A Scheme to Monitor Maximum Link Load with Load Ranking

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***Abstract*— Changing routes to avoid a link whose load is heavy reduces the traffic congestion in an Open Shortest Path First Traffic Engineering (OSPF-TE) network. The information of the maximum link load is monitored for maintaining routes. A node advertises the link information in the network when the link load is changed. The network controller, which is one of the OSPF peers, updates routing to reduce the congestion using the received information. This paper proposes a scheme to reduce the number of advertisements needed by the network to control routing. In the conventional scheme, every node in the network keeps all link information. Every time a link load is changed, the ingress node of that link advertises the updated link information due to the OSPF update mechanism. However, some advertised information is wasted since it may not be necessary for determination of the maximum link load. In the proposed scheme, only the link loads that lie within the predetermined top load set is kept at each node. Only the link information that is necessary for monitoring the maximum link load is advertised in the proposed scheme. Unlike the conventional scheme, which advertises the link information every time that the link load is updated, the proposed scheme creates advertisements only when really necessary for load control. Simulations show that the proposed scheme reduces the number of advertisements by at most 78% compared to the conventional scheme. The optimum number of ranks that achieves the minimum number of advertisements is found to be 11% of the number of links in the network.**

***Index Terms*—Link load, Network controller, Open shortest path first (OSPF) , Traffic engineering (TE)**

I. Introduction

ADOPTING an appropriate routing scheme can increase the network resource utilization and network throughput of Internet Protocol (IP) networks [1] – [6]. Realizing the goal of the optimum assignment of resources to traffic will allow additional traffic to be supported. It will also suppress network congestion and increases robustness against the traffic demand fluctuations, most of which are difficult to predict. One useful approach to enhance routing performance is to minimize the maximum link utilization rate, called the network congestion ratio, of all network links [7].

The OSPF traffic engineering (OSPF-TE) protocol [8], which is an extended version of the standard OSPF [9], is employed in OSPF networks for the purpose of traffic maintenance [10]. In the OSPF-TE network, traffic engineering link state advertisements (TE-LSAs) are used to transfer link information. LSA of the standard OSPF consists of source node, destination node, and the link load [8], [7]. The TE-LSA will be called advertisement hereafter. Each node floods the advertisements over the links connected to it. Network topology and a table that keeps link loads are built based on the information in the advertisements. Advertisements are created and transmitted upon startup and when either the network topology or the link load is changed.

An OSPF-TE network consists of a network controller and nodes, where the network controller is one of the OSPF peers in the network. The network controller is used to optimize routing in the network. When the network congestion ratio exceeds a specified value, the network controller determines the appropriate routes and establishes them in a centralized manner [7]. Route computation is performed using the advertised traffic demands so as to minimize the network congestion ratio [11].

In conventional schemes, such as [11], each node keeps the load information of every link in the network. An advertisement is issued every time a link load changes and the maximum link load is determined after the advertisement arrives at the controller. The controller uses the information of the maximum link load to avoid traffic congestion by setting routes appropriately. The updated information has to be advertised even though this information may not be needed to determine the maximum link load. We note that most advertisements are unnecessary, and waste a lot of bandwidth. If the link loads change frequently, the network can be overwhelmed by the advertisements. In addition, the controller has difficulty in determining the maximum link load. Therefore, the link utilization rate is reduced and the maximum link load may not be instantly determined.

This paper proposes a scheme to reduce the number of advertisements required for controlling network routing. The scheme is called link load ranking (LLR). In LLR, link loads are ranked in decreasing order. The rank number, R, is a parameter that indicates the maximum number of loads kept in the ranking tables. Each node has a ranking table, which keeps link loads if they lie within the R set. Other link information is ignored. The link information in the ranking table is ordered in descending

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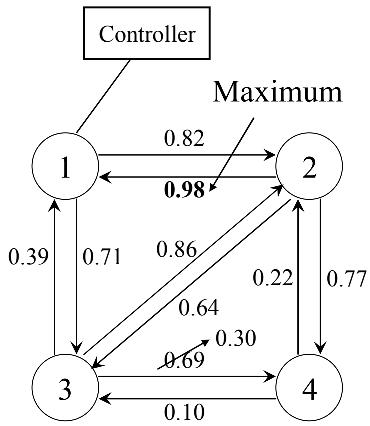


(a) Network model.

Rank	Link	Load
1	(2, 1)	0.98
2	(3, 2)	0.86
3	(1, 2)	0.82
4	(2, 4)	0.77
5	(1, 3)	0.71
6	(3, 4)	~~0.69~~ → 0.30 (Re-rank)
7	(2, 3)	0.64
8	(3, 1)	0.39
9	(4, 2)	0.22
10	(4, 3)	0.10

(b) Load ranking table.

Fig. 1. Link information table in conventional scheme.

order of link load. The link information with the highest link load occupies the first rank. An advertisement is needed only if the updated link information impacts the information in the ranking table. Otherwise, nothing is done and the ranking tables at all nodes remain unchanged. That is, a change in link information is not always advertised. The most appropriate value of R is investigated in terms of minimizing the number of advertisements.

The remainder of this paper is organized as follows. Section II describes the conventional scheme. Section III presents the LLR proposal. Section IV shows the performance evaluation results. Section V summarizes the key points.

II. Conventional Scheme

Each node in the network, including the controller, keeps all link information. Upon initialization, every node advertises the information of all known links. Link (i,j) is denoted as a link that transmits traffic from node i to node j. Node i takes responsibility for advertising the information of the link since it is the ingress node; node j is the egress node for (i,j). Every time a link load is changed, the ingress node of that link advertises the updated link information. Upon receiving an advertisement, each node updates its link information. The updated information is then re-ordered. The information of the maximum link load is changed if the updated link has the highest load in the network. Otherwise, the information of maximum link load remains the same. With this scheme, the information of link changes is advertised with every change, although it may not be necessary for determination of the maximum link load. Therefore, the bandwidth consumed by this information is wasted [12].

Figure 1 shows an example to clarify the conventional scheme. The network consists of four nodes, nodes 1 to 4, a controller, and 10 links. Note that the link between the controller and node 1 is not considered because it is not intended for data transmission. The arrows represent link direction. (i,j) represents link identification (ID) with direction from node i to node j. The number on each arrow represents link load. For example, link load of (1,2), is 0.82, and link load of (2,1), is 0.98. The maximum link load in this network is 0.98, which is the link load of (2,1).

If the link load of (3,4) is changed from 0.69 to 0.30, node 3 creates an advertisement with updated link information of (3,4). A node that receives this advertisement re-orders the load table. The link information of (3,4) becomes the eighth entry in the table, and (2,3) and (3,1) are the sixth and seventh entries, respectively. The maximum link load, which is 0.98 from (2,1), does not change. The value of the changed link load is automatically advertised to update the load table of every node due to the standard update mechanism. In this example, most of the changes in link loads are not used to monitor the maximum link load in the network.

III. Proposed Link Load Ranking Scheme

The link load ranking (LLR) scheme, proposed here, reduces the number of advertisements. In LLR, every node keeps the link information in a table, called the ranking table. The ranking table consists of rank number, link ID, and link load. The maximum ranks (R_{max}) held in the table is given. R is the number of ranks, where $R \le R_{max}$ and $R = R_{max}$ at the initial state. Only R_{max} loads are kept in the table. The information is ordered in decreasing order of link load, from the highest to the lowest. The link load of the first rank is thus the maximum link load.

When a link load in the network changes, the corresponding node creates an advertisement only if either of two conditions is satisfied. In the first condition, the new link load is higher than the lowest link load in the ranking table. In the second condition, the load of a link in the ranking table is changed. Otherwise, the node keeps silent.

After each node receives the advertisements, the information in the ranking table is updated. Due to the table updating process, R may be decreased or increased. If the load of a link in the table falls under the lowest rank, R is decreased. Since this load is no longer a candidate for the maximum load, it is deleted from the table. Therefore, R is decreased. R is increased when both changed load is higher than that of the lowest rank and $R < R_{max}$. The load of the changed link becomes a new candidate for determining the maximum load. Table updating can broken

	Load of link in ranking table is changed	Load of link in ranking table is not changed
Changed value of link load > value of link load of lowest rank	Case 1	Case 3
Changed value of link load ≤ value of link load of lowest rank	Case 2	Keep silent

Fig. 2. Three cases.

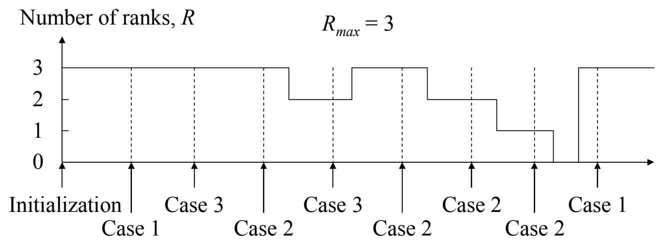


Fig. 3. Example of changes in the number of rank entries.

into three cases as follows, see Fig. 2.

- Case 1: If the link is listed in the ranking table, and its new load is more than that of the lowest rank, the information of that link is updated. The table entries are then re-ordered.
- Case 2: If the link is listed in the ranking table, and its new load is less than that of the lowest rank, the information of that link is deleted from the table. R is then decreased by one. The table entries are re-numbered as necessary.
- Case 3: If the link is not listed in the ranking table, and its new load is more than that of the lowest rank, the link information is added to the ranking table. The information in the ranking table is then re-ordered. Only the top R entries are kept so R is increased by one only if $R < R_{max}$.

A node advertises its new link information if it detects one of the three cases. Otherwise, the node keeps silent and does nothing.

Figure 3 shows an example of changes in R. It is assumed that R_{max} is three. In the initial state, R is three. R remains three if next the load change matches case 1. R is reduced by one the load change matches case 2. If the change matches case 3 and $R < R_{max}$, R is increased by one. Otherwise, R does not change. If R becomes zero, i.e. the ranking table has no entry, the system calls a reset and R is returned to three as in the initial state.

With small R, the probability that the updated link information is related to the information in the ranking table is low. However, the probability of ranking table reset is high, and reset triggers a large number of advertisements. With large R, the probability of ranking table reset is low. However, the probability that the updated link information is related to an entry in the ranking table is high. Therefore, the number of advertisements is also large. For this reason, the R_{max} that minimizes the number of advertisements should be adopted.

The algorithm for LLR uses the following terms.

r	Rank index in the table, where $1 \le r \le R$.
$\rho(i,j)$	Link load from node i to node j.
$\rho_{new}(i,j)$	New $\rho(i,j)$ if the link load of link (i,j) is changed.
$\rho(i_r,j_r)$	Link load of rth ranked entry from node i_r to node j_r, where $\rho(i_1,j_1)$ is the top ranked entry, i.e. the maximum link load, and $\rho(i_R,j_R)$ is the lowest ranked entry.

A. Initialization

- Step 1: All link details, including $\rho(i,j)$, are advertised in the network.
- Step 2: At each node, the received link information is ordered by $\rho(i,j)$.
- Step 3: The top R entries of $\rho(i,j)$s are kept. The other entries are dropped.
- Step 4: The kept $\rho(i,j)$s are changed to $\rho(i_r,j_r)$s to indicate their rank.

B. Action when $\rho(i,j)$ is changed to $\rho_{new}(i,j)$

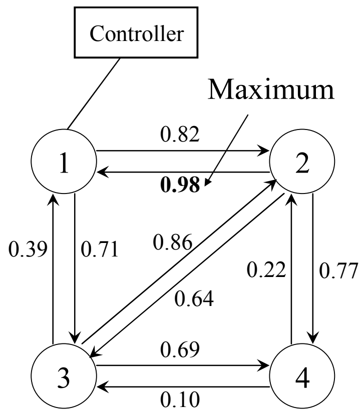
For each $\rho_{new}(i,j)$, if (i,j) is none of (i_r,j_r)s and the $\rho_{new}(i,j) \le \rho(i_R,j_R)$, do nothing. Otherwise, the link information of (i,j) is advertised in the network. After each node receives the advertisement, the following ranking process is performed.

For each updated link information

- Step 1: If $R = 0$, set R to R_{max}, and repeat from step 1 in the initialization process. Otherwise, go to step 2.
- Step 2: If (i,j) is one of (i_r,j_r)s and $\rho_{new}(i,j) > \rho(i_R,j_R)$, replace $\rho(i_r,j_r)$ with the $\rho_{new}(i,j)$, where $i = i_r$ and $j = j_r$, then go to step 5. Otherwise go to step 3.
- Step 3: If (i,j) is one of (i_r,j_r)s and $\rho_{new}(i,j) \le \rho(i_R,j_R)$, the link information of (i_r,j_r), where $i = i_r$ and $j = j_r$, is deleted from the ranking table, decrease R by one, and go to step 7. Otherwise, go to step 4.
- Step 4: Add link information of $\rho_{new}(i,j)$ into the ranking table, and increase R by one if $R < R_{max}$.
- Step 5: Re-order the link information by $\rho(i_r,j_r)$s and added $\rho_{new}(i,j)$s (if available).
- Step 6: The top R entries are kept. The others are dropped.
- Step 7: Retag $\rho_{new}(i,j)$s to $\rho(i_r,j_r)$s.

Figure 4 shows an example of how LLR works. The network topology is the same as that in Fig. 1. R_{max} is set to three. In the initial state, each node advertises its own (as ingress node) link loads. After each node receives the link loads, a ranking table is built with $R = 3$. It is determined that the maximum link load is 0.98 from (2,1), the second highest link load is 0.86 from (3,2), and the third highest link load is 0.82 from (1,2). Each node keeps the same ranking table.

If the link load of (4,2) changes from 0.22 to 0.50, no advertisement is issued since the new link load is less than the lowest link load entry, which is 0.82. Therefore, node 4 keeps



(a) Network Model.

Rank	Link	Load
1	(2, 1)	0.98
2	(3, 2)	0.86
3	(1, 2)	0.82

(b) Load ranking table.

Fig. 4. Ranking table in LLR.

silent.

If the link load of (2,1) changes from 0.98 to 0.84, node 2 detects case 1 and thus advertises the link information of (2,1). After each node receives this information, the information in the ranking table is updated and re-ordered since the new link load is higher than the lowest link load entry, which is 0.82. (3,2) and (2,1) become the first and second entries, respectively, while (1,2) remains the third rank.

If the link load of (2,1) changes from 0.98 to 0.70, node 2 detects case 2 and thus advertises the link information of (2,1). After each node receives this information, R is decreased from three to two and the link information of (2,1) is deleted from the ranking table since the new link load is less than the last entry, which is 0.82. The entries in the ranking table are re-ordered. (3,2) and (1,2) become the first and second ranks, respectively.

If the link load of (2,1) changes from 0.98 to 0.70 while R is one, case 2 is again indicated and node 2 advertises the information of (2,1). However, after each node receives this information, R is decreased from one to zero. The node determines that R has become zero and so issues a table reset. This forces all nods to advertise their current link information, as in the initial state. R is thus reset to three.

If link load of (4,2) changes from 0.22 to 0.84, case 3 is indicated and node 4 advertises the link information of (4,2). This information is added to each ranking table. The entries in the ranking table are re-ordered. Only the top three entries, (2,1), (3,2), and (4,2), are kept and the other, (1,2), is dropped.

If the link load of (4,2) changes from 0.22 to 0.90 while R is two, (2,1) and (3,2), case 3 is indicated and node 4 advertises the link information of (4,2) because the new link load of (4,2) is higher than the last entry, which is 0.86. This information is added into the ranking table and the ranking table entries are re-ordered. In this case, the table is fully populated so all entries, (2,1), (4,2), and (3,2), are kept.

C. Optimum R_{max}

Our goal is to minimize the number of advertisements by employing the optimum value of R_{max}. Let P be the probability that a link load changes in the network. The number of links in the network is defined as L. The range of R_{max} is $1 \le R_{max} \le L$. The ratio of the number of advertisements to the number of links whose loads change is denoted as $\theta(P,R_{max})$. The optimum R_{max} that minimizes $\theta(P,R_{max})$, $R_{\max}^{opt}$, is defined as

$$R_{\max}^{opt} = \arg \min_{1 \le R_{\max} \le L} \theta\left(P, R_{\max}\right). \tag{1}$$

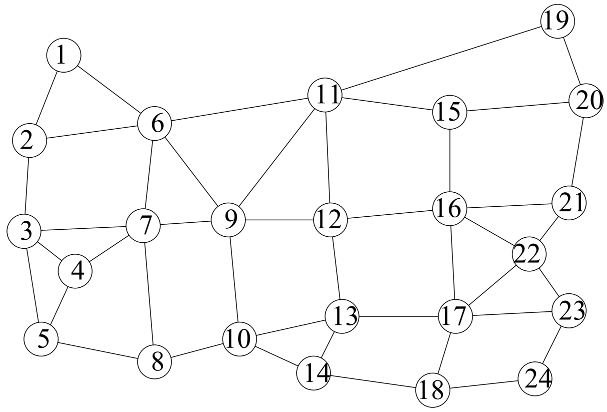
IV. Performance Evaluation

The performances of LLR were evaluated via computer simulation of the US IP backbone network topology [13], NSFNET [14], and European optical network (EON) [15]. The US IP backbone network topology consists of 24 nodes with 43 bidirectional connections so there are 86 links, as in Fig. 5(a). NSFNET topology consists of 14 nodes with 21 bidirectional connections so there are 42 links, as in Fig. 5(b). EON topology consists of 19 nodes with 38 bidirectional connections so there are 76 links, as in Fig. 5(c).

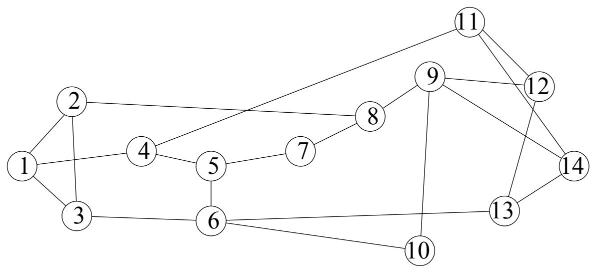
The simulation assumed that an advertisement from the node farthest from the controller reaches the controller within one time slot. The simulation was run for 10,000 time slots. The link load changes were decided by setting parameter P, the probability of a link load change.

Figure 6 shows the performances of LLR and the conventional scheme in terms of advertising ratio, which is the ratio of the number of advertisements to the number of changed links, in different network topologies. In the conventional scheme, with $R = R_{max}$, the advertising ratio is 1.0 because the link information is advertised every time that a link load is changed. For LLR, R_{max} was varied from one to the number of nodes in the network. The advertising ratio rapidly decreases as R_{max} is increased when R_{max} is less than ten, five, and nine in the US IP optical network, NSFNET, and EON topologies, respectively, for every P, and then increases. The reason is that the ranking table is often reset if R_{max} is small. However, the ranking table is more likely to hold the changed link if R_{max} is large. The optimum values of R_{max} are ten in the US IP backbone network (86 links), six in NSFNET (42 links), and nine in EON (76 links). From these observations, all the optimum values of R_{max} are 11% of the number of links in our examined networks. This value yields 78%, 67%, and 75% reduction in the number of advertisements, in the US IP backbone network, NSFNET, and EON, respectively, compared to the conventional scheme.

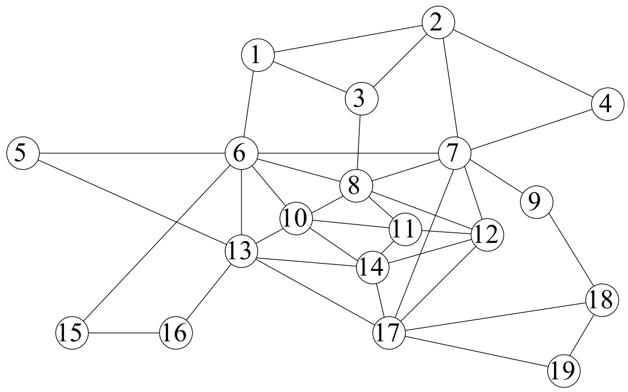
We investigate how often the ranking table is reset depending on R_{max} to analyze the results in Fig. 6. A table reset ratio is defined as the ratio of the number of table resets to the number of measured time slots. Figure 7 shows the table reset ratio in different R_{max}s. In every topology, the table reset ratio is the



(a) US IP backbone network topology.

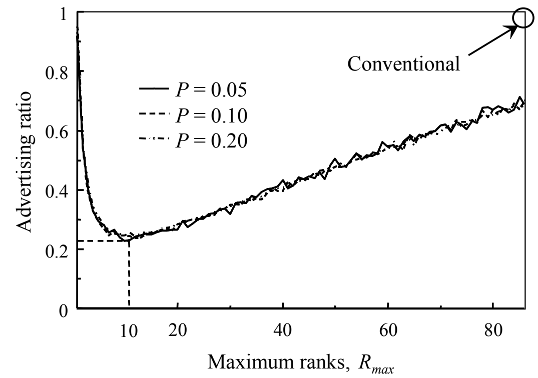


(b) NSFNET topology.

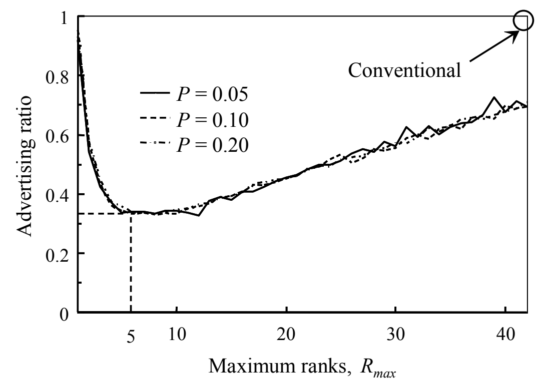


(c) EON topology.

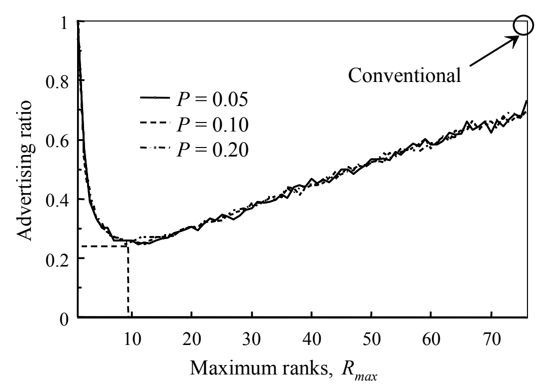
Fig. 5. Network topologies.



(a) US IP backbone network topology.



(b) NSFNET topology.



(c) EON topology.

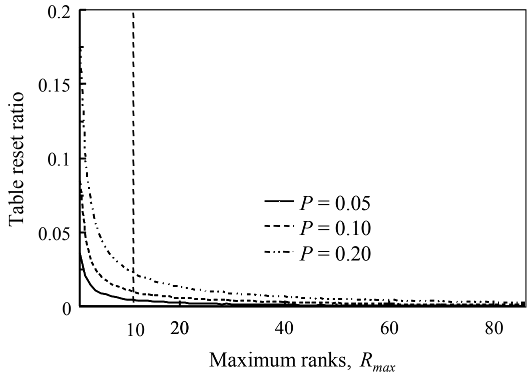
Fig. 6. Advertising ratio with different maximum entry numbers.

highest when R_{max} is one. It dramatically decreases with R_{max} in small R_{max}, and slightly decreases with R_{max} in large R_{max}. With the same R_{max}, the table reset ratio with high P is higher than that with low P. This is because the link load is easier to be changed with high P than low P. Therefore, the table reset with high P is more likely to occur than that with low P. It notes that the advertising ratio in Fig. 6 with small R_{max} is high, because the table reset ratio between R_{max} = 1 and the optimum R_{max}, as shown in Fig. 7, is high.

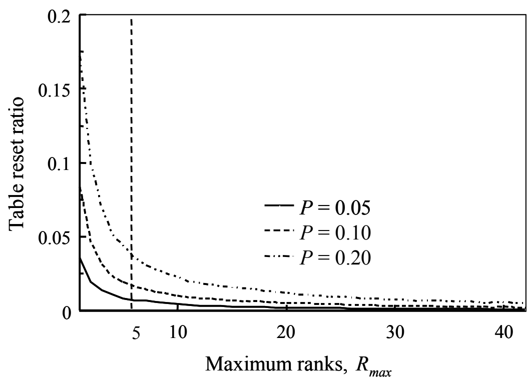
We confirm the LLR scheme using several network topologies. The results are similar in every topology.

V. Conclusions

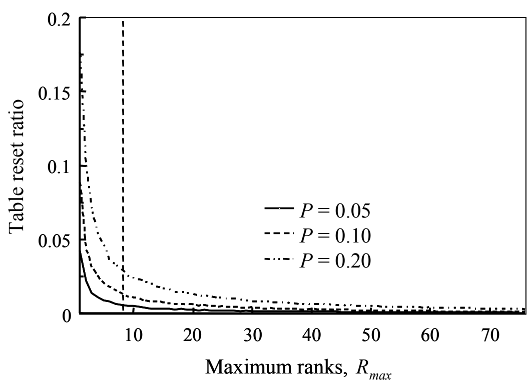
A link load ranking (LLR) scheme was proposed to reduce the number of advertisements needed by an OSPF-TE network to control routing. The controller determines the maximum link load from the received advertisements, and uses this information to avoid traffic congestion by setting routes appropriately. In the conventional scheme, each node in the network, including the controller, keeps all link information. Every time a link load is changed, the ingress node of that link advertises the updated link information. Some advertisements may waste the bandwidth since they may not be necessary for determination of the maximum link load. In LLR, each node keeps only a predetermined number of link loads instead of keeping all links as in the conventional scheme. Only link information that impacts the determination of the maximum link load is advertised by a ingress node of the link whose load changes. Otherwise, no advertisement is needed. As a result, LLR generates far fewer advertisements than the conventional



(a) US IP backbone network topology.



(b) NSFNET topology.



(c) EON topology.

Fig. 7. Table reset ratio at different maximum entry numbers.

scheme, which creates an advertisement every time a link load changes. A computer simulation showed that LLR generates at most 78% fewer advertisements if each node holds a maximum of 11% of link loads.

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REFERENCES

[1] M. Goyal, M. Soperi, H. Hosseini, K.S. Trivedi, A. Shaikh, and G. Choudhury, "Analyzing the Hold Time Schemes to Limit the Routing Table Calculations in OSPF Protocol," in Proc. *IEEE AINA'09*, pp. 74–81, 2009.

[2] M. Goyal, W. Xie, M. Soperi, S.H. Hosseini, and K. Vairavan, "Scheduling routing table calculations to achieve fast convergence in OSPF protocol," in Proc. *IEEE BROADNETS 2007*, pp. 863–872, 2007.

[3] M. Antic, N. Maksic, P. Knezevic, and A. Smiljanic, "Two phase load balanced routing using OSPF," *IEEE J. Sel. Areas in Commun.*, vol. 28, iss. 1, pp. 51–59, 2010.

[4] J. Chu and C. Lea, "Optimal link weights for maximizing QoS traffic," in Proc. *IEEE ICC 2007*, pp. 610–615, 2007.

[5] A. K. Mishra and A. Sahoo, "S-OSPF: a traffic engineering solution for OSPF based on best effort networks," in Proc. *IEEE Globecom 2007*, pp. 1845–1849, 2007.

[6] M. Antic and A. Smiljanic, "Routing with load balancing: increasing the guaranteed node traffics," *IEEE Commun. Lett.*, vol. 13, no. 6, pp. 450–452, June 2009.

[7] E. Oki and A. Iwaki, "Load-Balanced IP Routing Scheme Based on Shortest Paths in Hose Model," *IEEE Trans. Commun.*, vol. 58, no. 7, pp. 2088–2096, Jul. 2010.

[8] D. Katz, K. Kompella, and D. Yeung, "Traffic Engineering (TE) Extensions to OSPF Version 2," RFC 3630, Sep. 2003.

[9] J. Moy, "OSPF Version 2," RFC 2328, Apr. 1998.

[10] H.M. Alnuweiri, L.Y.K. Wong, and T. Al-Khasib, "Performance of new link state advertisement mechanisms in routing protocols with traffic engineering extensions," *IEEE Commu. Mag.*, vol. 42, iss. 5, pp. 151–162, 2004.

[11] Y. Koizumi, T. Miyamura, S. Arakawa, E. Oki, K. Shiomoto, and M. Murata, "Adaptive Virtual Network Topology Control Based on Attractor Selection," *IEEE/OSA J. Light. Tech.*, vol. 28, no. 11, pp. 1720–1731, Jun. 2010.

[12] N. Kitsuwan and E. Oki, "A Scheme to Maintenance the Maximum Link Load based on Load Ranking," in Proc. *IEEE ISAS2011*, pp. 218-221, 2011.

[13] J. Rak, "*k*-penalty: A Novel Approach to Find *k*-Disjoint Paths with Differentiated Path Costs," *IEEE Commun. Lett.*, vol. 14, no. 4, pp. 354–356, Apr. 2010.

[14] J. Triay and C. Cervello-Pastor, "An Ant-Based Algorithm for Distributed Routing and Wavelength Assignment in Dynamic Optical Networks," *IEEE J. Sel. Areas in Commun.*, vol. 28, iss. 4, pp. 542–552, 2010.

[15] A. Agusti-Torra, C. Cervello-Pastor, and M.A. Fiol, "Load-balanced wavelength assignment strategies for optical burst/packet switching networks," The Institution of Engineering and Technology, vol. 3, no. 3, pp. 381–390, 2009.

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