Designing Interconnected Networks for Improving Robustness and Efficiency

Masaya MURAKAMI
Murata Lab., Osaka Univ., Japan

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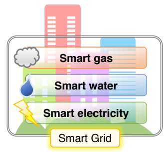
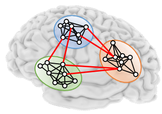
Research background

- Upcoming generation of IoT and Smart Cities
  - Intelligent and automated services
  - Services will be interconnected
    - E.g.: Smart-grids, Smart-homes, etc.
- High efficiency and robustness are required for interconnected networks
  - Efficiency promotes diffusion of useful information
  - Robustness prevents diffusion of malicious information





Inspiration by the mechanisms of interdependency in brain networks

Brain Network of Networks (NoN)[1]

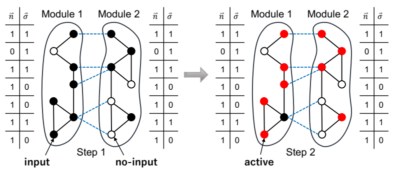
- Inspired by the mechanism of interdependency in brain
  - Control of activation of inter-modular links
    - Only active when both endpoint nodes are having input data
  - 3 states of node i are expressed by two binary variables (σ_i, n_i)

n_i: input variable (given)
σ_i: activation variable

$$\sigma_i = n_i \left[1 - \prod_{j \in F(i)} (1 - n_j)\right]$$

$F(i)$: set of neighbor nodes in other modules

$(\sigma, n) = (1,1)$	$(\sigma, n) = (0,1)$	$(\sigma, n) = (0,0)$
active	input	no-input



- Higher robustness than previous NoN model[2]
  - Brain NoN prevents cascading node failures

[1] F. Morone *et. al*, "A model of brain activation predicts the collective influence map of the human brain", Submitted to PNAS, 2012.
[2] B. Robert et. al, "Failures propagation in critical interdependent infrastructures", International Journal of Modelling, Identification and Control, vol. 3 pp. 69-78, May. 2008

Research objective and approach

Objective

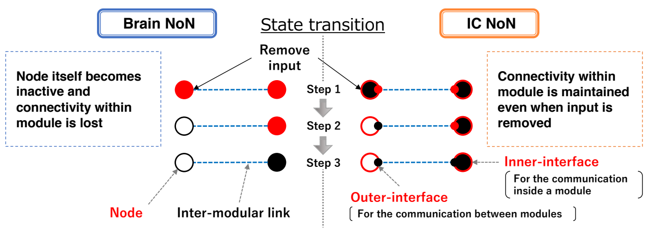
- Control of information diffusion speed over interconnected networks

Approach

1. Application of Brain NoN mechanism
   - Proposal of *Information Communication NoN* (IC NoN)
     - Control of activation of interfaces instead of nodes
     - Include time-scale of information flow
2. Analysis of speed of information diffusion changing connectivity of interconnected networks with IC NoN
   - Design of *intra*-modular connectivity
     - Node centrality (≒influence on diffusion)
   - Design of *inter*-modular connectivity
     - Centrality of endpoint nodes

Interpretation of "activation"

- In Brain NoN, state of endpoint node on inter-modular link affects the node on the other side
  - Difficult to assume applicable situation in information networking
- In IC NoN, we control the activation of interfaces
  - Outer-interfaces are activated depending on activation variable σ
  - Inner-interfaces are always active



Modeling information diffusion

- Introduce time-scale and information flow to evaluate performance of IC NoN
  - Probabilistically determine the input state $n_i \in \{0, 1\}$ of node i at time t based on the state of neighbor nodes at $t - 1$

Probability for node i to receive input at time t: $p_t(i)$
Probability to receive no input from within module: $\prod_{j \in S(i)} (1 - \delta n_j^{t-1})$
Probability to receive no input from other modules: $\prod_{j \in F(i)} (1 - \delta \sigma_i^{t-1} \sigma_j^{t-1} n_j^{t-1})$

	Brain NoN	IC NoN
Input	n_i (given)	$p_t(i) = 1 - \prod_{j \in S(i)} (1 - \delta n_j^{t-1}) \prod_{j \in F(i)} (1 - \delta \sigma_i^{t-1} \sigma_j^{t-1} n_j^{t-1})$
Activation	$\sigma_i = n_i \left[1 - \prod_{j \in F(i)} (1 - n_j)\right]$	$\sigma_i^t = n_i^t \left[1 - \prod_{j \in F(i)} (1 - n_j^t)\right]$

($S(i)$: Set of neighbor nodes within module, $F(i)$: Set of neighbor nodes outside of module, δ: Parameter for data propagation)

IC NoN: information diffusion model that does not allow unintentional information to pass through interconnecting links

7 Node centrality

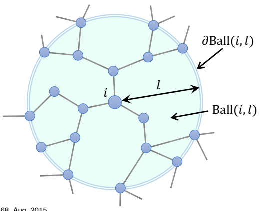
- Property determined by node's location in topology
  - Evaluate node's importance on connectivity or communication
  - Variety of node centrality metrics exist:
    - degree centrality, betweenness centrality, page-rank, etc.
- *Collective Influence* (CI)[3]
  - Superior performance in identifying influential nodes over other centrality metrics

Definition
- $\mathrm{CI}_{l=0}(i) = (k_i - 1)k_i$
- $\mathrm{CI}_{l\geq 1}(i) = (k_i - 1)\sum_{j\in\partial\mathrm{Ball}(i,l)}(k_j - 1)$

degree of node i

total degree of nodes l hops apart from node i

$\mathrm{Ball}(i,l)$: set of nodes within l hops around node i
$\partial\mathrm{Ball}(i,l)$: set of nodes on the edge of $\mathrm{Ball}(i,l)$



[3] F. Morone et. al, "Influence maximization in complex networks through optimal percolation", Nature, vol.524, pp.65-68, Aug. 2015.

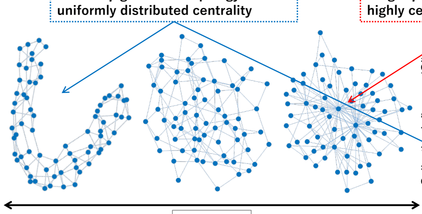
8 Connectivity within subnetworks

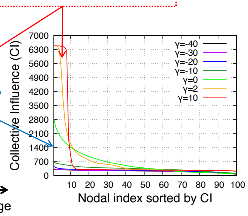
- Consider node centrality within subnetworks
  - Control node's influence on diffusion
  - Adopt preferential attachment
    - $p(i) = \frac{k_i^\gamma}{\sum_j k_j^\gamma}$ (k_i: degree of node i; $p(i)$: probability to choose node i; γ: parameter)

Parameter γ can realize a variety of centrality distributions

Smaller γ generates topology with uniformly distributed centrality

Larger γ generates topology with highly centralized nodes





9 Connectivity between subnetworks

- Generate inter-modular links considering centrality and its correlation of endpoint nodes
  - Define coefficients to evaluate centrality and its correlation

Coef.	Meaning	Definition
DC_{cnt}	centrality	$DC_{cnt}(h,i) = c_h + c_i$ (c_h: centrality of node h)
DC_{cor}	centrality correlation	$DC_{cor}(h,i) = \frac{(c_h - U)(c_i - U)}{\sigma^2}$ (U: expected value of c; σ^2: variance of c)
DC	dependencies between DC_{cnt} and DC_{cnt}	$DC(h,i) = \left[\frac{DC_{cnt}(h,i) - DC_{cnt}^{min}}{\overline{DC}_{cnt} - DC_{cnt}^{min}} + 1\right]^{r\cos\theta} + \left[\frac{DC_{cor}(h,i) - DC_{cor}^{min}}{\overline{DC}_{cor} - DC_{cor}^{min}} + 1\right]^{r\sin\theta}$ (centrality; centrality correlation; weight assignment) (θ: parameter for weight assignment; $r \in \{0,1\}$: parameter to switch effectiveness of weight assignment)

- Parameter θ controls dependency between DC_{cnt} and DC_{cor}
- Generate links between nodes with the highest DC in sequence

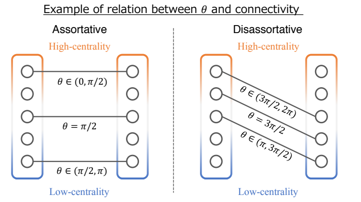
10 Connectivity between subnetworks

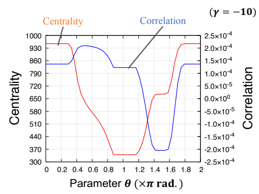
$DC(h,i) = \left[\frac{DC_{cnt}(h,i) - DC_{cnt}^{min}}{\overline{DC}_{cnt} - DC_{cnt}^{min}} + 1\right]^{r\cos\theta} + \left[\frac{DC_{cor}(h,i) - DC_{cor}^{min}}{\overline{DC}_{cor} - DC_{cor}^{min}} + 1\right]^{r\sin\theta}$

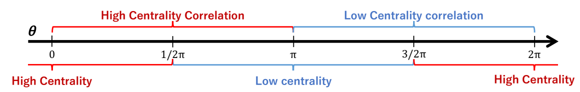
centrality; centrality correlation; weight assignment

Parameter θ can realize a variety of inter-modular connectivity types

Example of relation between θ and connectivity







11 Simulation of information diffusion

- Assume interconnected networks of 2 subnetworks
- Measure time to complete diffusion
- Diffusion starts from inter-modular links
- Comparative model
  - Pure NoN
    - Inner- and outer-interfaces are always active
    - Achieves the fastest diffusion on any interconnected topology
- Simulation settings
  - Number of nodes in subnetworks: 100
  - Number of intra-modular links: 197
  - Number of inter-modular links: 25
  - Maximum node degree for intra-modular links: 25
  - Maximum node degree for inter-modular links: 1
  - Parameter for DC: $r = 1$
  - Parameter for diffusion: $\delta = 0.5$

12 Evaluation on subnetworks

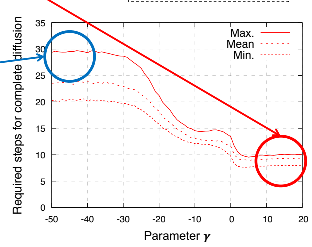
- Measure diffusion time over subnetworks
  - Diffusion starts at nodes with max/mean/min centrality

- With large γ, high-centrality nodes emerge
- High centrality nodes speed-up diffusion

Preferential attachment: $p(i) = \frac{k_i^\gamma}{\sum_j k_j^\gamma}$

- With small γ, centrality is uniformly distributed
- Large topology diameter decreases diffusion speed

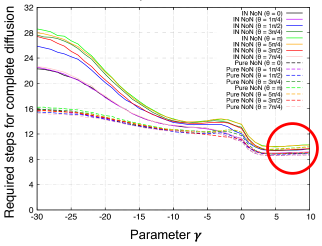
- With sufficiently large/small γ,
  - topology shape and diffusion speed converges



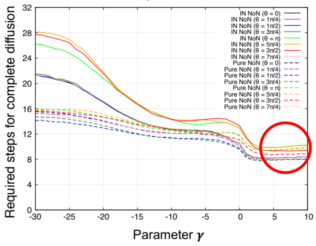
Evaluation on interconnected networks

Maximize speed of information diffusion	◻ **Intra-modular parameter: $\gamma \geq 2$** ◻ Centrality is extremely biased ◻ **Inter-modular parameter: $\theta \in (-0.25\pi, 0.25\pi)$** ◻ High centrality nodes are connected **IC NoN achieves fast and unhindered diffusion**

Diffusion from randomly selected inter-modular links



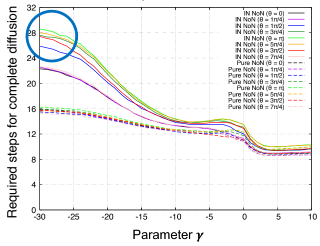
Diffusion from deliberately selected inter-modular links



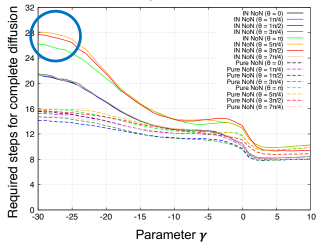
Evaluation on interconnected networks

Minimize speed of information diffusion	◻ **Intra-modular parameter: $\gamma \leq -30$** ◻ Centrality is low and uniform ◻ **Inter-modular parameter: $\theta \in (1\pi, 1.5\pi)$** ◻ Low centrality nodes are connected disassortatively **Diffusion slows as if inter-modular links are deactivated**

Diffusion from randomly selected inter-modular links



Diffusion from deliberately selected inter-modular links



Conclusion and future work

Conclusion

- **Proposal of IC NoN model**
  - Controls diffusion behavior across modules
- **Evaluated diffusion speed on interconnected networks where IC NoN is applied and connectivity changed**
  - Accelerated diffusion by connecting high centrality nodes
    - As fast as networks with unhindered diffusion
  - Decelerated diffusion by connecting low centrality nodes disassortatively
    - As slow as networks without inter-modular links

Future work

- **Evaluate diffusion starting from any nodes in modules**
- **Investigate scalability of IC NoN with respect to number of nodes/modules**