Cost Reduction of Reliable Networks Using Load Balanced Routing

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***Abstract*—The routing based on load balancing and shortest path routing (LB-SPR) was recently introduced, and it was shown to have advantages over the standard shortest path routing (SPR) algorithms: it can support higher guaranteed traffic loads, and it simplifies the resource reservation processes. In this paper, the cost of setting up the reliable network which is resilient to node or link failures is analyzed. In such a network, enough capacity has to be provisioned on all the links for routing the traffic even in the case of a failure. The cost of setting up the reliable network using the shortest path routing (SPR) is compared to the cost of setting up the reliable network using the load balanced shortest path routing (LB-SPR). It is shown that LB-SPR can significantly decrease the network cost.**

I. INTRODUCTION

RECENTLY, a novel routing algorithm based on load balancing and shortest path routing was introduced [1]–[5]. This algorithm, termed as LB-SPR (Load Balanced Shortest Path Routing), was shown to either increase the guaranteed node traffic loads for the given network topologies [1]–[4], or to decrease the cost of the network that passes the given node traffic loads [5]. The guaranteed node traffic loads can always be routed through the network regardless of the traffic pattern. In [1], [2], it was shown that in the realistic networks, the guaranteed node traffic loads increase 2 to almost 8 times when LB-SPR is used instead of standard shortest path routing (SPR) protocols, depending on the network topology. Also, it was shown that the cost of the network that passes the given node traffic loads is 2 to 3.5 times lower when LB-SPR is used [5]. The practical implementation of the LB-SPR, based on OSPF, was presented in [3], [4], and its performance was analyzed in the simulation environment that was created using virtual machines. The algorithm was shown to distribute the total load more evenly among the links in the network, while the side effects of the load balancing do not seriously affect the quality of transmission.

There are several advantages of LB-SPR over the other oblivious routing schemes. First, the actual traffic pattern (in the form of the traffic matrix) is not needed for the routing optimization, as it is in [6], [7]. It is enough to assume only the total traffic loads generated and received by the network nodes, or their ratios in the case of the given network, which are much easier to predict. Also, due to the use of the standard shortest path routing as the underlying routing strategy, the linear optimization program is of a smaller size, and the optimization is performed much faster than for the schemes presented in [8], [9], which also use load balancing in a similar fashion. The LB-SPR allows simple and agile bandwidth reservations at a lower cost. Namely, after the routing optimization is performed, every router in the network knows the maximum traffic load it is allowed to generate. Also, it keeps track of the already reserved bandwidth for the active sessions. When a new session is to be initiated, only the routers through which that session's traffic enters and leaves the network have to process the bandwidth request. If there is enough available bandwidth (the requested bandwidth is lower than the difference between the guaranteed and the already reserved capacity for these two routers), the capacity for the session in question can be reserved. Also, each router handles bandwidth reservations only for the flows that are either entering or leaving the network through that router.

So far, we did not consider the network node and link failures. The network is considered to be *reliable*, if it can pass the given traffic node loads when any of the nodes, or links fails. To provide such a reliable network, the link capacities need to be overprovisioned. Whenever a failure occurs, both LB-SPR and OSPF adjust the routing so that the given traffic loads are passed. The LB-SPR recalculates the guaranteed node traffic loads as implemented in [3], which should be higher than the given node traffic loads. In this paper, the costs of the reliable networks that use either LB-SPR or OSPF will be analyzed and compared. It will be shown that the network using LB-SPR requires less overprovisioning than the network using OSPF, and consequently has the lower cost.

II. CAPACITY ALLOCATION FOR RELIABLE NETWORKS

The reliable network is the one that maintains the end-to-end availability for the customers even in the failure states. There are two types of failure states: node failures and link failures. In this paper, it is assumed that only one node or one link can be in the failure state at the time, which is a realistic assumption.

The network $\Gamma = (V, E)$ is defined by the set of nodes V ($|V| = N$) and the set of links E ($|E| = M$). Denote by s_i the total traffic generated by a node $i \in V$, and by r_i the total traffic received by i. The vectors $\mathbf{R} = [r_i]_{1\times N}$ and $\mathbf{S} = [s_i]_{1\times N}$ will be referred to as the in-traffic and out-traffic vectors, respectively. For the analyzed backbone networks, it will be assumed that $r_i = s_i$ for all $i \in V$. It is assumed that the traffic demands $\mathbf{R} = \mathbf{S}$ are known, as well as the network topology (i.e. sets V and E). In order to provide a reliable network, the sufficient capacity has to be provisioned on all the links, so that the given traffic demands are routed even in the case of failures. Our goal is to minimize the cost of such reliable networks.

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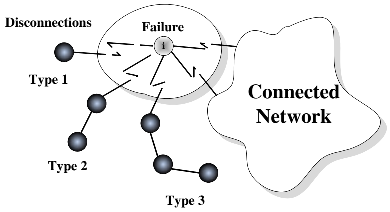

Fig. 1: Three types of disconnections: various groups consisting of one, two or three nodes can get disconnected.

Generally, the network cost comprises the cost of the links and of the router ports. The setup cost of the links can be neglected because the large number of optical fibers are already laid along the relevant routes, and offer the capacities that can be considered arbitrarily high. On the other hand, the cost of the router ports is proportional to the total capacity of the links entering (leaving) the network node. Therefore, the sum of the link capacities in the network can be defined as the cost of the network setup. In this section it is first described how the optimal capacity allocation that minimizes the network cost is found for the arbitrary network using the LB-SPR protocol, and which is resilient to the failures. Then it is explained how the cost of the resilient network using the SPR protocol is determined.

There are two cases that will be analyzed separately: node failures and link failures. Define the failure type indicator as $t \in \{0,1\}$, with $t=0$ denoting the node failure, and $t=1$ denoting the link failure. It is realistic to assume that only a single resource r of the type t can be in the failure state at the time. Although single failures are assumed, they sometimes cause the disconnection of a number of nodes attached to the malfunctioning node/link, for certain network topologies. Three types of disconnections presented in Fig. 1 may occur in the analyzed existing networks. In these cases, only the remaining part of the network could be made reliable. This network will be denoted by $\Gamma(r,t) = (V(r,t), E(r,t))$, with $N(r,t)$ nodes and $M(r,t)$ links. Let the value $r=0$ denote the state without any failures, i.e. the state with all the functioning nodes/links. This complete network without failures will be denoted by $\Gamma_0 = \Gamma(0,0) = \Gamma(0,1) = (V_0, E_0)$, with N_0 nodes and M_0 links. Therefore, for the failure type $t=0$, the failed resource (node) can take values $r \in R_0 = \{0,1,\ldots,N_0\}$, and for the failure type $t=1$ the failed resource (link) can take values $r \in R_1 = \{0,1,\ldots,M_0\}$.

A. Load Balanced Shortest Path Routing (LB-SPR)

In the network with LB-SPR, every flow is routed in two steps, instead of being sent directly from the source to the destination router. In the first step, the flow between a pair of nodes is split into portions, which are directed to the balancing routers. These portions are determined by the balancing coefficients k_i assigned to the balancing routers $i \in V$. In the second step, the balancing routers forward the received packets to their final destinations. The shortest path routing is used to deliver the traffic from the source to the balancing routers, and from the balancing routers to the destination node. Detailed explanation of how the routing is performed can be found in [1]–[5]. Here, the minimal link capacities required to provide a reliable network are determined.

For the failure type t, observe the link $l \in E_0$. It should be allocated enough capacity, to route the traffic in the case when it is most heavily loaded. At the same time, the network cost should be minimized. For every state (r,t), in which the resource $r \in R_t$ of type t failed, the optimal capacity allocation that minimizes the network cost is determined by the linear program (non-negativity of all the variables is assumed):

$$\begin{array}{l} \min \sum\limits_{l\in E(r,t)} C^l_{lbr}(r,t) \\ \hline (1)\ \sum\limits_{i\in V(r,t)} k_i(r,t) = 1 \\ (2)\ \forall l \in E(r,t): \\ \sum\limits_{(i,m)\in(V(r,t)\times V(r,t))} F^l_{im}(r,t)\,[k_i(r,t)s_m + k_m(r,t)s_i] \le C^l_{lbr}(r,t) \end{array} \tag{1}$$

Here, $F^l_{im}(r,t)$ is a binary variable that takes the value 1 if in the network $\Gamma(r,t)$ the link l is on the shortest path from i to m, and 0 otherwise. The balancing coefficient assigned to the router i in the network $\Gamma(r,t)$ is denoted by $k_i(r,t)$. $C^l_{lbr}(r,t)$ is the capacity required for the link l when LB-SPR is used, and the resource r of the type t is in the failure state. This capacity is chosen in a way that minimizes the cost of the network $\Gamma(r,t)$, given by the sum $\sum_{l\in E(r,t)} C^l_{lbr}(r,t)$. When the link l does not belong to the connected network after the failure, $l \notin E(r,t)$, its capacity is $C^l_{lbr}(r,t) = 0$.

The cost of setting up the reliable network with LB-SPR, which is resilient to the failures of type t, equals the sum of the required link capacities:

$$\mathbf{C}_{lbr}(t) = \sum_{l\in E_0} \max_{r\in R_t} C^l_{lbr}(r,t). \tag{2}$$

B. Shortest Path Routing (SPR)

In order to determine the required link capacity for the standard shortest path routing (SPR) protocols, it is necessary to find the worst-case traffic pattern for every link, in every possible network state. This is the traffic that causes the highest possible load on that link, and it should be accommodated by the link capacity.

The worst-case load of the link $l \in E_0$ in the network $\Gamma(r,t)$ where resource r of type t failed, can be determined by calculating the maximum flow in the bipartite graph assigned to that link, as described in [5]. Let us denote this capacity by $C^l_{spr}(r,t)$.

$$\forall l \in E(r,t) : C^l_{spr}(r,t) = f^l_{max}(r,t) \tag{3}$$

Here, $f^l_{max}(r,t)$ is the value of the maximum flow in the graph assigned to the link l of the network $\Gamma(r,t)$. If $l \notin E(r,t)$, it can be considered that $C^l_{spr}(r,t) = 0$. Each link $l \in E_0$ has to be allocated enough capacity to route the traffic in the worst of the possible states.

The cost of the network resilient to failures of the type t when SPR is used equals to the sum of the required link capacities:

$$\mathbf{C}_{spr}(t) = \sum_{l\in E_0} \max_{r\in R_t} C^l_{spr}(r,t). \tag{4}$$

TABLE I: Disconnected nodes distribution for the analyzed topologies

AS	AS3967	AS1755	AS1221	AS6461	AS3257	AS1239
N_0	79	87	104	138	161	315
M_0	294	322	302	744	656	1944
P	6	11	19	4	24	28
(d, p_d)	$(1, 5)$ $(2, 1)$	$(1, 6)$ $(2, 5)$	$(1, 9)$ $(2, 6)$ $(3, 1)$ $(6, 1)$ $(10, 1)$ $(17, 1)$	$(1, 2)$ $(3, 1)$ $(4, 1)$	$(1, 8)$ $(2, 8)$ $(3, 5)$ $(4, 2)$ $(6, 1)$	$(1, 25)$ $(2, 3)$

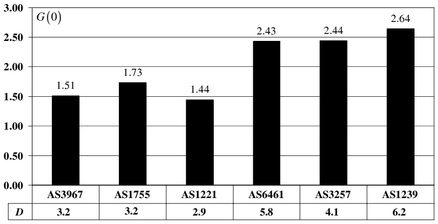

Fig. 2: Comparison of network costs for LB-SPR and regular SPR in the case of node failures.

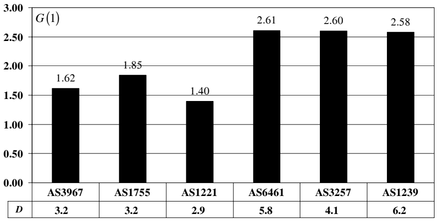

Fig. 3: Comparison of network costs for LB-SPR and regular SPR in the case of link failures.

III. RESULTS

As previously said, two types of failures are analyzed: node failures and link failures. In both of these cases, the cost of network setup is determined for LB-SPR as described in Section II. A, and for SPR as in Section II. B. These two costs are then compared and the gain is calculated:

$$G(t) = \mathrm{C}_{spr}(t)/\mathrm{C}_{lbr}(t). \tag{5}$$

The cost of the reliable network resilient to failures of the type t is $G(t)$ times lower when LB-SPR is used instead of SPR.

The analysis is performed for the six realistic network topologies published in [10]: Exodus (AS3967), Ebone (AS1755), Telstra (AS1221), Abovenet (AS6461), Tiscali (AS3257), and Sprintlink (AS1239). The link weights in Dijkstra algorithm are set to be equal to one, when determining the shortest paths between the network nodes and the coefficients $F^l_{im}(r, t)$ in (1). This way, the SPR minimizes the path cost, i.e. the total capacity of links from the source to the destination. It is supposed that the traffic loads s_i are proportional to the number of inhabitants serviced by the network node, as in [2]. The routing optimization in (1) is performed using the open-source software LP_Solve [11].

As already said, the failure of a resource r of type t can cause the disconnection of a number of nodes, as in Fig. 1. The number of failure states (r, t) when this occurs is denoted by P. In p_d of these states, d nodes get disconnected. Of course, $P = \sum_d p_d$.

1) Node Failures: For the analyzed networks, the number of possible node failure states N_0, the number of failure states when disconnections occur P, as well as the distribution of the number of disconnected nodes (d, p_d) are represented in Table I. We calculated the network cost for LB-SPR and SPR, and the ratio $G(0)$ defined in (5). The results are plotted in Fig. 2. The network cost is from 1.44 to 2.64 times lower for the networks using LB-SPR, than for the networks using SPR. It can be observed that the gain increases for the topologies with the higher average node degree, given by the value D in the table on the bottom of the graph in Fig. 2.

2) Link Failures: The numbers of possible link failure states M_0 for the analyzed topologies are represented in Table I. The number of states when disconnections occur P, and the distribution of the number of disconnected nodes (d, p_d) are the same as in the case of the node failures. The results for $G(1)$ are plotted in Fig. 3. The gain grows from 1.40 to 2.61, as the average node degree in the network increases. Again, the network setup cost is significantly lower for the networks using LB-SPR, than for the networks with SPR.

IV. CONCLUSION

The load balanced shortest path routing, LB-SPR, was shown to have certain advantages over the existing shortest path routing schemes. It supports higher node traffic loads than the shortest path routing algorithms, and can facilitate fast and scalable bandwidth reservations. In this paper we showed that LB-SPR can also considerably decrease the cost of setting up the reliable network, which is resilient to node and link failures.

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