Robustness based low-energy multiple routing configurations for fast failure recovery

T Hatanaka¹,² and T Tachibana¹,³

¹Graduate School of Engineering, University of Fukui, 3-9-1 Bunky, Fukui-shi, Fukui, 910-8507, Japan
²takayuki-h@network.fuis.u-fukui.ac.jp; ³takuji-t@u-fukui.ac.jp

Abstract. Fast failure recovery and the energy consumption are important issues in communication networks. A low-energy based multiple routing configurations is proposed for realizing both the fast failure recovery and the low energy consumption. However, in this method, the network robustness and the performance of data transmission are degraded regardless of the low energy consumption. In this paper, for turning some link ports off while maintaining network robustness, we propose a robustness and low-energy based MRC by extending low-energy based MRC. Our proposed method utilizes an algorithm that determines some excluded links based on the network robustness. With the proposed method, the energy consumption can be reduced so as not to degrade the network robustness significantly. We evaluate the performance of our proposed method in some network topologies with simulation.

1. Introduction

Fast failure recovery is an important issue in communication networks because the communication networks such as the Internet are indispensable in our daily lives [1]. MRC (Multiple Routing Configurations) has been proposed as one of the fast failure recovery methods in [2]. In this method, multiple backup networks have been prepared for the failure recovery in advance.

The energy consumption is also one of the important issues for communication networks. ICT in 2030 may consume 51% of the global electricity supply [3]. In [4], MRC has been extended in order to both perform the fast failure recovery and reduce the energy consumption. With this method, the power consumption can be reduced by turning unused links off while performing the first failure recovery as is the case with MRC. However, the network robustness is degraded because all links that are not needed for the failure recovery are turned off.

In this paper, we propose a method called Robustness base Low-Energy MRC by extending [4]. Our proposed method utilizes an algorithm that determines some excluded links based on the network robustness. By using the proposed method, the energy consumption can be reduced while maintaining the network robustness. We evaluate the performances of our proposed method with simulation.

The rest of this paper is organized as follows. Section 2 introduces related work about low-energy based MRC and evaluation of network robustness. Section 3 explains our proposed method. Section 4 shows some numerical examples, and finally section 5 denotes conclusions.
2. Related work

2.1. Low-energy based multiple routing configurations

[4] has extended MRC so as to both perform the fast failure recovery and reduce the energy consumption. In this method, \( K \) backup configurations \((K \geq 2)\) are designed previously as shown in figure 1. When a failure occurs at a single node or a single link, a network is switched to one of the \( K \) backup configurations. In each backup configuration, there are two kinds of nodes and four kinds of links. Nodes are classified into non-isolated node and isolated node, and links are classified into normal link, isolated link, restricted link, and unnecessary link according to those link weights (see figure 1). Restricted links are used to isolate nodes from traffic forwarding, isolated links are not used to transmit traffic, and unnecessary links are turned off.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Normal configuration and backup configurations in a case of \( K = 3 \).

At first, in this method, \( K \) backup configurations are generated by using MRC. Then, a set \( L^* \) of links that are necessary for MRC is derived so that links in \( L^* \) satisfy the following two conditions:

1. Each isolated node is connected to one or more restricted links.
2. In each backup configuration, a connected graph is generated from all non-isolated nodes and all normal links.

When the failure occurs at a single node or a single link, it is possible to recover from the failure by using an appropriate backup configuration that does not use the failed node or the failed link.

2.2. Evaluation of network robustness with network criticality

As a metric for network robustness, network criticality has been proposed [5]. Now, let \( W \) be a weight matrix of a network and \( D \) be a diagonal matrix of weighted degrees for nodes that are in the network. From \( W \) and \( D \), Laplacian matrix \( L \) is given by \( L = D - W \).

In addition, let \( N \) be the number of nodes and \( n_i \) be the \( i \)-th node \( n_i (i = 0, \ldots, N) \) in the network. Let \( L^* \) be a pseudo inverse matrix of the Laplacian matrix and \( L^*_{ij} \) be the \( i \)-th row and \( j \)-th column of pseudo inverse matrix \( L^* \). Here, the network criticality \( \tau_{ij} \) of link \( l_{ij} \) between \( n_i \) and \( n_j \) is given by \( \tau_{ij} = L^*_{it} + L^*_{jt} - 2L^*_{ij} \).

Now, let the amount of traffic from \( n_s \) to \( n_t \) \((s \neq t)\) be denoted as \( y_{st} \). In addition, the impact of the amount of traffic from \( n_s \) to \( n_t \) on the performance of the network is denoted as \( \alpha_{ij} \). From the total amount of traffic \( \gamma = \sum_i \sum_j y_{ij} \), \( \alpha_{ij} \) is given by \( \alpha_{ij} = \gamma + \gamma_{ij} + \gamma_{ji} + 2 \sum_k (\gamma_{ki} - \gamma_{ik}) / N \).

Finally, network criticality \( \tau' \) based on the amount of traffic is given by

\[
\tau' = \sum_i \sum_j \alpha_{ij} \tau_{ij}.
\]  

(1) 

When the network criticality \( \tau' \) is small (large), the robustness of the network is high (low).
3. Robustness based low-energy multiple routing configurations

In this section, we propose a Robustness based Low-Energy MRC so as not to degrade the network robustness by extending [4].

In this method, at first, unnecessary link set $\tilde{L}$ is derived by using [4]. Then, the network robustness for the original communication network is evaluated by using a performance metric called network criticality $\tau'$ of subsection 2.2. Here, our proposed method utilizes new unnecessary link sets $\tilde{L}_i$ ($i = 0, \ldots, |\tilde{L}|$) that includes $i$ unnecessary links. Moreover, the network robustness of the communication network where $i$ links are excluded is denoted as $\tau'_i$ ($i = 0, \ldots, |\tilde{L}|$).

In our proposed method, in order to exclude some links based on the network robustness, $\tilde{L}_i$ are derived according to three steps. At the first step 1), $\tilde{L}_0$ is set to $\emptyset$ and network criticality $\tau'_0 = \tau'$ is calculated in a case where no link is excluded. Then, $i$ is increased by one. Then, at the next step 2), for each link in $\tilde{L} \setminus \tilde{L}_{i-1}$, network robustness $\tau'_i$ is calculated for the communication network where all links in $\tilde{L}_{i-1}$ and a link in $\tilde{L} \setminus \tilde{L}_{i-1}$ are excluded. Finally, at the last step 3), a link $l$ is selected from $\tilde{L} \setminus \tilde{L}_{i-1}$ so that $\tau'_i$ becomes the minimum. Then, $\tilde{L}_i = \tilde{L}_{i-1} \cup l$ is derived.

Here, the threshold $\tau_{th}$ for the network robustness is given in advance and the network criticality is expected to be smaller than $\tau_{th}$. Hence, from $\tau_{th}$ and $\tau'_i$, the proposed method determines the number $\xi$ of links that are excluded according to the following equation.

$$\xi = \max \tau'_i,$$

subject to: $\tau'_i < \tau_{th}$.

Then, all unnecessary links in $\tilde{L}_\xi$ are turned off for reducing the energy consumption.

4. Numerical examples

In this section, we evaluate the performance of proposed method based on network robustness for the two network topologies in figure 2. In those topologies, the bandwidth for each link is 1,000 [Mbps] and the amount of communication traffic $\gamma_{sd}$ between source node $s$ and destination node $d$ is 1.0 [Mbps].

![Figure 2. Two network topologies.](image)

![Figure 3. Number of excluded links for proposed method against threshold in COST239.](image)

In the following, the proposed method is used to reduce the energy consumption by excluding unnecessary links while satisfying equation (2). For the performance comparison, we also consider a random method where unnecessary links are selected at random unless equation (2) is satisfied. We also consider an optimal method where unnecessary links are selected by using exhaustive search so that the energy consumption becomes the minimum while satisfying equation (2).
Figure 3 shows the average number of excluded links against the threshold $\tau_{th}$ for COST239. Note that the threshold $\tau_{th}$ is normalized by the network criticality $\tau_0$. From figure 3, we find that proposed method is effective for reducing the amount of energy consumption while maintaining the network robustness of network topology. This figure shows that the performance of proposed method is almost the same as that of the optimal method regardless of $\tau_{th}$.

Moreover, figure 4 shows the number of excluded links against the number $K$ of backup configurations for COST239. Here, the threshold $\tau_{th}$ of the network robustness is equal to 1.25 times the initial value $\tau_0$. From this figure, we find that the number of excluded links increases as the number of backup configuration increases. However, in COST239, the number of excluded links is almost constant when $K$ is larger than three. This is because the network criticality dissatisfies the threshold $\tau_{th}$ if the number of excluded links increases by one. Moreover, we find that the number of excluded links for the random method is the minimum and the number of excluded links for proposed method is almost the same as that for the optimal method. From these results, proposed method can exclude a larger number of links according to the algorithm in Section 3 while maintaining the network robustness.

Figure 5 also shows the number of excluded links for NSFnet. In this figure, when $K$ is smaller than five, the number of excluded links for proposed method is almost the same as those for other methods. When $K$ is equal to or larger than five, the number of excluded links for the random method is the minimum. On the other hand, proposed method can exclude approximately the same number of links as the optimal method.

5. Conclusion
In this paper, in order to maintain the network robustness in addition to realize fast failure recovery and low energy consumption, we proposed Robustness based low-energy MRC. We evaluated the performance of our proposed method in some network topologies with simulation. From numerical examples, we found that the amount of energy consumption can be reduced by using our proposed method while maintaining the network robustness. Therefore, our proposed method can realize fast failure recovery and low energy consumption. From numerical results, our proposed method are expected to be implemented and utilized in future communication networks by using MTR and SDN.

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