Emergent Rewirings for the Defense of Cascading Failures on Complex Networks

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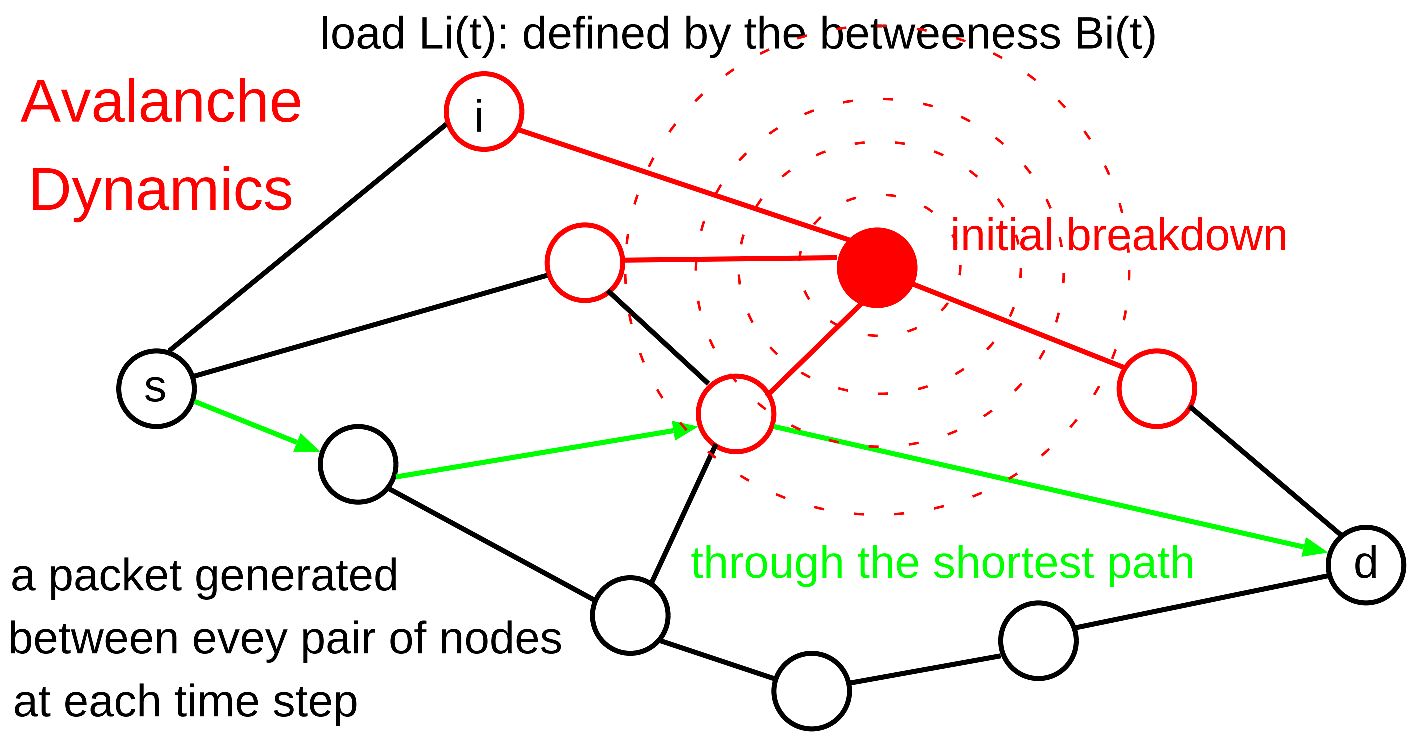
1. Motivation

- Recent studies of attacks on complex networks suggest that small initial breakdowns can lead to global cascades of overload failures in communication, economic trading, and so on, considering the defense methods is very important to reduce the huge damage.
- In spite of the observations of scale-free (SF) structure with degree-degree correlations in many real networks, the effect of correlations on cascades is not yet studied.
- We propose defense strategies based on emergent rewirings between neighbors, and investigate the damaged sizes for the correlations and the effective range of tolerance.

2. Cascading Failures

From initial breakdown(s), overload failures and the removals of the corresponding nodes and links are propagated by changing the shortest paths in the step-by-step process, until $L_k(T) \leq C_k$ for all $k \in V$.



3-1. Conventional Defense Str.

Intentional Removals as sacrifice of heavy nodes

IR: The fraction f of nodes with smallest $\Delta_i \stackrel{\text{def}}{=} L_i(0) - L_i^g$ are removed to avoid the generation of packets from the peripheral nodes, where the total load generated by node i is

$$L_i^g \stackrel{\text{def}}{=} \sum_j (D_{ij} + 1) = (\bar{D}_i + 1)(N - 1),$$

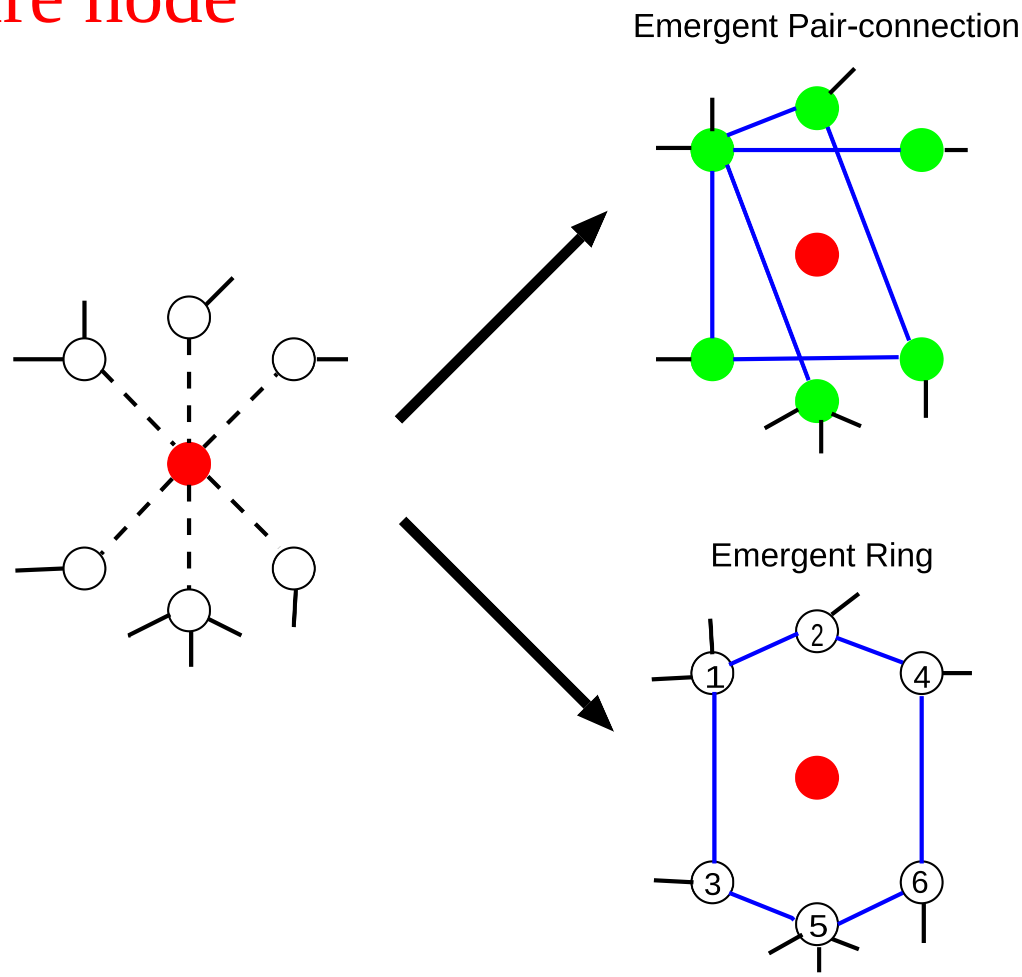
where $\bar{D}_i = \sum_j D_{ij}/N$, and D_{ij} is the shortest path length between nodes i and j at time $t = 0$.

$\Rightarrow$ This procedure needs global information !

M.E. Motter, PRL 93, 098701, 2004.

3-2. Proposed Defense Str.

Rewirings for the disconnected links (dashed) by the initial failure node



The number in each circle denotes the order of C_i/k_i.

3-3. Our Strategies in Local

EP: In the neighbors of the initial attack, pairs of nodes are linked according to the decreasing order of

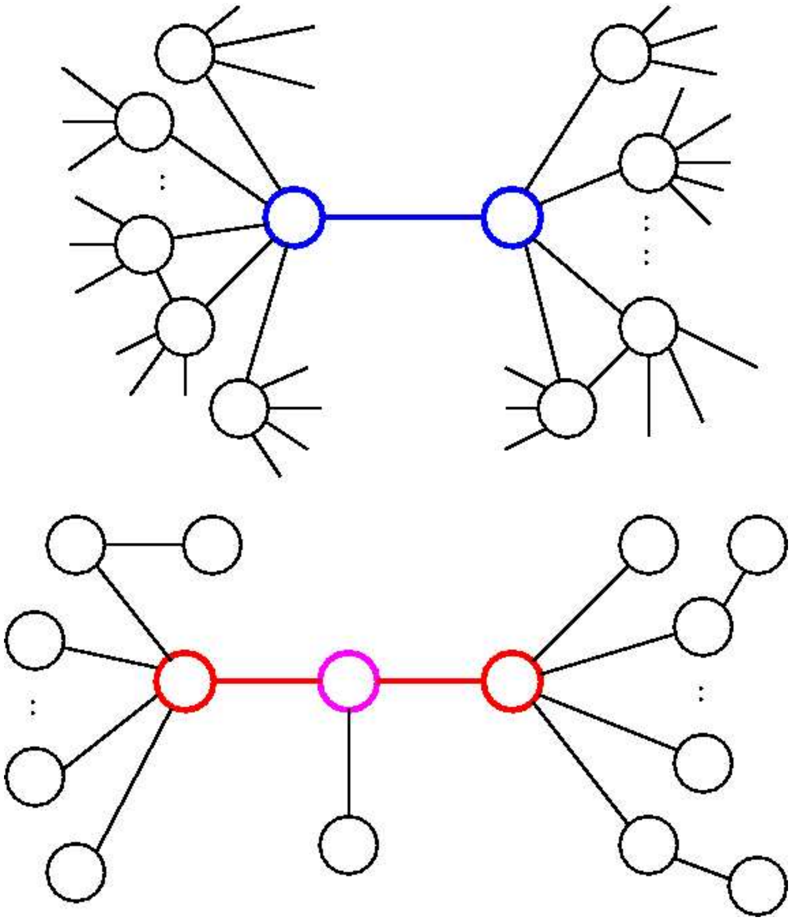
$$W_{ij} \stackrel{\text{def}}{=} C_i/k_i + C_j/k_j,$$

where the capacity $C_i \stackrel{\text{def}}{=} \alpha L_i(0)$, $\alpha \geq 1$, k_i and k_j denotes the degrees of nodes i and j. Note that large C_i/k_i corresponds to large $B_i(0)$ and small k_i that mean: the node i is a bridge node between subgraphs and important to construct bypass routes.

ER: In the neighbors, a ring is rewired according to the decreasing order of C_i/k_i.

4-1. SF Nets with Correl.

Assortative and Disassortative correlations observed in social and technological/biological networks



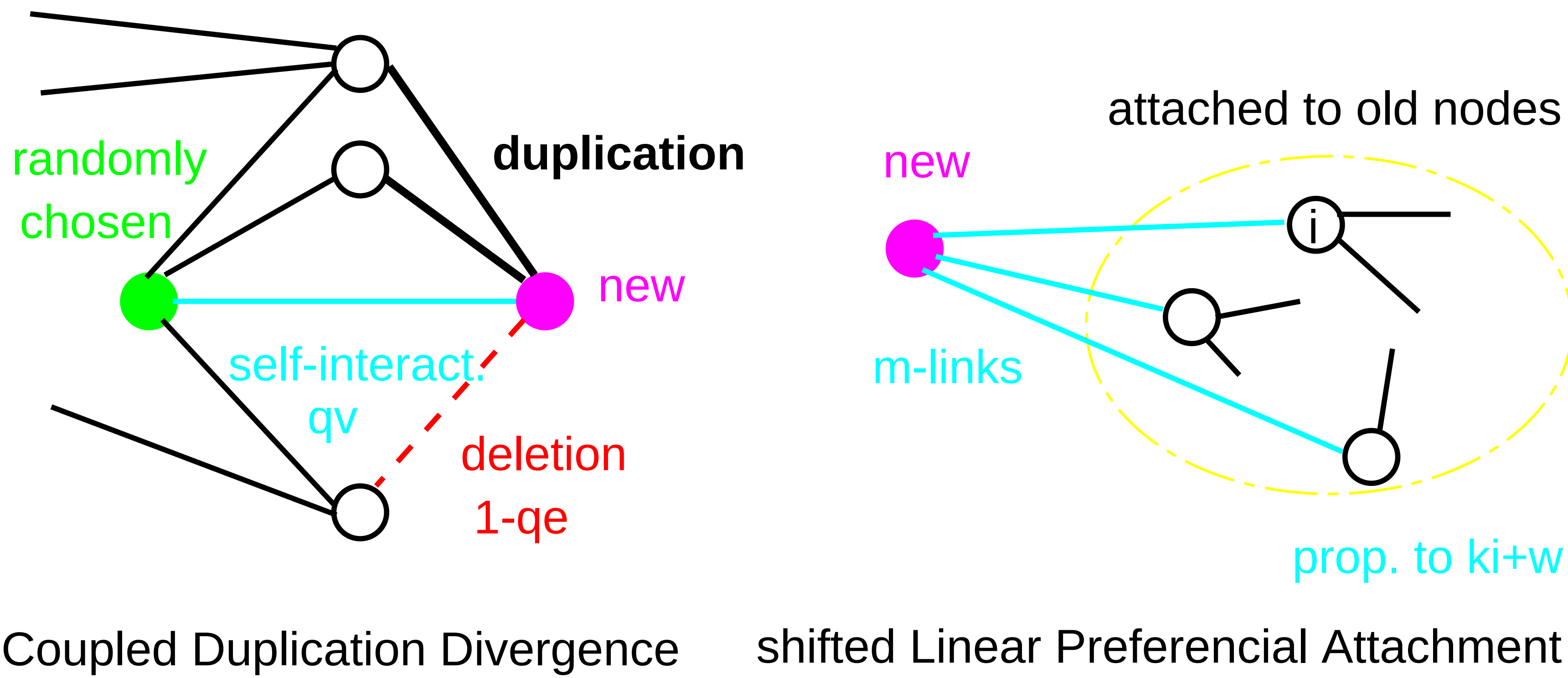
Ass: tend to have connections between similar peers

Dis: between hubs and peripheral nodes with low degrees

M.E.J. Newman, PRE 67, 026126, 2003.

4-2. CDD and LPA Models

Only these models are known to have parametrically controllable degree-degree correlations between Ass and Dis



4-3. CDD: Network Generation

Coupled Duplication Divergence model

1. At each time step, a new node i' is added.
2. Simultaneously, a node i is randomly chosen, and new connections between all the neighbors j of i and the new node i' are **duplicated**.
3. With probability q_v, a connection between i and i' is established (self-interaction).
4. In the divergence process, each duplicated connection is removed with probability $1 - q_e$.

A. Vázquez, PRE 64, 056104, 2003.

4-4. LPA: Network Generation

shifted Linear Preferential Attachment model

1. At each time step, a new node is added and linked to old nodes by m new connections.
2. The attached nodes are randomly chosen by the shifted linear preference: a node i with degree k_i is chosen as the terminal of a new connection with probability proportional to $k_i + w$, $|w| < k_{min} = m$.

A. Barrat and R. P.-Satorras, PRE 71, 036127, 2005.

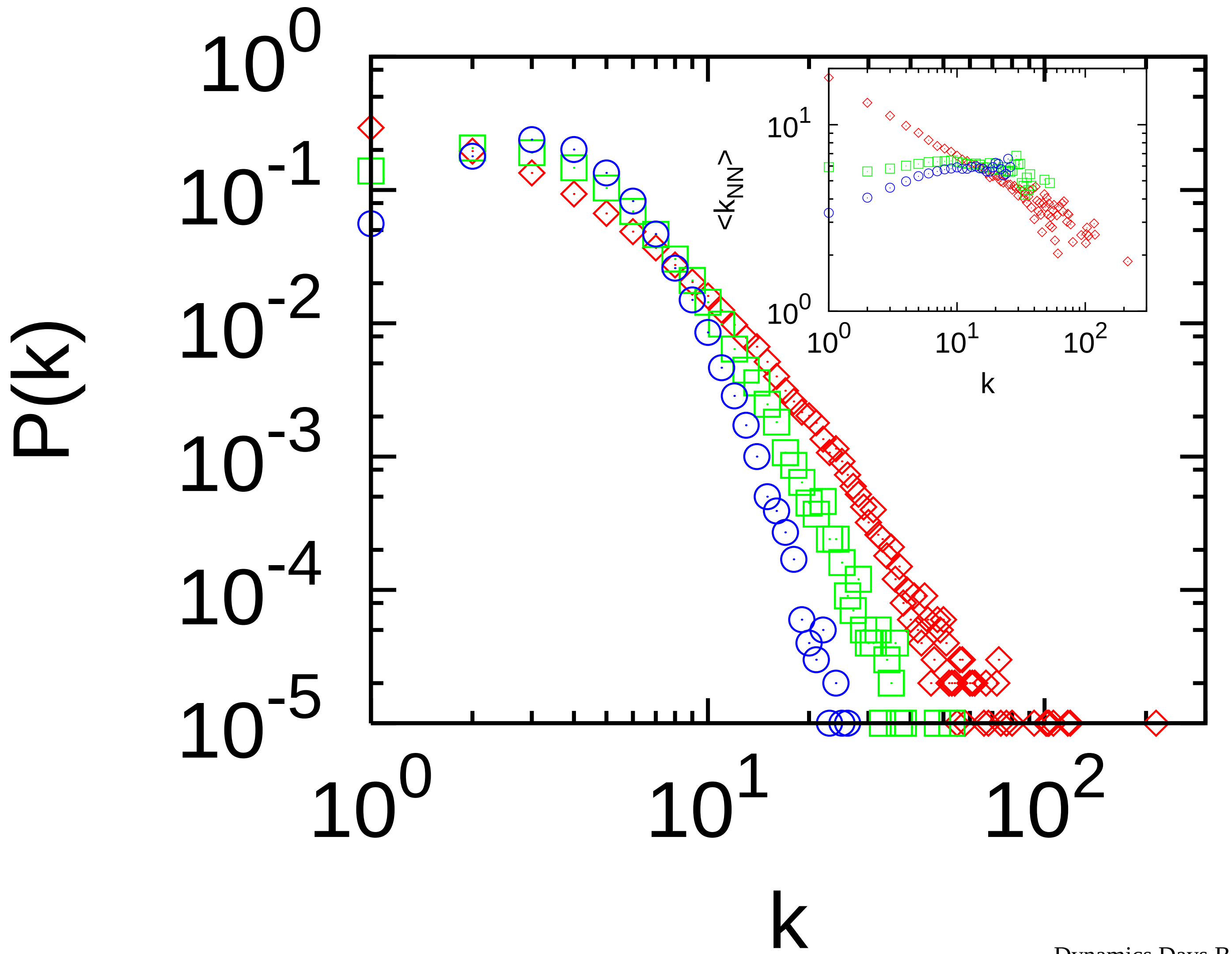
4-5. Control Param. for Correl.

	CDD		LPA	assortativity
Type	q_v	q_e	w	r
Ass	1.0	0.26		0.19
Nearly Unc	0.5	0.35		0.02
Dis	0.0	0.42		-0.29
Weak Ass			1.8	-0.01
Nearly Unc			0.0	-0.08
Dis			-1.8	-0.49

These are measured over 100 realizations of each network model with $N = 1,000$, $\langle k \rangle \approx 4$, $m = 2$.

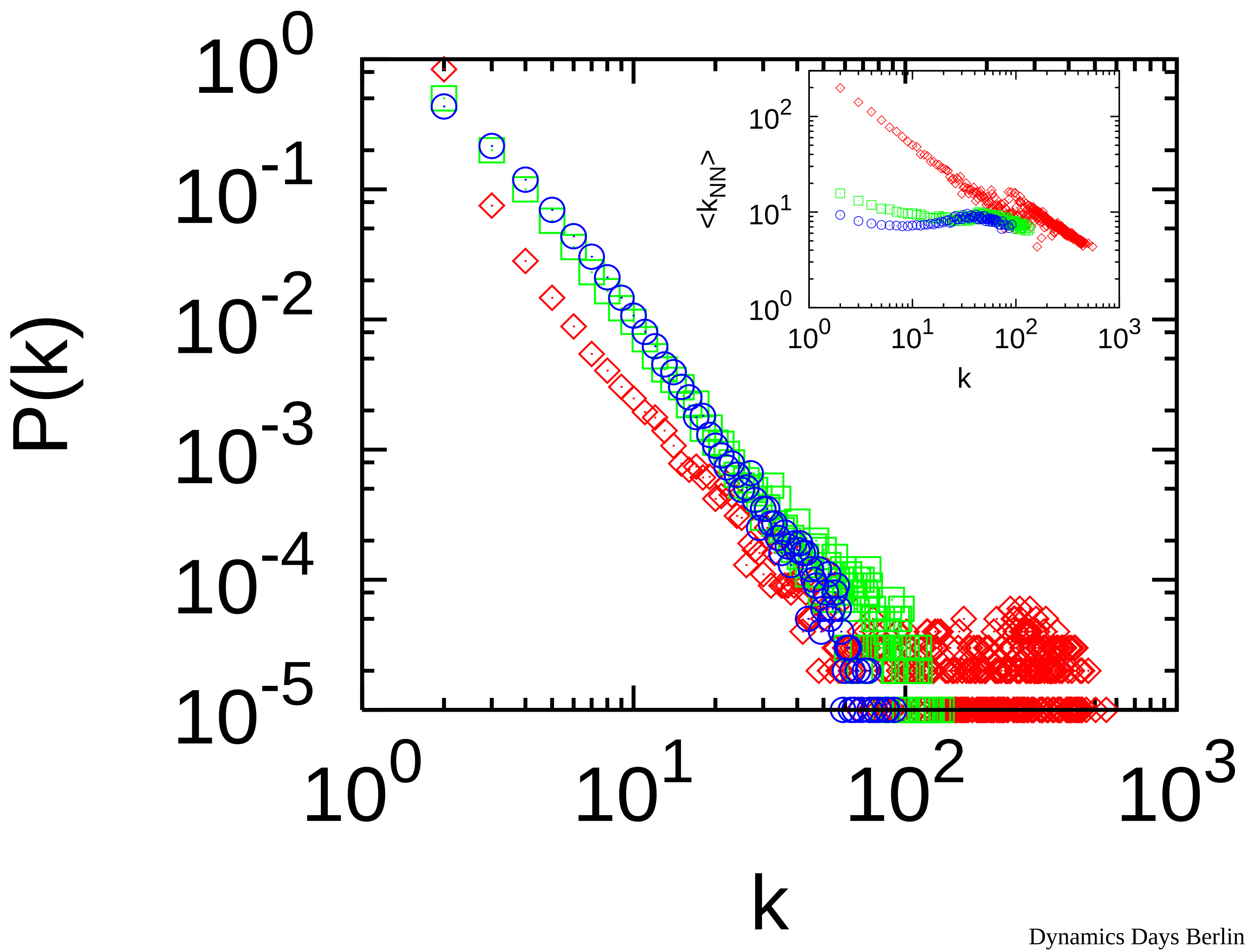
5-1. Distributions in CDD

degree dist. $P(k)$ and degree-degree correl. $\langle k_{NN} \rangle$



5-2. Distributions in LPA

degree dist. $P(k)$ and degree-degree correl. $\langle k_{NN} \rangle$



5-3. Simulation Results

Comparing the ratio of the sizes $GC = N'/N$ (after cascading from load-based attack on the hub / initial) as a function of the tolerance parameter α on the following defense strategies

NO-defense: red lines

IR: green lines with marks $*$: removal rate $f = 0.1$ and $+$: $f = 0.2$ as the nearly best fractions

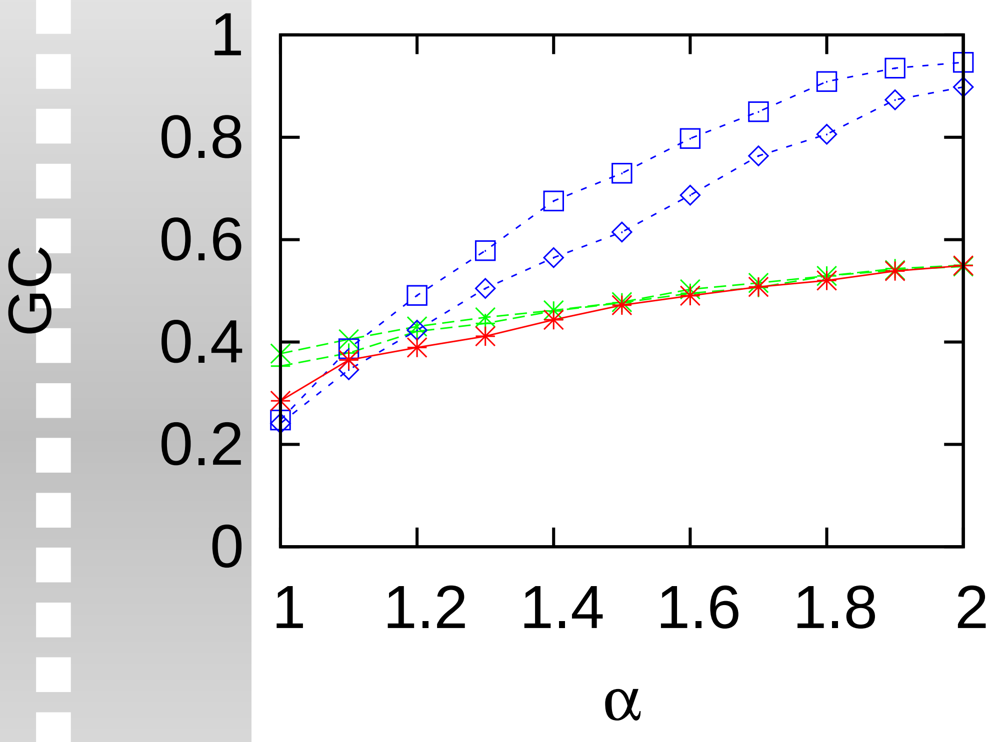
EP: blue line with marks $\Box$

ER: blue line with marks $\Diamond$

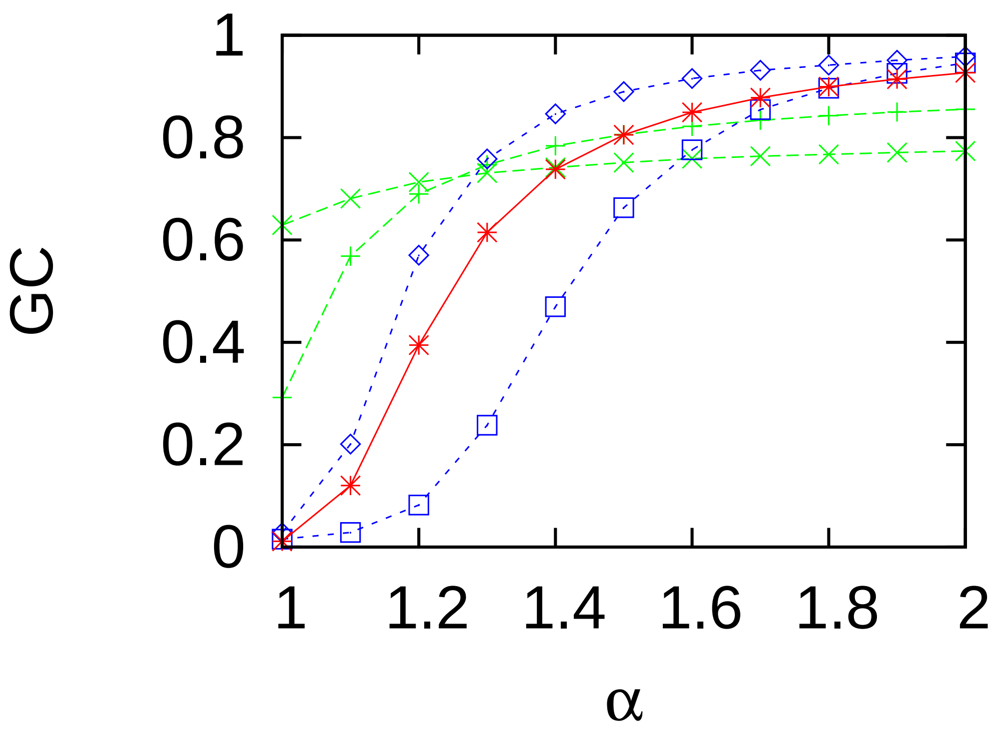
$\Rightarrow$ The parts of lines above NO show the effect.

(for the averaging of 100 realizations)

For the cases of Ass



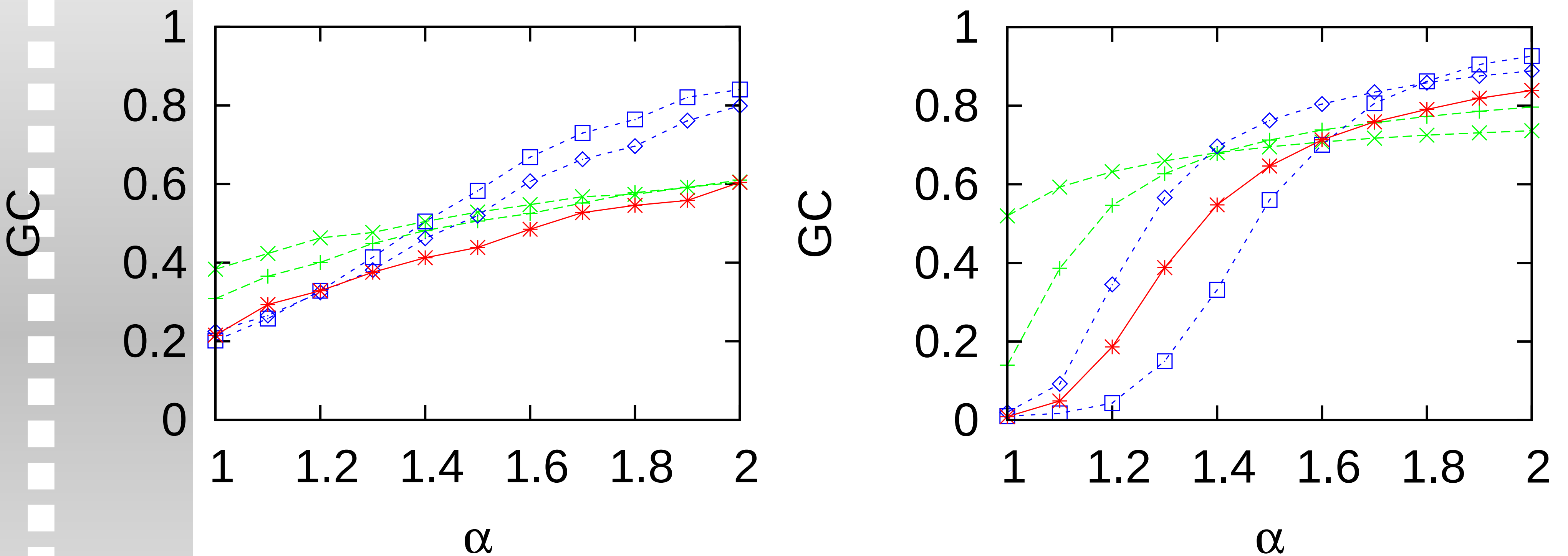
CDD



LPA

$\Rightarrow$ IR is strongly saturated, while EP and ER are effective in large α for CDD. ER is the best for LPA.

For the cases of Unc

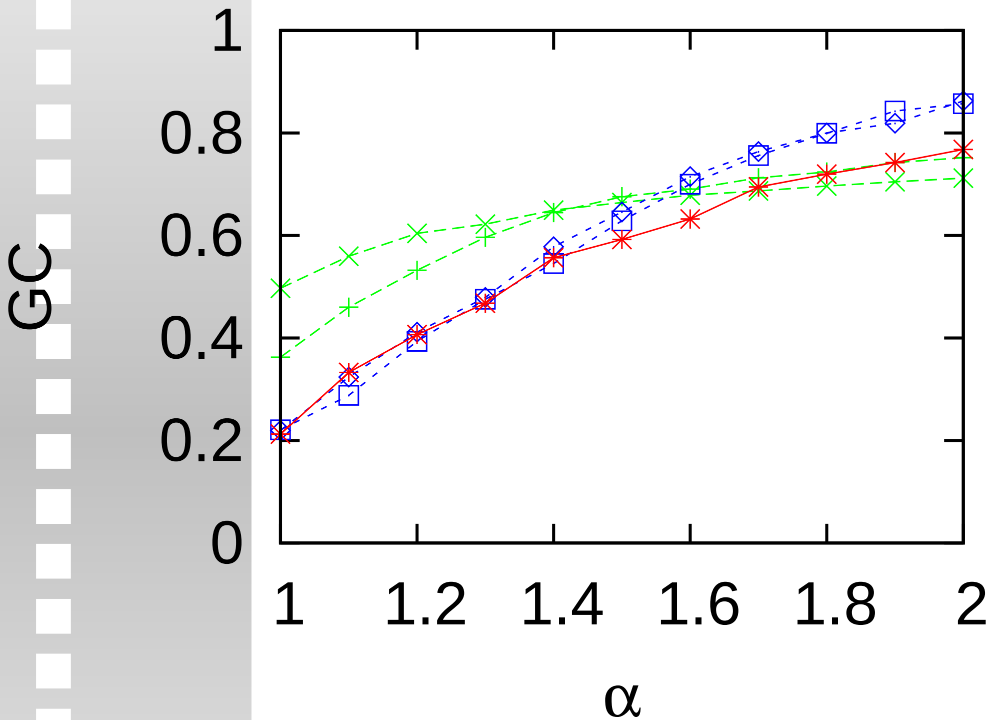


CDD LPA

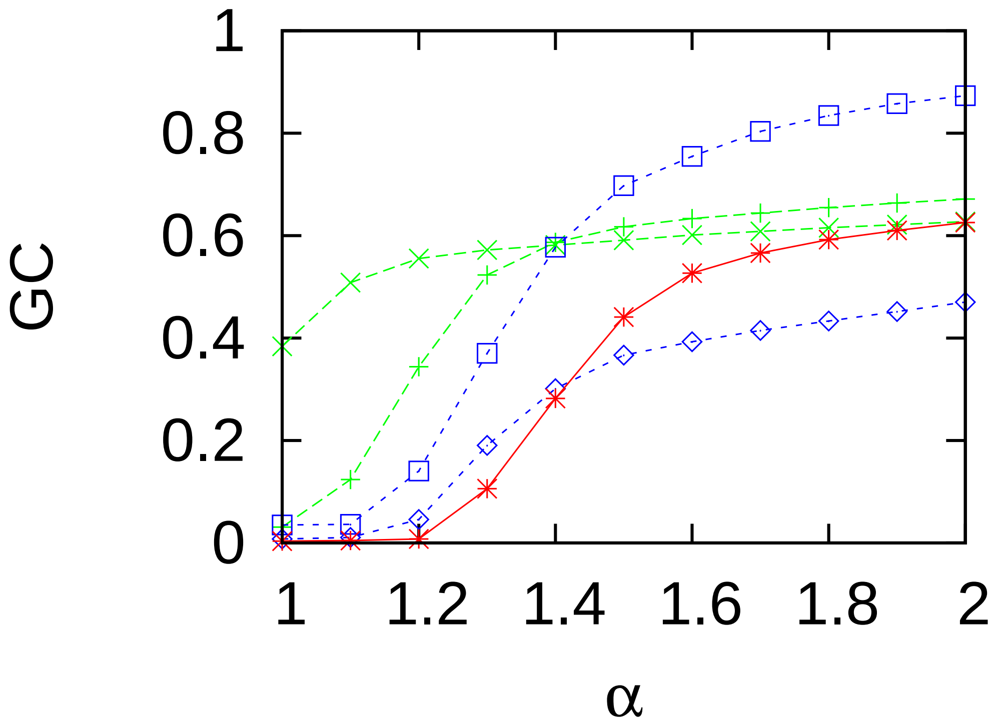
$\Rightarrow$ The effective ranges are similar as the cases of Ass:

IR in $\alpha < 1.4$, EP and ER in $\alpha > 1.4$.

For the cases of Dis



CDD



LPA

$\Rightarrow$ The damage in IR is improved than the case of Ass for CDD, but LPA is vulnerable, especially in small α.

6. Summary

- The size of cascades can be reduced by our defense strategies based on emergent rewirings between bridge nodes with large C_i/k_i, and the effect is slightly different for the correlations.
- They are more complicated: the conventional IR works better in tight capacity ($\alpha < 1.5$ for CDD with Dis and for LPA), but the proposed EP or ER do in reasonable capacity ($\alpha > 1.5$ for CDD with Ass and LPA with Dis).
- The rewirings in distributed manners will be useful for protecting and sustaining our social or technological infrastructures from huge damage.

$\Rightarrow$ see the details in arXiv:cond-mat/0503615

Appendix 1.

Cascades of overload failures triggered by initial small breakdowns are sometimes occurred and grown into very large damage in real networks:

- power grid (**blackout**)
- Internet (**packet congestion**),
- economic trading (**bankruptcy**)
- traffic system (**jamming**), etc.

Not only the topological structure of network but also the heterogeneously distributed load or capacity is deeply related to the intrinsic dynamics of packet flow and to the size of cascade.

Appendix 2.

Existing a surprisingly common structure: SF net.
the degree dist. exhibits $P(k) \sim k^{-\gamma}$, $2 < \gamma < 3$.

Social: acquaintance, world trading, actor-collabo., citation, language

Technological: Internet, WWW, email, power grid

Biological: neural net, genome, metabolic pathway, foodweb

One of the fundamental generation mechanism has been proposed: Growth & Preferential Attachment

Barabási and Albert, Physica A, 272, 1999