Effective Self-Healing Networks against Attacks or Disasters in Resource Allocation Control

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Short Resume

He received the B.E. and M.E. degrees in electrical and electronic engineering from Toyohashi University of Technology in 1985 and 1987, and Dr.E. degree in applied mathematics and physics from Kyoto University in 1995. In 1987, he joined the Fuji Xerox Corporation. From 1991 to 1994, he was with the ATR (Advanced Telecommunications Research institute international). From 1997, he is in JAIST.

Researcher of
Network Science

He has researched on learning algorithm of neural network models, nonlinear dynamics with bifurcation in recurrent neural networks, information geometry, interior-point methods in mathematical programming, load balancing by diffusion, and complex networks.

Research Interest

My current interest includes self-organization, robustness of connectivity (percolation analysis), statistical physics approach for optimization, and autonomous distributed system especially in complex network science as interdisciplinary area of computer science and physics.

There exist several papers, for example as recent ones, in Physical Review E, Physica A, Network Science, Scientific Reports, and Proc. of IEEE SASO (Self-Adaptive and Self-Organization), etc.

http://www.jaist.ac.jp/ yhayashi/reports/rep_list.html

Current Project (2017-2020): "Extended-design of resilient self-organized and self-healing networks and resource allocation" JSPS KAKENHI Grant Number JP.17H01729 in Japan.

Related Topics

- Fundamentals and design of adaptive system
- Adaptive entities:
  $\rightarrow$ adaptive algorithm
- Adaptive mechanisms
- Self-adaptation:
  $\rightarrow$ self-adaptive network, system, behavior and topology/structure
- Self-adaptation application:
  $\rightarrow$ self-healing

1-1. To be Resilient

Network infra. support our daily life, while the frequency of large disasters or attacks increase.

Resilience means the ability to sustain basic objective and integrity, and includes reconstruction of the system beyond the recovery.

C.Folke, Global Enviromental Change 16, 2006.

The concept of safety should be extended

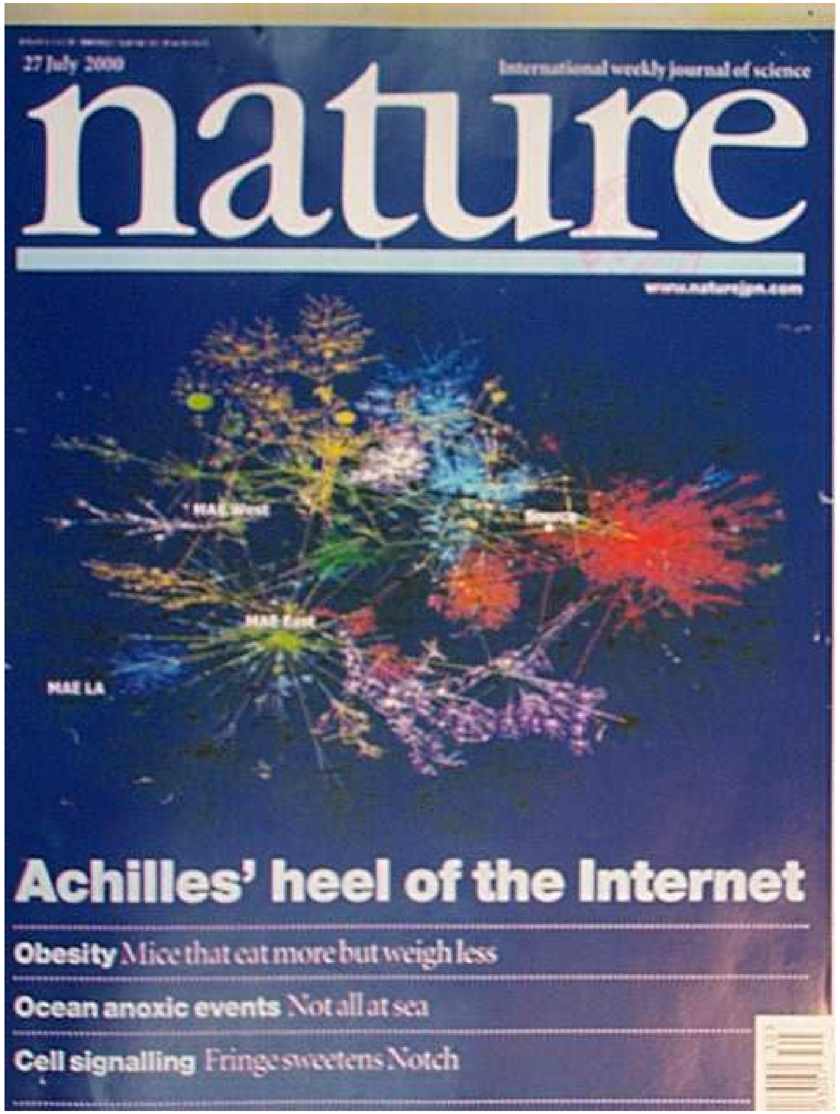
- From "as few things as possible go wrong" To "**as many things as possible go right**",
- From "reactive, respond when something happens" To "**proactive, continuously trying to anticipate developments and events**",

E.Hollnagel, eds. Safety-I and Safety-II, CRC Press, 2014.

1-2. Why Not Recovery !

Many real networks have a common topological structure called Scale-Free: $P(k) \sim k^{-\gamma}$, but are extremely vulnerable against attacks.

Recovery to the original vulnerable network is inadvisable.
$\Rightarrow$ How to reconstruct a sustainable and resilient network in changing the structure under limited resource ?



R.Albert, et al., Nature 406, 2000.

1-3. Self-Healing

Rewirings (reuse of undestroyed links) are performed by changing directions or ranges of flight routes or wireless beams in a local distributed healing process.

Two types of **reusable resource** to maintain the connectivity in a network

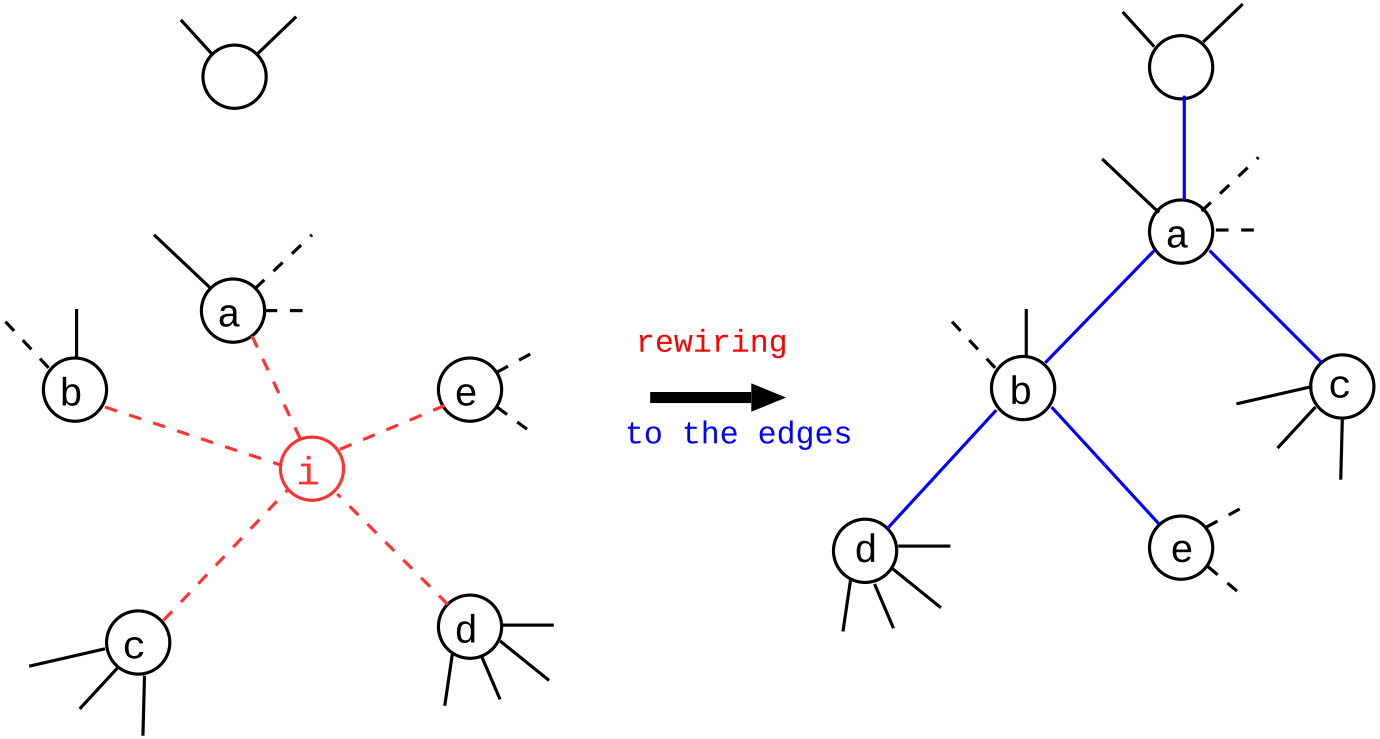
Links: wire cables, wireless communication or transportation lines between two nodes, etc.

Ports: channels or plug sockets at a node, etc.

We consider that ports work independently from links, as similar to a relation of airport runaway (or plug socket) and flight by airplane (or cable line).

Note: k_j ports are reusable at the undamaged $j \in \partial i$ side, but its links may be partially

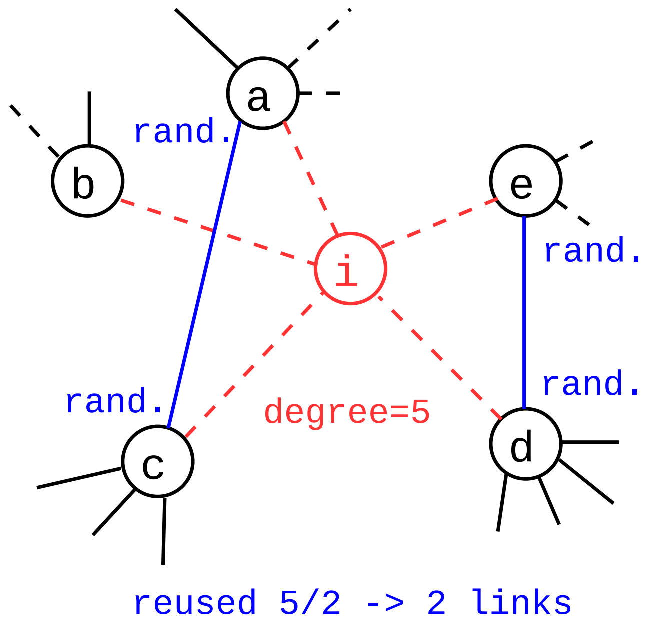
2-1. Heuristic Healing (1)

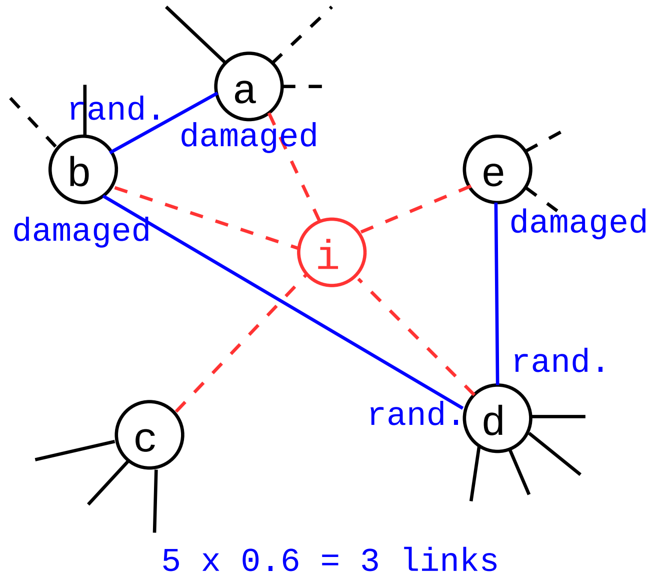


ForgivingTree: the removed node and its links are replaced by a binary tree, however the robustness is not taken into account in the limited rewiring, it rather focuses to shorten the path length $< O(\log k_{max})$

T.Hayes et al., Proc. of 27th ACM Principles Dist. Comp., 2008.

2-2. Heuristic Healing (2)(3)





Bypass Rewiring: randomly chosen only one time by using $\lfloor k_i/2 \rfloor$ half links with a strong constraint

J.Park and S.G.Hahn, Phys. Rev. E 94, 2016

Simple Local Repir: rewiring with a priority to more damaged node $k_{dam}/k_{orig} < \theta$ in a given fraction f_s

L.K.Gallos and N.H.Fefferman, Phys. Rev. E 92, 2015.

2-3. Reserved Resource

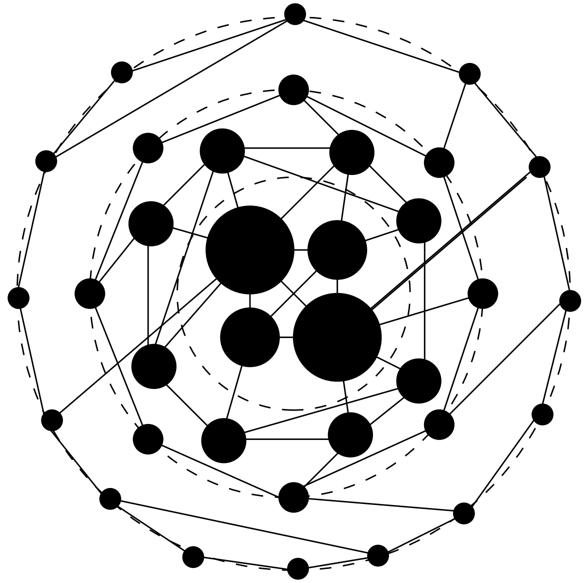
Method	*Additional links*	*Additional ports*
(1) ForgivingTree (ACM PDC 2008)	Unnecessary, enough by the original under all the reuse	Two or three at most in a binary tree
(2) Bypass Rewiring (PRE94 2016)	Unnecessary, if about half is reusable from the original	Unnecessary, enough by the original
(3) **Simple Local Repair** (PRE92 2015)	Controllable by $f_s(1-q)N$	Necessary according to f_s and attack rate q
Our Proposed Method	Controllable by $M_h = r_h \times \tilde{\sum}_{i \in D_q} k_i$ $\vert D_q \vert = q \times N$	Necessary according to reusable rate r_h and attack rate q

3. Optimal against Attacks

∃ Prospective structure to improve the robustness

Onion-like networks with positive degree-degree correlations are optimal.

C.M.Shneider et al., PNAS 810(10), 2011, T.Tanizawa, S.Havlin, and H.E.Stanley, Phys. Rev. E 85, 2012.



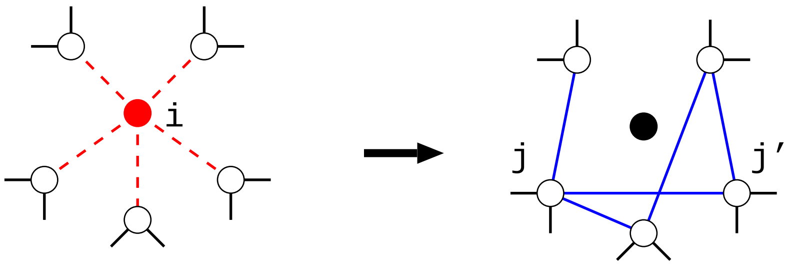
⇒ We focus on **enhancing loops** (that make bypasses) rather than correlations, so as not to be trees as possible by node removals. This idea is supported from e.g., Equiv. of dismantling and decycling problems, Incrementally growing onion-like nets.

A.Braunstein et al., PNAS 113(44), 2016. Y.Hayashi, IEEE SASO 2014, Network Science 6(1), 2018.

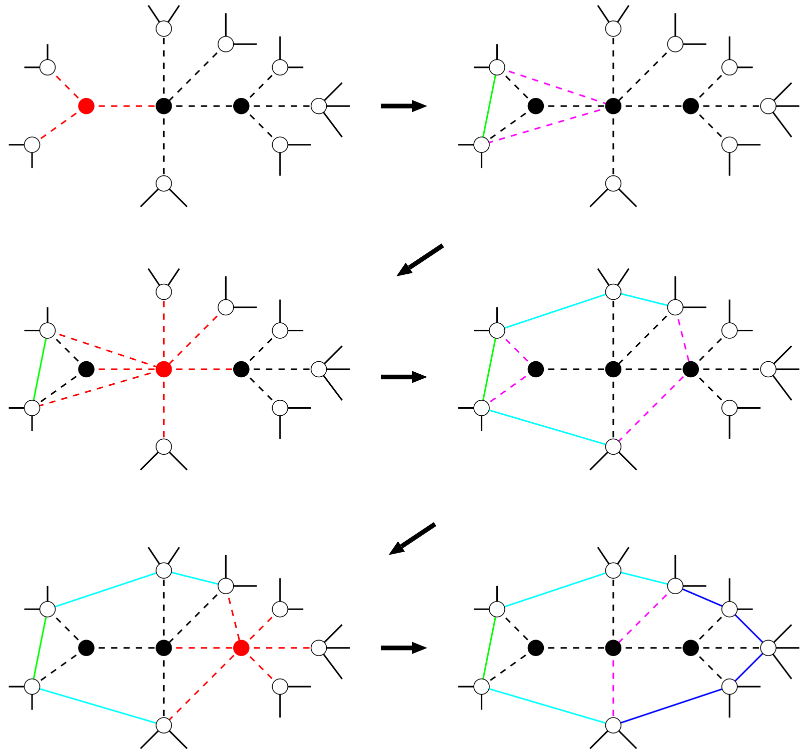
4-1. Our Proposed Methods

After detecting attacks to qN nodes, the proposed healing process is initiated and repeated for $M_h \stackrel{\text{def}}{=} r_h \times \tilde{\sum}_{i \in D_q} k_i$ links.

Enhancing loops for smaller $q_j^0 + q_{j'}^0$ whose j, j' nodes tend to belong to dangling subtrees



Ring formation to maintain the connectivity on the extended neighbors



4-2. By Applying MP

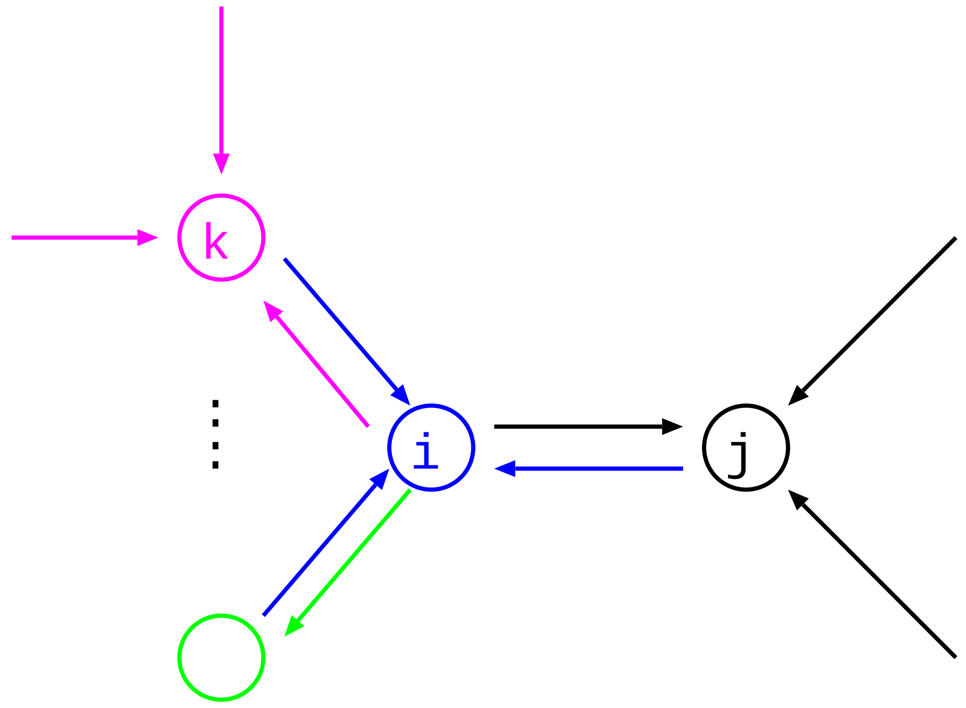
$$q_i^0 = \frac{1}{z_i(t)},$$

$$q_{i \to j}^i = \frac{e^x \Pi_{k \neq j} \left[q_{k \to i}^0 + q_{k \to i}^k \right]}{z_{i \to j}(t)},$$

$$q_{i \to j}^0 = \frac{1}{z_{i \to j}(t)},$$

where $z_i(t)$ and $z_{i \to j}(t)$ are the normalization const.

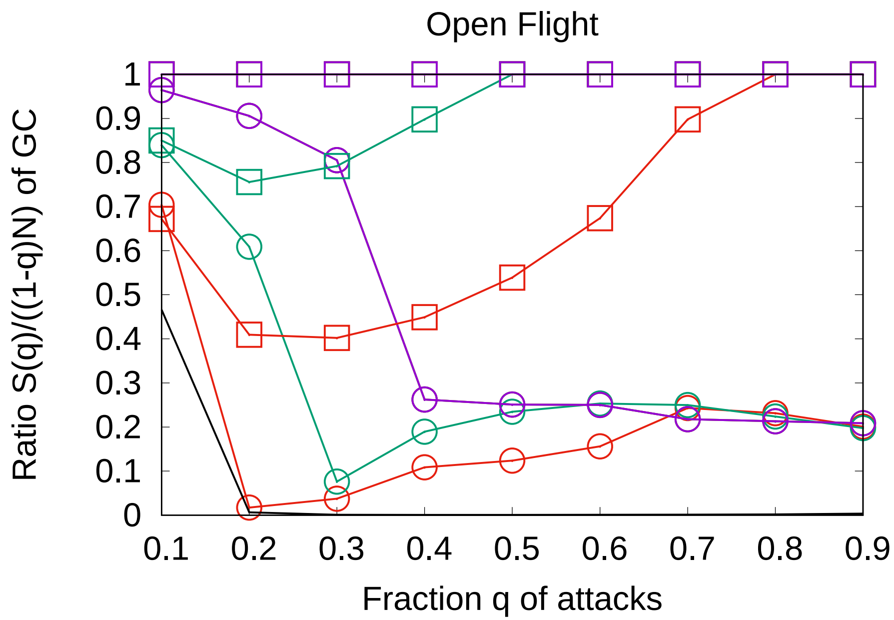
Repeat these calculations of the marginal prob. by using MP until to be self-consistent in principle but practically to reach appropriate rounds.

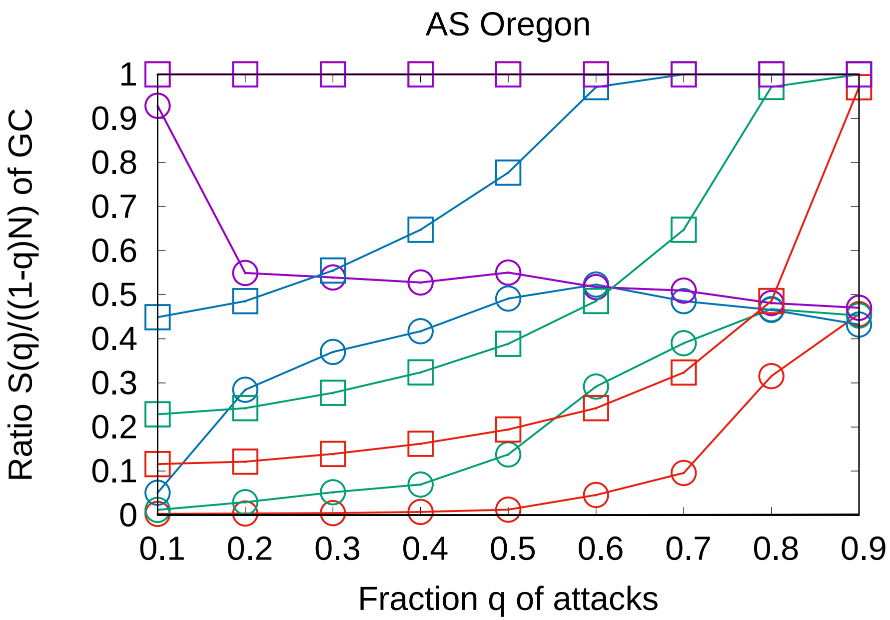


H.-J.Zhou, Euro.Phys. J. B 86, 2013.

5-1. Results for Connectivity

□ **Higher ratio** than ◯ the conventional SLR method with a priority of rewirings to more damaged nodes
In particular, net. func. can be revived if $r_h \geq 0.5$

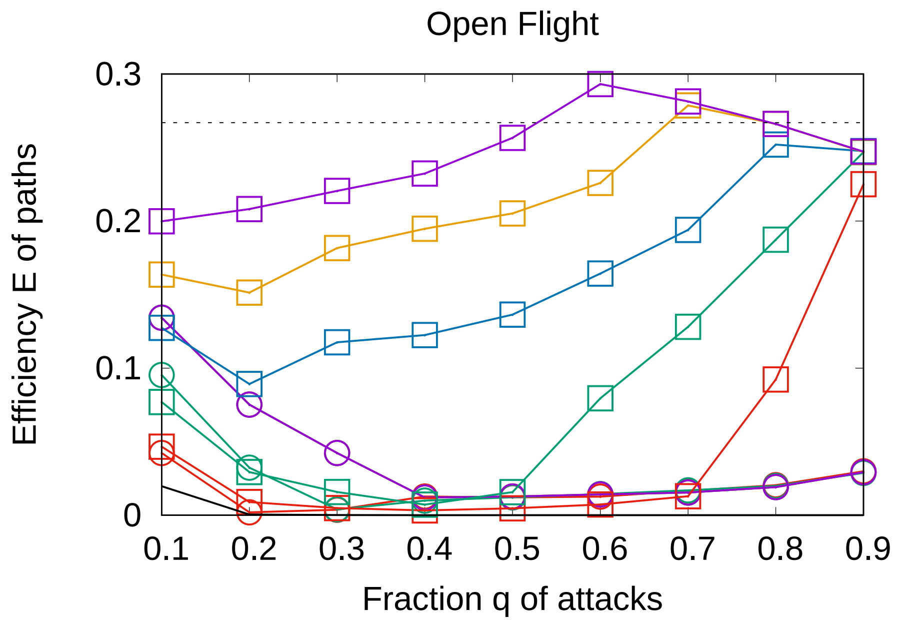


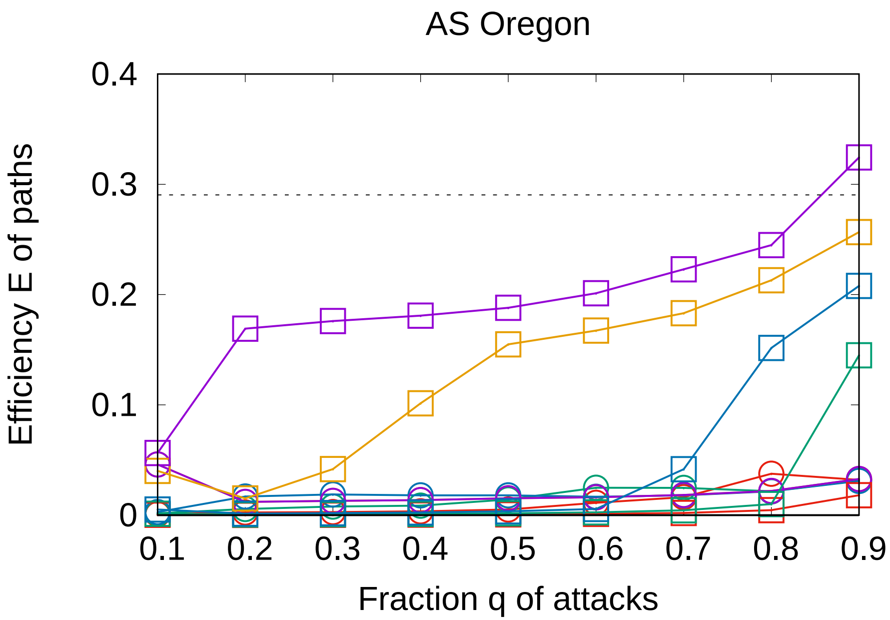


Reusable rate $r_h = 0.05$, 0, 1, 0.2, 0.5, and 1.0 for □: our comb. and ◯: the conventional Simple Local Repair (SLR) methods.

5-2. Results for $\frac{1}{N(N-1)} \sum_{i \neq j} \frac{1}{L_{ij}}$

□ **Higher efficiency** of paths than ◯ the conventional SLR method



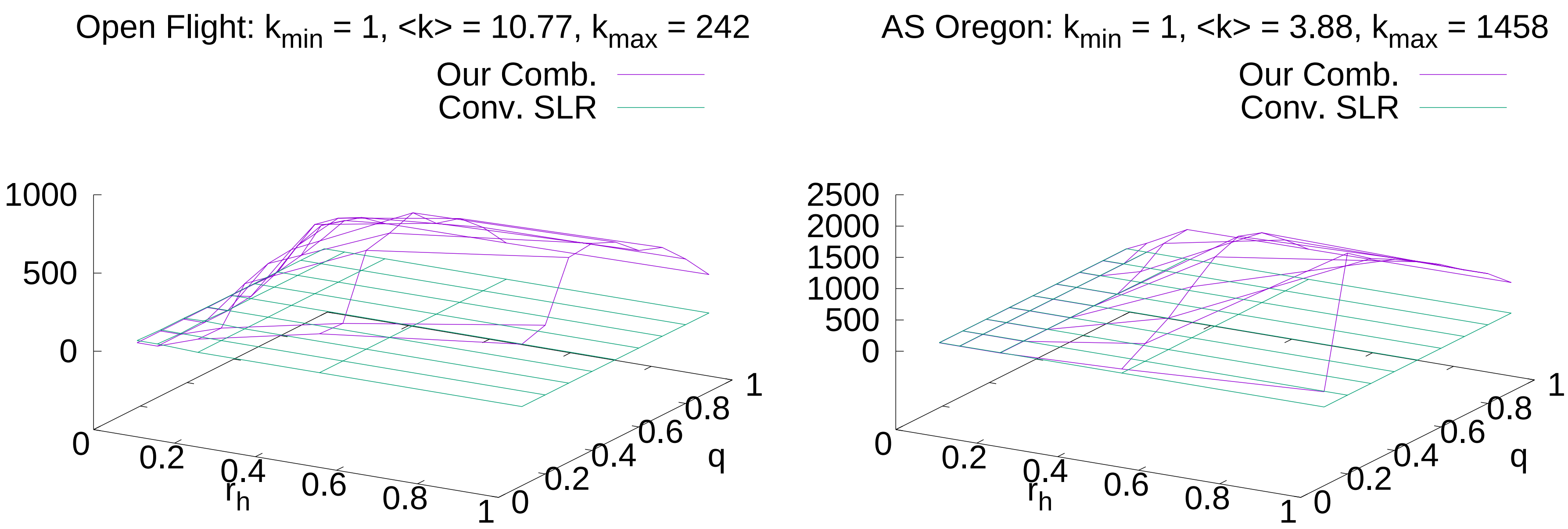


Reusable rate $r_h = 0.05, 0, 1, 0.2, 0.5$, and 1.0 for □: our comb. and ◯: the conventional Simple Local Repair (SLR) methods.

Note $E = 0.3$: ave. 3 hops, 0.2: ave. 5 hops, 0.1: ave. 10 hops

5-3. Results for # of Add. Ports

$\max\{\Delta k_j\}$: number of additional ports which should be prepared in advance besides reusable ports



⇒ The # tends to be larger ranging from a few to nearly $2k_{max}$, as q and r_h increase in much more required than the conventional SLR method.

6. Summary

- We have proposed self-healing methods for **reconstructing a resilient network** by rewirings against attacks or disasters in resource allocation control of links and ports.
  The healing strategy is based on maintaining the connectivity by ring formation and enhancing loops for improving the robustness.
- Our proposed combination method is better than the conventional method, although reserved additional ports are required much more.
- In particular, the whole connectivity can be revived with high efficiency of paths, when more than half links emanated from attacked nodes work.

A1. Asymp. Equiv. Problems

Decycling $\Longleftrightarrow$ Dismantling

Dismantling (or decycling) problem is to find the minimum set of nodes in which removal leaves a graph broken into connected components whose maximum size is at most a constant (or a graph without loops).

In random sparse graphs with p_k, the size ratios are

$$\theta_{dec}(p_k) = \lim_{N \to \infty} E[\theta_{dec}(G)],$$

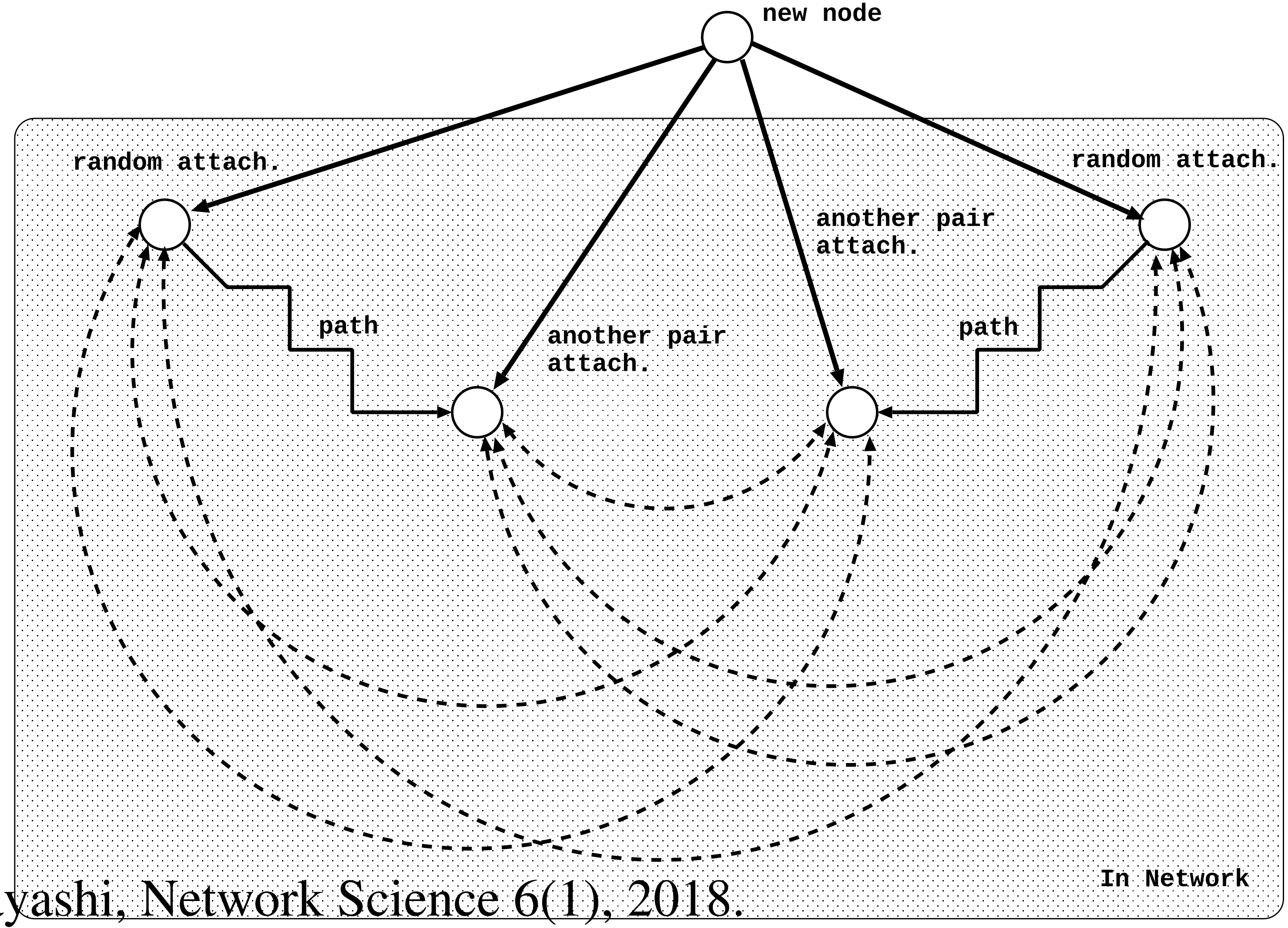
$$\theta_{dis}(p_k) = \lim_{N \to \infty} \lim_{C \to \infty} E[\theta_{dis}(G, C)].$$

- For any degree distribution, $\theta_{dis}(p_k) \leq \theta_{dec}(p_k)$
- If $\langle k^2 \rangle < \infty$, $\theta_{dis}(p_k) = \theta_{dec}(p_k)$

A.Braunstein et al., PNAS 113(44), 2016.

A2. Emergent Onion-like Net.

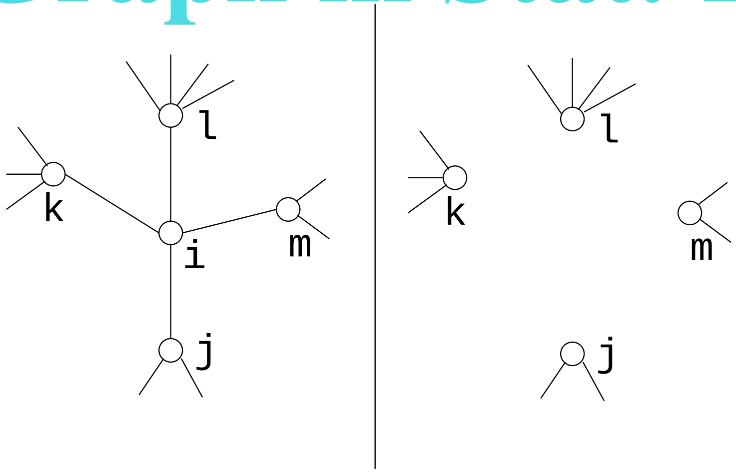
At each time step, from a new node, one of the attached node is chosen randomly, another is the mim. degree node at a few hops via intermediation.



Y.Hayashi, Network Science 6(1), 2018.

A3. Cavity Graph in Stat. Phys.

Bethe-Peierls approx. by independent marginal



$$\mathcal{P}_{\backslash i}(A_j : j \in \partial i) \approx \Pi_{j \in \partial i} q_{j \to i}^{A_j}.$$

1. $A_i = 0$: i is empty (removed). Since i is unnecessary as a root, it belongs to FVS.
2. $A_i = i$: i becomes its own root. The state $A_j = j$ of $j \in \partial i$ is changeable to $A_j = i$ when node i is added.
3. $A_i = k$: one node $k \in \partial i$ becomes the root of i when it is added, if k is occupied and all other $j \in \partial i$ are either empty or roots.

A4. Marginal Probability

H.-J.Zhou, Euro.Phys. J. B 86, 2013. The corresponding prob. to the above three states are represented by

1.

$$q_i^0 \stackrel{\text{def}}{=} \frac{1}{z_i(t)},$$

2.

$$q_i^i \stackrel{\text{def}}{=} \frac{e^x \prod_{j\in\partial i(t)} \left[q^0_{j\to i} + q^j_{j\to i}\right]}{z_i(t)},$$

3.

$$q_i^k \stackrel{\text{def}}{=} \frac{e^{x \frac{(1-q^0_{k\to i})}{q^0_{k\to i}+q^k_{k\to i}}} \prod_{j\in\partial i(t)} \left[q^0_{j\to i} + q^j_{j\to i}\right]}{z_i(t)}.$$

A5. Normalization Const.

$$z_i(t) \stackrel{\text{def}}{=} 1+e^x \left[1 + \sum_{k\in\partial i(t)} \frac{1-q^0_{k\to i}}{q^0_{k\to i} + q^k_{k\to i}}\right] \Pi_{j\in\partial i(t)} \left[q^0_{j\to i} + q^j_{j\to i}\right],$$

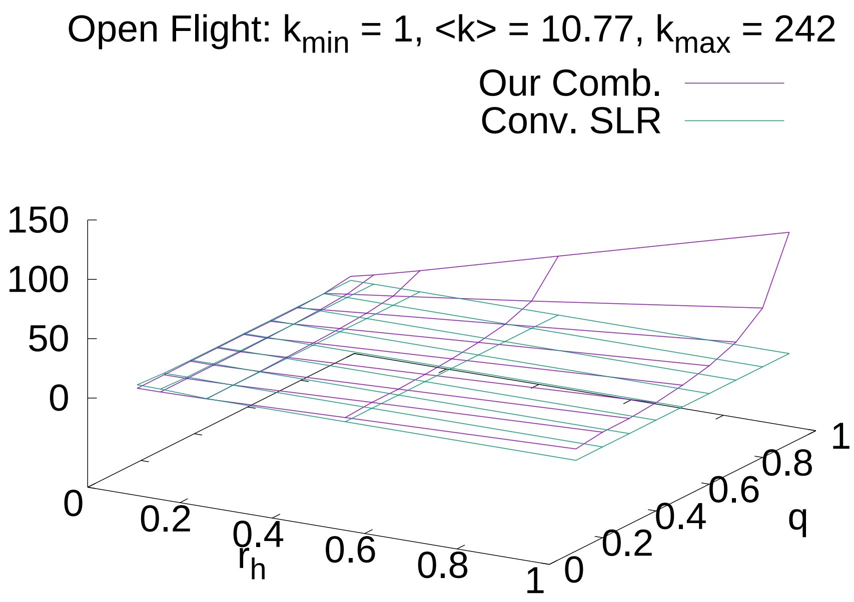
$$\begin{aligned} z_{i\to j}(t) \stackrel{\text{def}}{=}\; & 1 + e^x \Pi_{k\in\partial i(t)\backslash j} \left[q^0_{k\to i} + q^k_{k\to i}\right] \\ & \times \left[1 + \sum_{l\in\partial i(t)\backslash j} \frac{1-q^0_{l\to i}}{q^0_{l\to i} + q^l_{l\to i}}\right], \end{aligned}$$

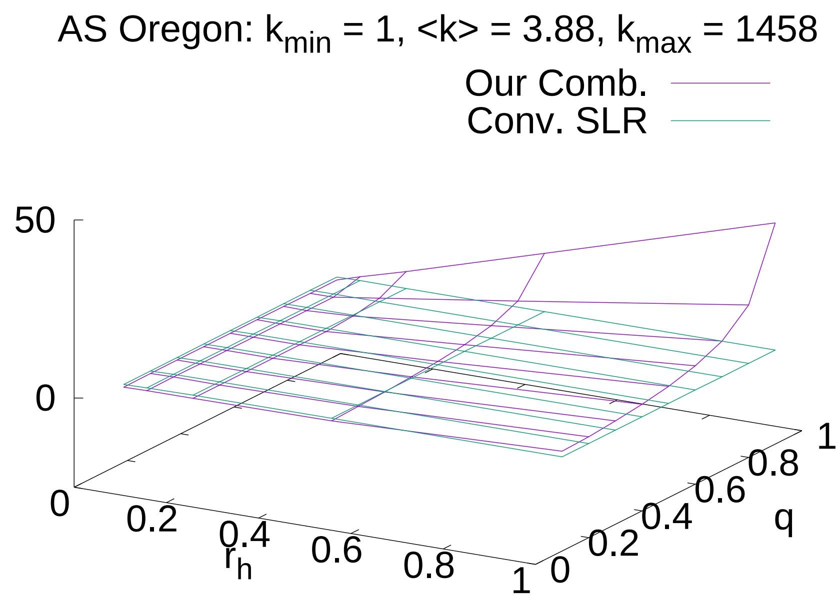
to be satisfied for any node i and link $i \to j$ as

$$q^0_i + q^i_i + \sum_{k\in\partial i} q^k_i = 1, \quad q^0_{i\to j} + q^i_{i\to j} + \sum_{k\in\partial i} q^k_{i\to j} = 1.$$

A6. Ave. # of Add. Ports

The average number $\langle \Delta k_j \rangle$ of additional ports at a node decreases one-digit-or-more compared to $\max\{\Delta k_j\}$.





$\Rightarrow$ The cost for reserved resource is so much inexpensive because of the small #.

A7. Two Measures

Robustness index:

$$R \stackrel{\text{def}}{=} \frac{1}{N} \sum_{q=1/N}^{1} S(q),$$

where $S(q)$ denotes the # of nodes included in the GC after removing qN nodes, q is a fraction of removed nodes by attacks.

As the Pearson correlation coefficient for degrees:

$$r \stackrel{\text{def}}{=} \frac{4M \sum_e (k_e k'_e) - [\sum_e (k_e + k'_e)]^2}{2M \sum_e (k_e^2 + k'^2_e) - [\sum_e (k_e + k'_e)]^2},$$

where k_e and k'_e denote degrees at both end-nodes of link e, M is the total # of links.