A proposal of distributed algorithm to reconstruct a robust network by self-healing

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ADAPTIVE 2021 April 18-22, 2021 – Porto, Portugal

Objective of Method

Many infrastructures are represented by a common structure called scale-free which is extremely vulnerable against malicious attacks. Moreover, these systems are frequently damaged by natural disasters.

To reconstruct such a weak network, our method can repair it to the optimally robust onion-like network based on enhancing loops.

BIO
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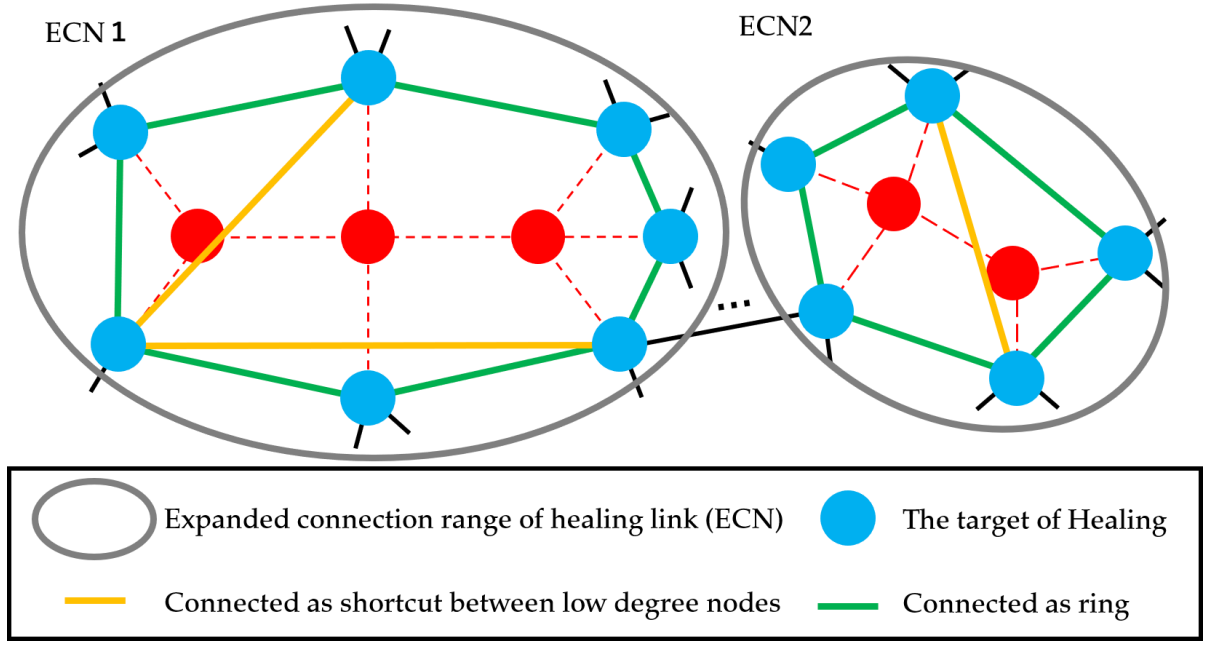
Our Method



Outline of method (Slightly different version from [1]) after stopping normal delivery

1. To expand the connection range for healing links, each node transfers messages to other nodes in three hops by using other lines for control signals instead of delivery. The nodes which lose a part of their links are a target of healing in connecting to other nodes in the same ECN.
2. A ring as the simplest loop is created within the extended neighbors to maintain the larger connectivity. The order of linking is decreasing order of connected component sizes belonging to targets.
3. If healing links are residual after making rings, loops on the rings are enhanced between low degree nodes.

[1] Hayashi, Y., Tanaka, A., & Matsukubo, J. (2021). More Tolerant Reconstructed Networks Using Self-Healing against Attacks in Saving Resource. *Entropy*, *23*(1), 102.

Measures

Effectiveness of our self-healing method

1. Connenctivity ($S_q(q)$; $[0, 1]$)

$$S_q(q) = \frac{S(q)}{(1-q)N}$$

2. Robustness (R; $[1/N, 0.5]$)

$$R = \frac{1}{N}\sum_{q'=\frac{1}{N}}^{1} S_{q'}(q')$$

3. Efficiency (E; $[0, 1]$)

$$E = \frac{1}{N(N-1)}\sum_{i \neq j}^{N} \frac{1}{d_{ij}}$$

※ The number of links used in healing

$$\alpha \cdot \sum_{i}^{\sim} k_i \; ; \; (i \in [\text{The set of removed nodes}]、\; k_i\text{: Degree of node i})$$

(α: The ratio of reusable links $(0 < \alpha \leq 1)$)

The neighbors of attacked nodes lose a part of their links, while the unbroken links of removed nodes can be reused. Therefore, we assume that some links emanated from removed nodes are reused as healing links.

q: *the ratio of removed nodes*
$S(q)$: *the size of largest connected component when the q nodes are removed*
N: *the number of nodes in a network*
d_{ij}: *the length of shortest path between nodes i and j*

Conventional Self-Healing

Effectiveness of our self-healing method

To evaluate our method, we compare with conventional self-healing method [2].
In this distributed local healing, each damaged node has new connection with randomly selected node in its second-nearest neighbors.

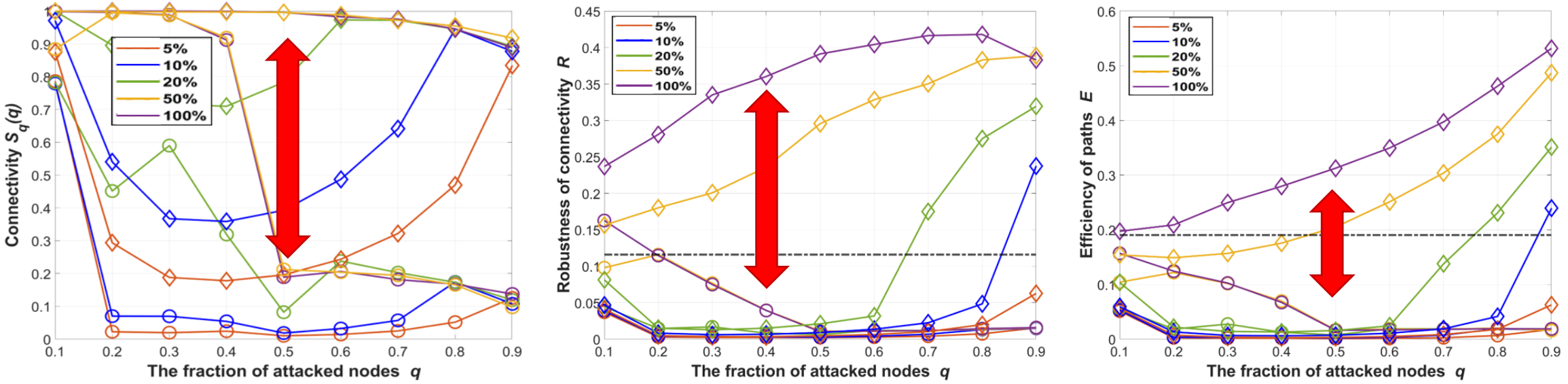
The number of healing links are controllable by choosing the node in accordance with extent of damage. In other words, Only nodes which the ratio of remaining neighbors ($q = k_{attacked}/k_{original}$) is under the threshold (q_c) are chosen for healing.

[2] Gallos, L. K., & Fefferman, N. H. (2015). Simple and efficient self-healing strategy for damaged complex networks. Physical Review E, 92(5), 052806.

Result for Infrastructure Network

Effectiveness of our self-healing method

Properties of reconstructed network by our proposed (marked by diamond) and the conventional (m arked by circle) methods [2]. Here, colors represent the ratio (5~100%) of reused healing links.

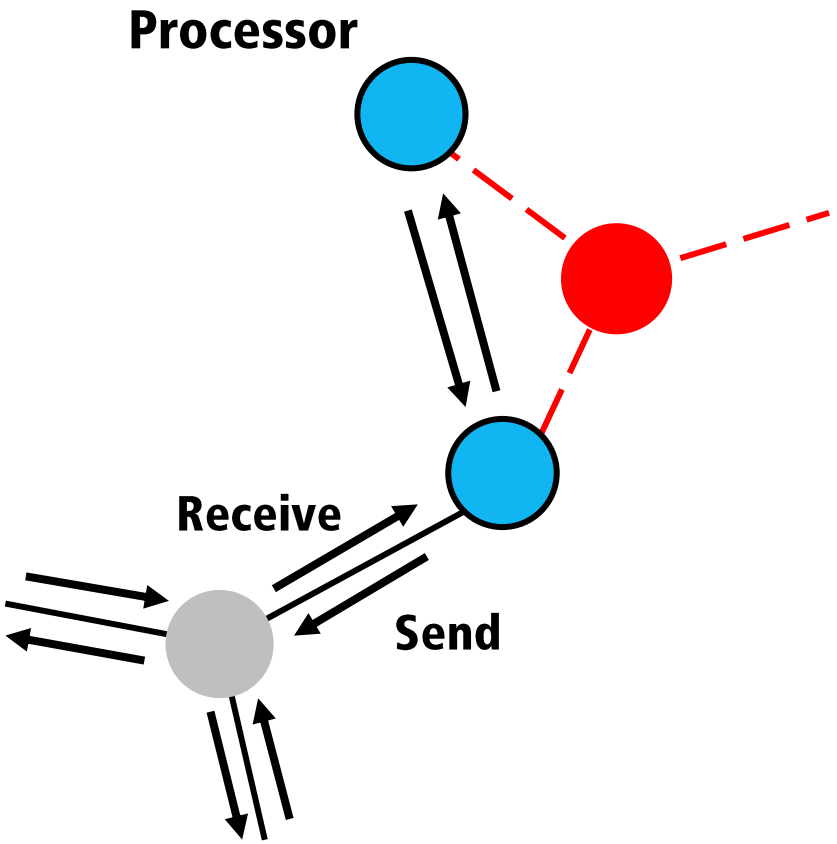


⬆ The results of applying both methods on AirTraffic network. All these results are similar to other systems such as flight routes and Internet.

∴ The reconstructed networks by our method have both higher robustness of connectivity and efficiency of paths than ones by the conventional method and the original network [3].

[3] Kim, J. and Hayashi, Y. (2020). Self-Healing Strategy for Improving Robustness in Limited Resource. International Conference on Complex Systems 2020, Book-of-Abstracts, pp.166, Online, Dec. 4-11.

Distributed algorithm of our self-healing method



Assumptions

- ✓ No additional malfunction events while processing.
- ✓ Ignore the time lag of message transfer and processing speed.
- ✓ FIFO in queue.
- ✓ No waiting after process.
- ✓ No shared global memory.
- ✓ Processes use only Send/Receive actions

Outline of Algorithm Description

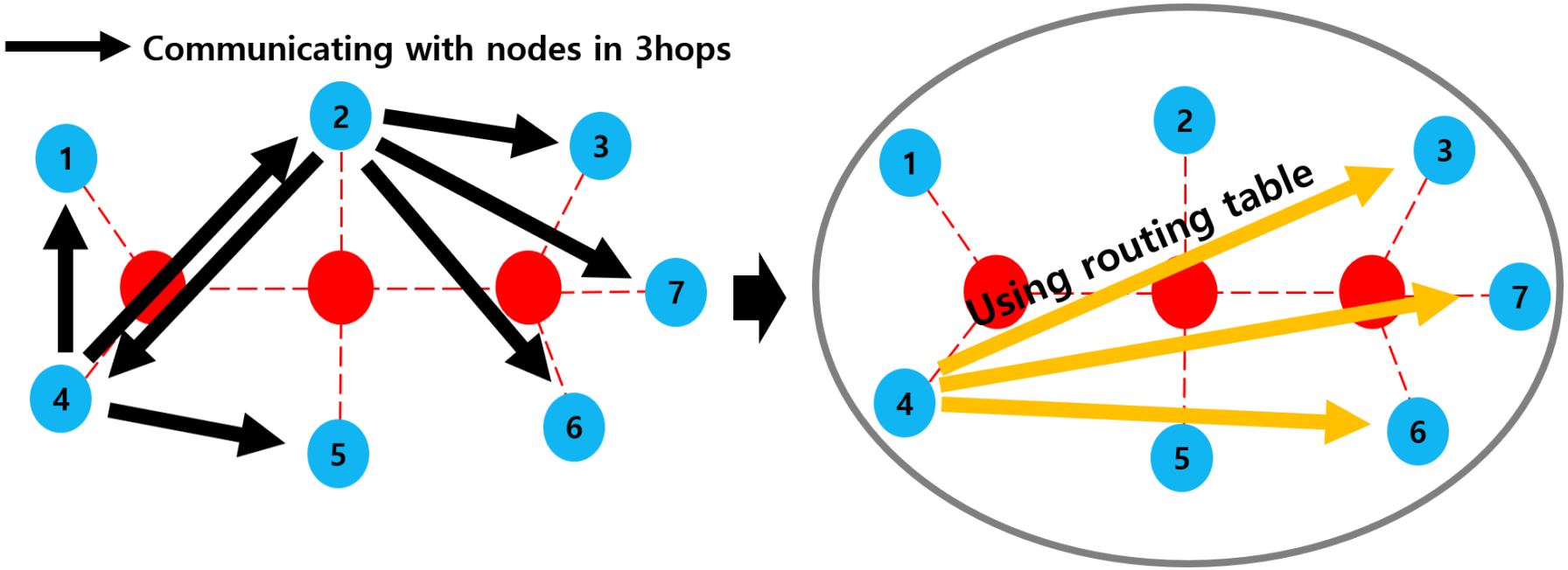
Distributed algorithm of our self-healing method

1. Expand the connection range for healing links.
   Each node (healing node) detects malfunction events autonomously and sends messages as control signals to other healing nodes in three hops.
   Through sending and receiving messages, each healing node knows the IDs of nodes over three hops.

2. Making a ring in order of the size of connected components.
   A root node gathers the size of its component by using delivery trees for control signals.
   Select a leader node in the expanded connection range.
   Each leader determines the order of connections on a ring.

3. A leader assigns new connection ends to other healing nodes
   A leader receives the messages of component size from other healing nodes to determine the order of connection on a ring for the case: the number of healing links are insufficient.
   After a leader determines the order, sends command messages for making a ring.
   The healing nodes make a new connection after receiving the above messages.

Expanding the Connection Range

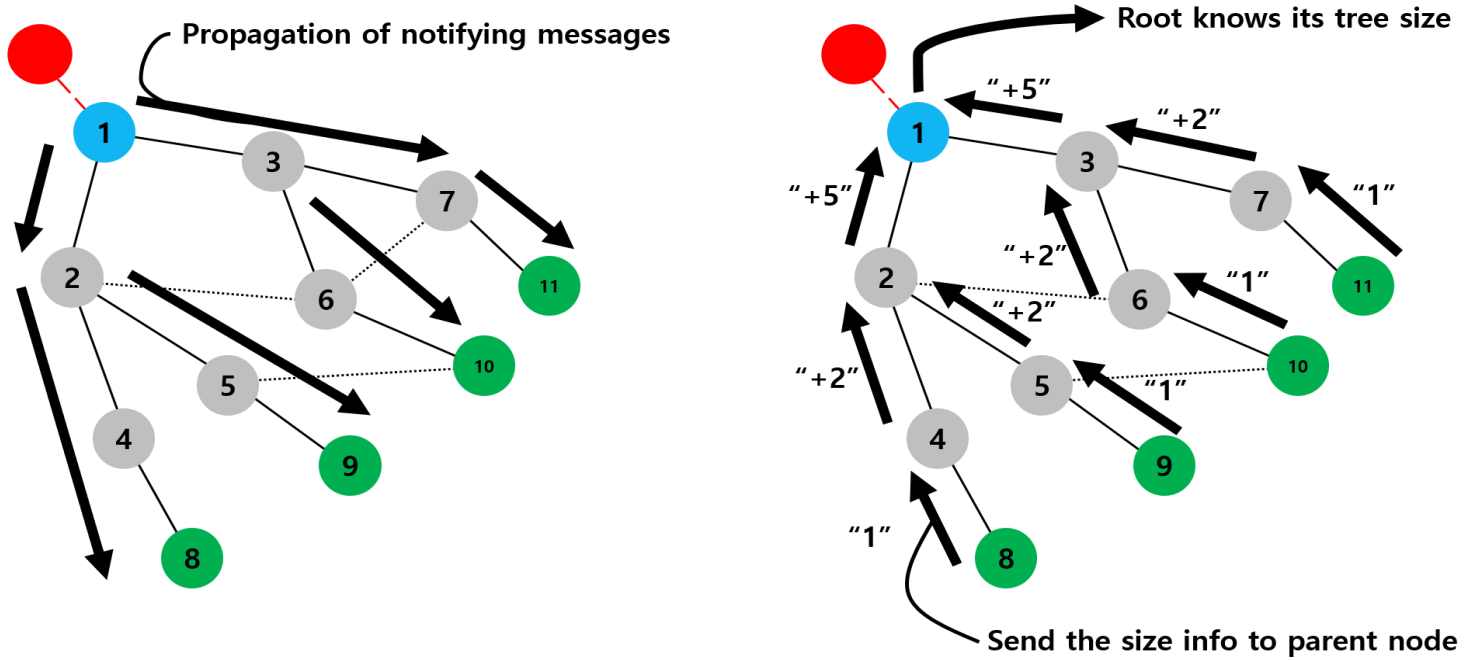


(Left) After the detecting malfunction nodes (red circles) as initiation, node 4 receives messages for notifying their node's IDs from nearest neighbor nodes 1,2,5.
But node 2 receives from node 3,6,7 as well as node 1,2,5 (black arrows).

(Right) After node 4 receives the message from node 2, node 4 knows the IDs of nodes 3,6,7.
In such process, node 4 makes a temporary routing table for communicating with nodes over three hops (yellow arrows).
Then, gray ring is created in the expanded connection range for healing links.

Calculation of Component Size

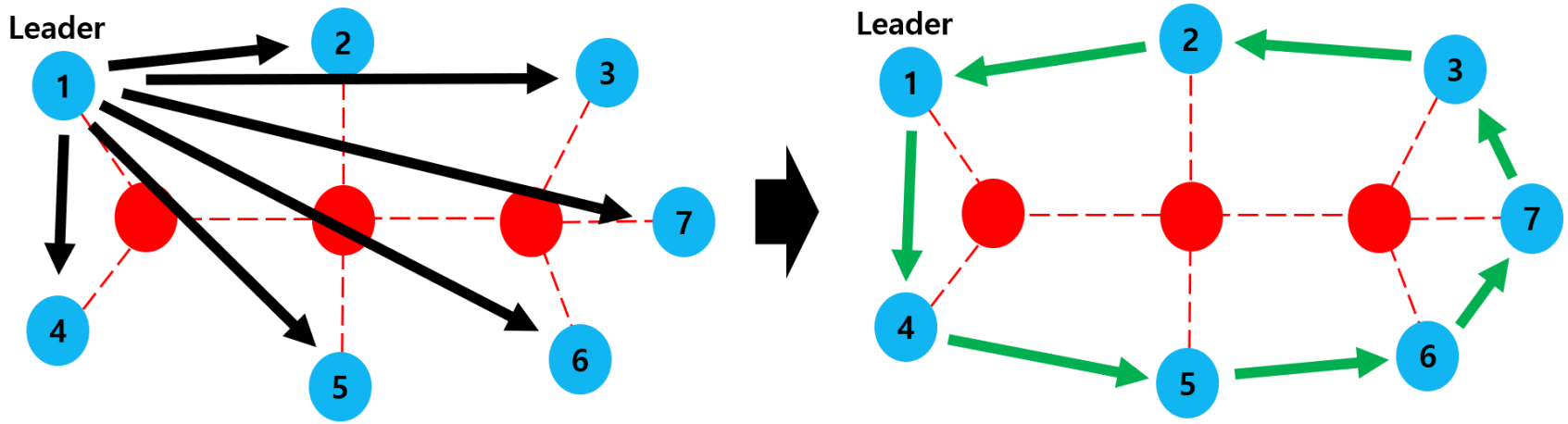
Distributed algorithm of our self-healing method



(Left) A root sends messages for notifying malfunction events to other connected nodes (gray and green circles). The forward messages are disseminated from a root to leaf nodes.

(Right) If the leaf nodes receive the messages, they send the backward message of own size "1" to its parent nodes.
Parent node gathers those messages of size and sends again gathered messages to its grand-parent. After the recursive process, the root knows its tree size.

The Roles of Leader Node



(Left) Select a leader node in the expanded connection range to avoid wasteful floodings.
The leader determines the order of connections for healing according to component sizes received from node 2~7.
Each leader distributively sends the command messages for making a ring (black arrows).
For example, node 5 makes a new connection to node 6.

(Right) After received command messages, each pair nodes can make a new connection independently (green arrows).
Consequently, a ring is created.

Summary

- Since many infrastructures have structural weakness and are threaten by natural disasters, we propose the self-healing method to reconstruct them to a better structure.
- The reconstructed network by our method becomes more robust than the original network.
- We describe a distributed algorithm for applying our self-healing on real systems. Our ongoing focus is ensuring performance of algorithm.