.705	0	0.818
v7	1.342	0	0	0	0	1.705	0	1.303	0
v8	0.913	0	0	0	0	0	1.303	0	1.33
v9	0	0.69	0	0	0	0.818	0	1.33	0

Although network traffic prediction of the link is essential in transmitting the non-real-time network traffic, prediction is a relatively independent process so that we only need to know the residual bandwidth $c_p(e)$ of each link e at every time period in the particular network topology. Because the SDN has the global control ability in the network, the size of the $c_p(e)$ will also be influenced by the SDN controller. To simulate the process of SDN controller, the size of $c_p(e)$ is generated randomly between 100 to 600 which is illustrated in the table 2. Residual bandwidth $c_p(e)$ of each link will be used to transmit the non-real-time network traffic in the given time period p (p=1,...,8).

Table 2. The residual bandwidth of each link in each period

	T1	T2	T3	T4	T5	T6	T7	T8
(v1, v7)	465	469	443	591	594	342	311	358
(v1, v8)	111	441	312	522	150	441	171	160
(v2, v3)	450	418	460	439	410	249	145	365
(v2, v4)	116	212	282	448	592	366	447	471
(v2, v5)	527	557	146	363	250	401	343	567
(v2, v9)	449	218	477	161	334	470	192	426
(v3, v2)	468	176	159	474	420	146	420	177
(v3, v4)	380	433	481	391	529	154	479	312
(v4, v2)	234	240	569	512	308	253	342	290
(v4, v3)	369	220	596	194	126	352	152	398
(v4, v5)	288	331	365	500	266	464	298	220
(v5, v2)	311	320	422	494	202	328	175	180
(v5, v4)	434	272	485	539	356	269	427	162
(v5, v6)	245	336	231	141	188	403	448	511
(v6, v5)	314	330	342	349	424	490	118	479
(v6, v7)	539	194	452	108	307	136	415	439
(v6, v9)	259	329	574	121	468	533	453	497
(v7, v1)	344	405	391	542	526	126	485	442
(v7, v6)	232	270	477	430	265	152	165	181
(v7, v8)	147	417	295	281	187	264	225	190
(v8, v1)	269	489	370	394	536	320	202	301
(v8, v7)	230	145	109	531	481	499	167	504
(v8, v9)	427	485	435	240	192	283	256	320
(v9, v2)	591	359	423	155	171	248	218	442
(v9, v6)	591	195	321	545	159	374	103	547
(v9, v8)	335	204	298	344	552	474	451	110

Note. (v1, v7) represent links (similarly hereinafter) and T1~T8 denote time intervals.

The optimal solution is acquired by using the GNU Linear Programming Kit (GLPK) software package. In the following figure, the routings and flow of the optimal solution (Opt) and the Heuristic Algorithm (HA) are given from the figure 1 to figure 8 of the transmission process.

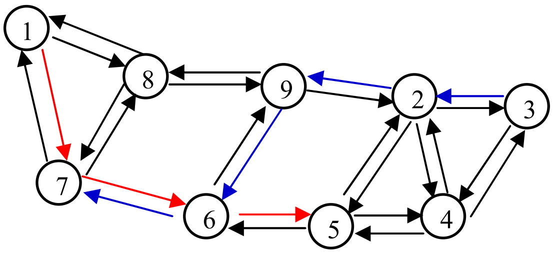

Figure 1. the Transmission of Period 1

Note. HA: 1→7→6→5 (232), 3→2→9→6→7 (449); Opt: 1→8→9→2→5 (111), 1→7→6→5 (88)3→2→9→6→7 (294), 3→4→5→6→7(245)

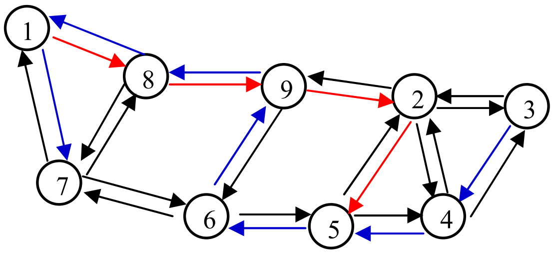

Figure 2. the Transmission of Period 2

Note. HA: 1→8→9→2→5 (359), 3→4→5→6→9 →8→1→7 (204); Opt: 1→8→9→2→5 (359), 1→7→6→5 (270),3→4→5→6→7(194)

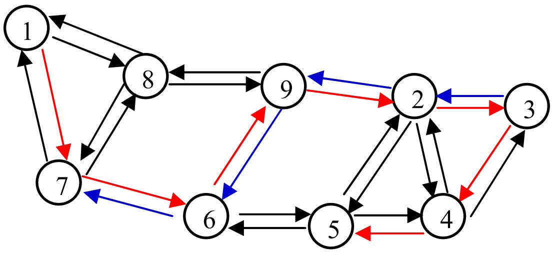

Figure 3. the Transmission of Period 3

Note. HA: 1→7→6→9→2→3→4→5 (365), 3→2 →9→6→7 (159); Opt: 1→8→9→2→5 (146), 1→7→6→5 (342), 3→4→5→6→7(231)

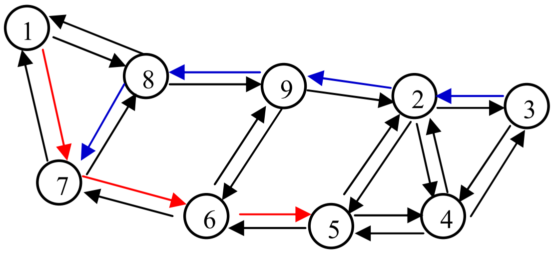

Figure 4. the Transmission of Period 4

Note. HA: 1→7→6→5 (349), 3→2→9→8→7 (161); Opt: 1→8→9→2→5 (155), 3→4→5→6→7(108)

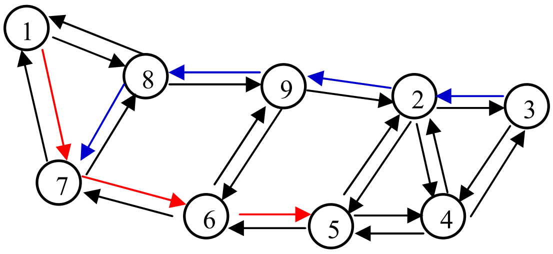

Figure 5. the Transmission of Period 5

Note. HA: 1→7→6→5 (265), 3→2→9→8→7 (334); Opt: 1→8→9→2→5 (150), 3→2→9→6→7 (86), 3→4→5→6→7(188)

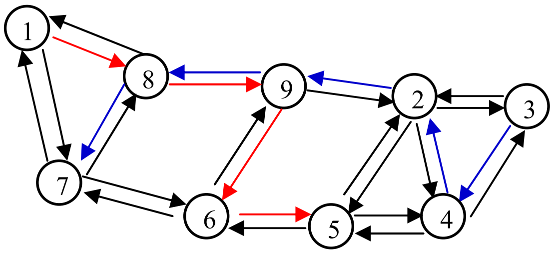

Figure 6. the Transmission of Period 6

Note. HA: 1→8→9→6→5 (283), 3→4→2→9→8 →7 (154);Opt: 1→8→9→2→5 (248), 3→4→5→6→7(136)

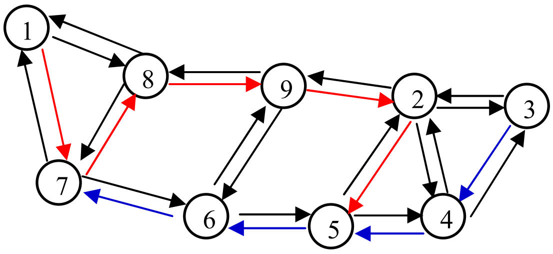

Figure 7. the Transmission of Period 7

Note. HA: 1→7→8→9→2→5 (218), 3→4→5→6 →7 (298); Opt: 1→8→9→2→5 (171), 3→4→5→6→7(298)

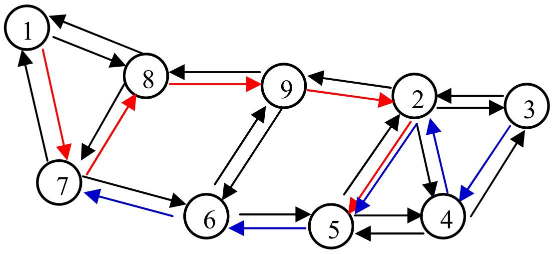

Figure 8. the Transmission of Period 8

Note. HA: 1→7→8→9→2→5 (129), 3→4→2→5 →6→7 (241); Opt: 1→8→9→2→5 (160)3→4→5 →6→7(220)

Table 3. The network traffic of every time period

	T1	T2	T3	T4	T5	T6	T7	T8	total
HA(1-5)	232	359	365	349	265	283	218	129	2200
Opt(1-5)	199	629	488	155	150	248	171	160	2200
HA(3-7)	449	204	159	161	334	154	298	241	2000
Opt(3-7)	539	194	231	108	274	136	298	220	2000

Note. cost(HA)= 20071.186, cost(Opt)=17260.5, |cost(HA)- cost(Opt)|/ cost(Opt)=16.28%.

4.2 Results Analysis

According to the Figure 1~8 and table 3, the routing of the optimal solution is almost multi-path transmission while the heuristic algorithm is single path. Although the cost of the heuristic is 16.28 percent higher than the optimal algorithm, the heuristic algorithm is superior in computing speed and the single path resulting from heuristic algorithm occupies fewer links in the network topology for the non-real-time network traffic. From the perspective of the time complexity, global optimization gotten by interior point (Monteiro & Adler, 1989) requires $O((k|E| \cdot |T|)^{3.5}L)$ time where L is a number relative to the scale of the problem while the running time of heuristic algorithm is in $O(n^2T)$, noting that n is the request number. However, when the differences of link cost are little, the effect of heuristic algorithm is more excellent than the optimal algorithm.

5. Conclusions

In this paper, we propose a heuristic algorithm to transmit the non-real-time network traffic in a particular network topology. When getting the information of the link bandwidth based on the network traffic prediction, residual bandwidth with the existed network topology constructs the residual network which serves the non-real-time network traffic transmission. The optimal solution on the basis of global optimization is achieved by solving the linear programming with interior point algorithm so that most of the routings are multi-path transmission. By contrast, the heuristic algorithm approximating greedy strategy gains the single path transmission which saves the link resources with low time complexity and not exceeding the optimal cost too much. In SDN, the management and maintenance of the network become more flexible and easy for operation.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (71171189), the key project of the National Natural Science Foundation (11331012), 973 project (2011CB706901) and Huawei Technology Co. Ltd.

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