Osaka University

Topological analysis of the brain functional networks

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Research Background

- **Internet as a social infrastructure**
  - A lot of systems essential for our life are provided on the Internet
  - It is desired to make the Internet into higher quality to handle rapidly increasing traffic demand and the number of devices
- **Internet as a large-scale and complex network**
  - It consist of interconnections of many Autonomous Systems (ASes)
  - Since ASes construct connections to other ASes selfishly, it has been pointed out that a lot of traffic will concentrate on some ASes[13]

The Internet is now on the way to fragileness

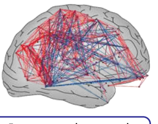
We focus on
Brain Functional Networks (BFNs)
as clues to construct the high-quality Internet


AS-level Topology

[13] M. Palacin, et al. The impact of content delivery networks on the internet ecosystem. *Journal of Information Policy*, 3:304-330, July 2013.

Brain Functional Networks (BFNs)

- **Networks reflecting brain functional interaction**
  - Divide a brain into tens of thousands of voxels (measuring points)
  - Construct a link between voxels where brain activity transition is similar



- **Properties of BFNs**
  - High efficiency communication
  - Robustness and Adaptability against environmental change
  - Very small energy consumption

The Internet also need these properties

We expect that the Internet can be high quality by incorporating some of BFNs' topological characteristic

"High quality" means 1) High communication performance
2) Robustness against node and link failures and traffic changes
3)High energy efficiency

Comparison of Topological Characteristic

- **There are many researches analyzing a topology with graph theory[5,7,9,12]**

	BFNs	Internet
# of nodes	Very large	Very large
Degree distribution	Power-law	Power-law
Small-world-ness	✓	✓
Modularity	High	High
Fractality	✓	X

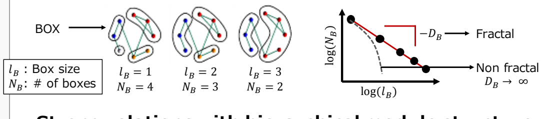
Significant Difference

[5] E. Bullmore and O. Sporns. Complex brain networks: graph theoretical analysis of structural and functional systems. *Nature Reviews Neuroscience*, 10(3):186-198, Mar. 2009.
[7] V. M. Eguiluz,et al. Scale-free brain functional networks. *Physical Review Letters*, 94(1):1-4, Jan. 2005.
[9] L. K. Gallos,et al. A small world of weak ties provides optimal global integration of self-similar modules in functional brain networks. *PNAS*, 109(8):2825-2830, Feb. 2012.
[12] D. Meunier,et al. Hierarchical modularity in human brain functional networks. *Frontiers in Neuroinformatics*, 3(37):1-12, Oct. 2009.

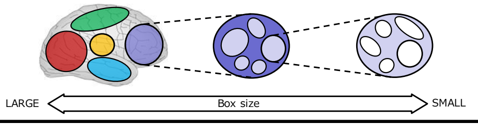
Fractality[14]

[14] C. Song, S. Havlin, and H. Makse. Self-similarity of complex networks. *Nature*, 433:392-395, Jan. 2005.

- **A property of repeating structures at every scale**
  - A topology has fractality when D_B is finite, calculated by $N_B(l_B) \sim l_B^{-D_B}$



- **Strong relations with hierarchical module structure**
  - Regard box as module with different box size



Research Objective

- **Our Research Goal**
  - Produce the Internet with BFNs' fractality for making it higher quality

For attaining this goal, **in this research...**

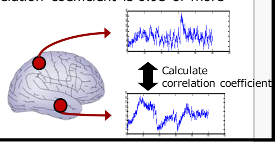
1. **Reveal the topological structure of BFNs**
2. **Reveal the quality of BFNs from a information network perspective**

Topology Data

- **Brain activity measurement with fMRI**
  - One male subject under resting-state conditions
  - 80130 voxels, 2000 time steps
- **Processing measurement data**
  - Apply motion correction (Realignment) and slice timing correction by using SPM8
- **Obtaining topology**
  - Calculate correlation coefficient between two voxels by Piasson's method
  - Add links between voxels where correlation coefficient is 0.95 or more

Obtain topology with **11420 nodes and 44040 links**

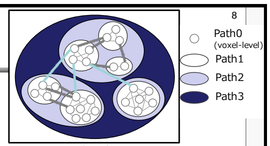
Voxel-level topology

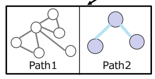


Topology Decomposition

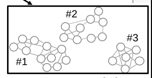
- **Two types of topology by hierarchical modules**
  - Module-level topology
  - Inner-module topology

* We use "**Louvain method**[3]" for extracting modules.
* We call the level of hierarchy as "Path".





Module-level topology



Inner-module topologies at Path2

Decompose whole topological structure into (1) module-level, (2) inner-module, and (3) inter-module

Aim to reveal these three topological structure

Path	# of nodes	# of links
0	11420	44049
1	1989	3007
2	432	654
3	179	288
4	146	236

[3] V. Blondel, et al. Fast unfolding of communities in large networks, *Journal of Statistical Mechanics*, pages 1-12, July 2008.

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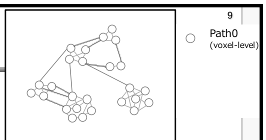

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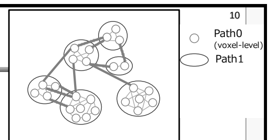
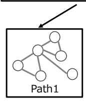
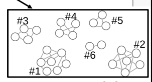




Module-level topology



Inner-module topologies at Path1
(6 topologies)

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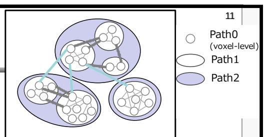
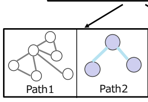
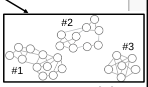
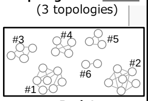




Module-level topology



Inner-module topologies at Path2
(3 topologies)



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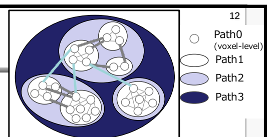
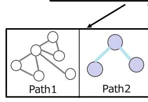
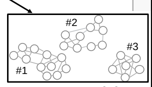




Module-level topology



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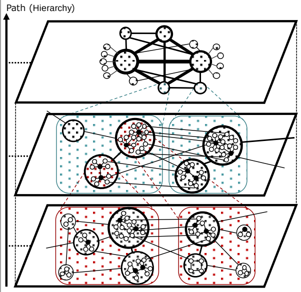
Summary of Analysis of Topological Structure

Sharing similar structure over all Paths



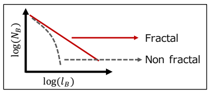
Module-level Topology
- Fractality
- Power-law degree distribution
- Hub-hub repulsion (low degree-correlation)

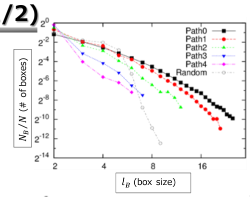
Inner-module Topology
- Power-law degree distribution
- High degree-correlation

Inter-module Link
- A large module constructs many links to various modules
- A small module constructs a few links to a small variety of modules
- A node with average degree of inner-module constructs lots of links

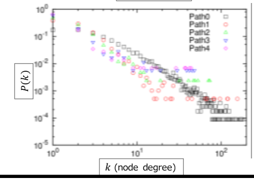
Module-level Topology (1/2)

- **Fractality**
  - Module-level topologies at all Paths have fractality





- **Degree distribution**
  - Module-level topologies at all Paths follow power-law



Module-level Topology (2/2) [results of topology at Path2]

- **Degree-Correlation**

Method

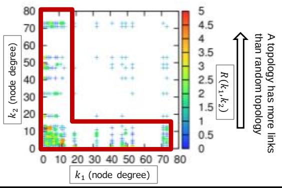
$$R(k_1, k_2) = P(k_1, k_2)/P_r(k_1, k_2)$$

* $P(k_1, k_2)$: probability of finding a node with k_1 links connected to a node with k_2 links
* $P_r(k_1, k_2)$: random uncorrelated counterpart of $P(k_1, k_2)$

- When $R(k_1, k_2)$ takes high values , a topology has more links than random topology between nodes with degree (k_1, k_2)

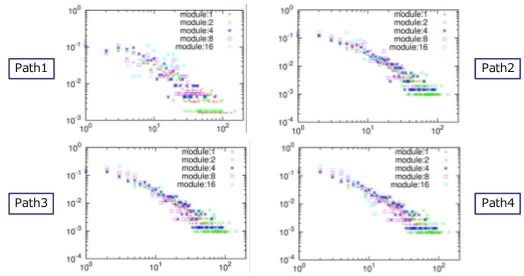
Result

- Hub-Hub repulsion
  - Only a few links exist between nodes with high-degree



Inner-module Topology (1/2)

- **Degree distribution**
  - Inner-module topologies at all Paths follow power-law



Inner-module Topology (2/2) [results of topology at Path2]

- **Degree-Correlation**

The method of $R(k_1, k_2)$ is not applicable because it is difficult to calculate $R(k_1, k_2)$ for small-scale topology

Method

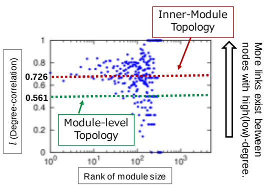
$$l = (L - L_{min}) / (L_{max} - L_{min})$$

* L : $\sum_{(i,j)\in E} k_i \cdot k_j$, where E is a set of links and k_i is a degree of node i
* L_{max} (L_{min}) : max (min) value of L among topology with same degree sequence

- When l takes high value, high(low)-degree nodes tend to be connected with high(low)-degree nodes

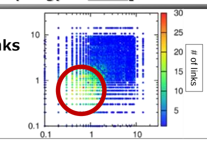
Result

- Higher degree-correlation
  - $l = 0.726$
    (average value of topologies with more than 100 nodes)



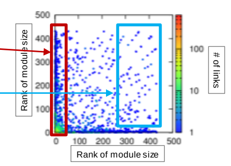
Inter-module Links [results of topology at Path2]

- **Correlation between node degree and the number of inter-module links**
  - Inter-module links tend to exist between nodes whose degree is average degree of each inner-module topology

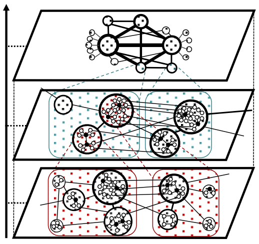


[Both axes] the value of dividing the degree of node by the average degree of inner-module topology which the node belongs to

- **Correlation between module size and the number of inter-module links**
  - Large module
    - constructs many links to various modules
  - Medium or small module
    - constructs a few links to a small variety of modules



Summary of Analysis of Topological Structure



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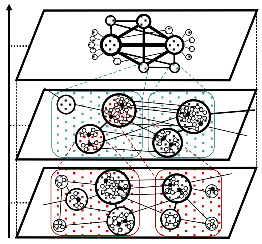


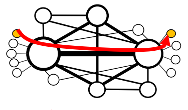
Our expectation of BFNs' quality from information network perspective

1. **BFNs have high communication quality and redundancy**
2. Node failures in a certain module does not spread to other modules
3. Node or module failures at lower hierarchy does not spread to topology at higher hierarchy

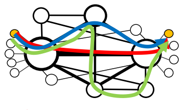
We verify these expected quality through evaluation

Communication Quality Evaluation

- **Evaluate quality and redundancy of paths (routes) at module-level topology**
  - communication quality = hop count along the path
- **Calculate average hop count of K shortest paths**
  - K is ranged from 1 to 300
    - We use Yen's algorithm for deriving K shortest loop-less paths
  - Compare with other topologies (next page)



Shortest hop count: 3



Shortest hop count: 3
2nd shortest hop count: 4
K-th shortest hop count: 6

Topologies for Comparison

- **4 model-based topologies**
  - Selected models are used in the field of neuroscience and/or reflect a part of topological properties of BFNs as follows:

BA	・Reflect the power-law degree distribution
Random	・Construct links randomly
Watts-Strogatz (WS)	・Reflect the integration of local optimality and global efficiency and small-world-ness
Waxman	・Reflect the property that functional modules in anatomically near position are densely connected

- The number of nodes and links is set to the same to that of module-level topology at each Path

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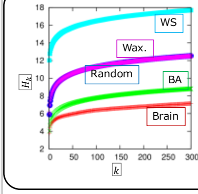
Results of Evaluation [results of topology at Path2]



	Brain	BA	Rand.	WS	Wax.
H_1	3.79	4.02	5.90	12.03	6.01
H_{300}	7.14	8.81	12.53	17.70	12.52
Average	6.48	7.90	11.43	16.63	11.42
Variance	0.30	0.68	1.13	0.99	1.11

H_K: average hop count of K-th shortest path

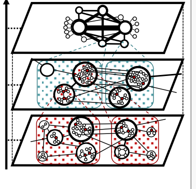
- **Minimum average value**
  - BFNs have high quality paths in terms of the hop count
- **Minimum variance value**
  - BFNs have a lot of paths with similar quality

BFNs have many superior paths at module-level compared to other topologies

Conclusion and Future Works

- **Conclusion**
  - We reveal the topological structure of BFNs
  - We reveal that BFNs' path quality at module-level is superior to other topologies

We obtain a fine perspective of making the Internet higher quality by incorporating BFNs' fractality



- **Future works**
  - Reveal additional advantages of BFNs
    - such as robustness against node or module failures
  - Deep studies on the relation between fractality and topological performance
  - Devise an algorithm or ASes' policy of link construction to make the fractal Internet