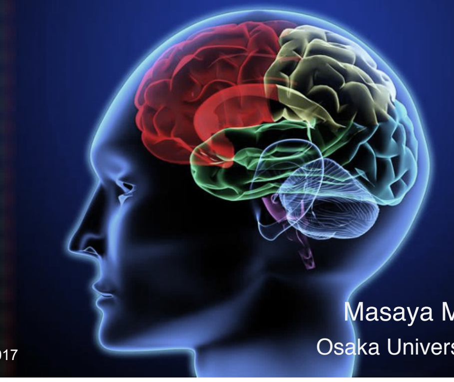
Constructing Virtual IoT Network Topologies with a Brain-Inspired Connectivity Model



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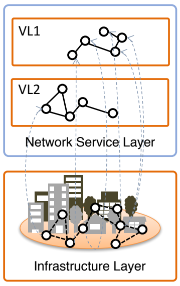
Background

- Development of Wireless Sensor Networks (WSN) and application to the Internet of Things (IoT)
  - Explosive increase in
    - Number of wireless devices
    - Type of application services
- Realization of IoT by **Virtualized WSN (VWSN)**[1]
  - Virtual IoT network constructed by VWSNs enables
    - Flexibly reuse of physical network resources
    - Accelerate service development on different network layers
    - Overcome heterogeneity among network resources

[1] Md. Motaharul Islam et. al, "A Survey on Virtualization of Wireless Sensor Networks", Sensors, vol.12, pp. 2175-2207, Nov. 2012.

Problems in VWSN[1]

- VWSN is composed of **Infrastructure** and **Service** Layers
  - Infrastructure providers form individual physical networks
  - Service providers construct virtual layers over Infrastructure Layer
- Problems of VWSN:
  - Diversification in services causes **frequent reconfiguration** of networks
  - Expansion of network scale costs high **computational complexity** for designing efficient networks



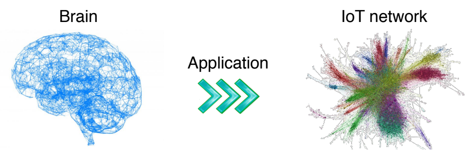
Get inspiration from brain networks: well-known for high efficiency

[1] Md. Motaharul Islam et. al, "A Survey on Virtualization of Wireless Sensor Networks", Sensors, vol.12, pp. 2175-2207, Nov. 2012.

Approach and Goals

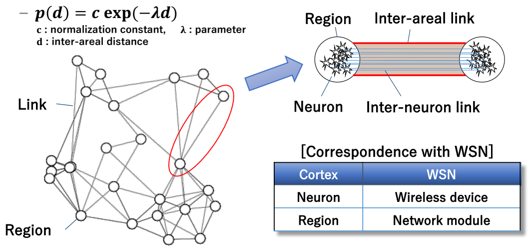
- Our research focuses on the connectivity in the human brain's cerebral cortex
  - The human brain's cerebral cortex
    - is an **ultra large scale** network with over 10 billion neurons
    - optimizes the trade-off between **metabolic cost** and **communication efficiency**

Propose a new method to construct VWSN and apply features of the brain into IoT network



Connectivity Model of the Cerebral Cortex[2]

- **Exponential Distance Rule** (EDR)
  - Simple model that Describes cerebral connectivity under **geometrical constraints**
  - Probability of existence of neural connections that exponentially decays with the inter-areal distance
    - $p(d) = c\exp(-\lambda d)$
      c : normalization constant, λ : parameter
      d : inter-areal distance



[Correspondence with WSN]

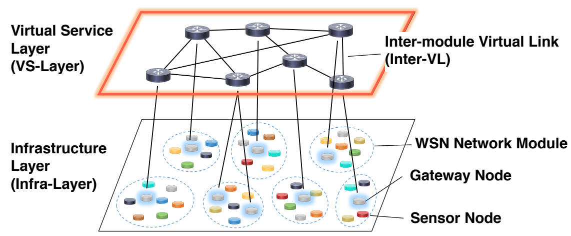
Cortex	WSN
Neuron	Wireless device
Region	Network module

[2] M. Ercsey-Ravasz et al., "A predictive network model of cerebral cortical connectivity based on a distance rule," Neuron, vol. 80, pp. 184–197, Oct. 2013.

Overview of VWSN Model

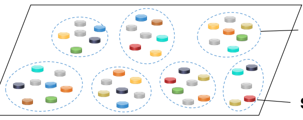
- Physical resources are deployed on Infra-Layer
- Virtual links are formed on VS-Layer

Our question: "How can we generate an efficient VS-Layer?"



Construction of Infra-Layer

I. Randomly deploy N nodes over a square area
II. Connect nodes within communication range r
III. Divide nodes into modules using InfoMap[3] method
  - Select representative nodes in the process of InfoMap through which the largest amount of flow passes
  - Representative nodes define the coordinates of modules
IV. Delete links between modules and generate M modules



[3] M. Rosvall and C. T. Bergstrom, "Maps of random walks on complex networks reveal community structure," Proceedings of the National Academy of Sciences, vol. 105, no. 4, pp. 1118– 1123, 2008.

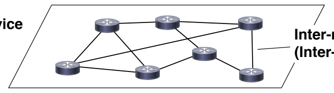
Construction of VS-Layer

- Generate virtual links between modules (Inter-VLs)

I. Randomly choose a pair of modules
  - Each pair can have multiple Inter-VLs
II. Form an Inter-VL following $p'(d_n)$ ← Key Idea
  - $p'(d_n) = \exp(-d_n/\alpha)$

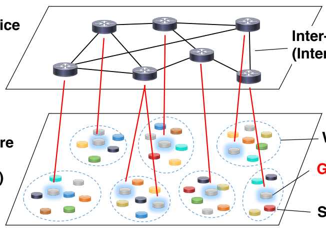
d_n: normalized distance between modules, α: parameter within (0,1]

III. Repeat until $L = M \times m$ Inter-VLs are formed
  - M: the number of modules
  - m: parameter (average degree of each module)



Assigning Endpoints of Inter-VLs

- Assign endpoints of Inter-VLs as gateway nodes
  - Choose pairs of nodes as gateways so that the sum of the degrees becomes highest among all possible pairs
    - Exclude pairs on which Inter-VLs already exist
    - Multiple Inter-VLs can coexist between a pair of modules



Evaluation of Structural Properties

- Settings
  - $(N, L, E, r) = (4000, 1000, 300, 8), (2000, 500, 300/\sqrt{2}, 8)$

N: Number of nodes, L: Number of Inter-VLs, E: Length of square area, r: communication range

- Metrics
  - Average Path Length (APL)
    - Average of the smallest sum of link-length between nodes
  - Average Hop Count (AHC)
    - Average of the minimum number of hops between nodes
  - Wiring Cost (WC)
    - Squared sum of link-lengths that constructs VS-Layer
  - Modularity
    - Extent of community structure: $Q = \sum_i (e_{ii} - a_i^2)$
      - e_{ii}: fraction of links with both endpoints in module i
      - a_i^2: expectation value of e_{ii}

Evaluation of Structural Properties

- Types of VS-Layer
  - EDR model
    - Proposed method with $p'(d_n) = \exp(-d_n/\alpha)$
  - Random model
    - Modules connected at random
  - BA model[4]
    - New node j is connected to node i with probability $p_i = k_i / \Sigma_l k_l$
      - k_l is the degree of node l
  - Full-Link model
    - Inter-VLs are formed between all pair of modules
    - Minimizes AHC and APL
  - Min-Link model
    - Minimum Spanning Tree with Inter-VLs assigned between closest modules
    - Minimizes WC

[4] A.-L.Barabási and R.Albert, "Emergenceofscalinginrandomnetworks," *science*, vol.286, no.5439, pp.509–512, Oct.1999.

Structural Properties

- EDR$_{\alpha=0.025}$ has both good and bad aspects
  - WC and APL are close to optimal solution
    - WC is low since it connects close modules
    - Community structure leads to low APL and high Modularity
  - AHC is comparatively high
    - Trade-off with the decrease of cost (WC)
    - BA can suppress AHC since it considers node degree

[Evaluation of structural properties on $N = 4000$]

	Min-Link	EDR$_{\alpha=0.025}$	EDR$_{\alpha=0.10}$	EDR$_{\alpha=0.40}$	Random	BA	Full-Link
APL $[m]$	*504*	**193**	197	247	297	296	**171**
AHC	*35.3*	**9.53**	7.01	6.86	6.91	**6.57**	**4.15**
WC $[10^5 m^2]$	**0.00594**	**0.0583**	0.492	1.51	2.19	2.17	*47.6*
Modularity	0.365	0.690	0.426	0.285	0.285	0.255	1.00

Comparison of Different Scales

- Divided results of $N = 4000$ by those of $N = 2000$
  - Evaluate effect of scaling the number of modules
- EDR$_{\alpha=0.025}$ showed good performance
  - Reduction of increase on APL and WC
  - Suppression of AHC

Our method proposes high scalability when the number of modules increased

[(Results of $N = 4000$) / (Results of $N = 2000$)]

	Min-Link	EDR$_{\alpha=0.025}$	EDR$_{\alpha=0.10}$	EDR$_{\alpha=0.40}$	Random	BA	Full-Link
APL	*1.51*	1.29	1.39	1.47	1.48	1.48	1.38
AHC	*1.54*	1.11	1.10	1.12	1.10	1.10	1.03
WC	1.37	2.28	2.59	2.58	2.60	2.63	*4.78*

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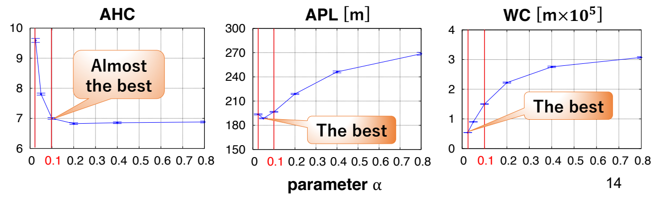
Trade-off Between Cost and Efficiency

- We evaluated the influence of α on AHC, APL, and WC of networks with $N = 4000$
  - In the range of $\alpha \in [0.025, 0.10]$,
    - Trade-off between WC and AHC appears
    - All metrics are close to their optimal values

Our method reaches high performance in trade-off



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Evaluation of Information Spreading Speed

- Settings
  - $(N, L, E) = (5000, 2500, 200)$
    - Number of nodes: N
    - Number of Inter-VLs: L
    - Length (in meters) of one side of square area: E
- Metrics
  - Flooding simulation
    - Measure the time needed for a packet to spread over all nodes
    - Compare topologies with the same Wiring Cost (WC)
  - Topologies
    - I. EDR model using parameter $\alpha = 0.05$
    - II. Random Weight model
      - Randomly change the weight of inter-module connections of I.
    - III. Random Shape model
      - Randomly rewire inter-module connections of I.

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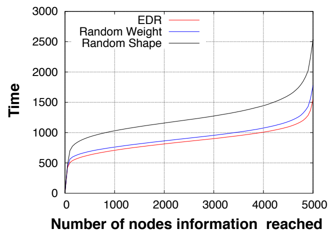
Information Spreading Speed

- Random Shape showed the lowest performance
  - The topological shape of our proposed method accelerates spreading of information
- EDR showed higher speed than Random Weight
  - EDR generates much more connections between close modules

Our method of assigning inter-module links shows higher efficiency and scalability



Conclusion and Future Work

- Conclusion
  - We proposed a method to construct VWSN over large-scale IoT infrastructure networks
    - Networks showed a good performance in the trade-off between cost and efficiency when our method uses $\alpha = 0.05$
    - Networks are scalable when the number of modules or number of nodes in each module increases
- Future Work
  - Adding non-geometrical factors when constructing VS-Layer
    - E.g., node degree, homophily, etc.
  - Taking stricter constraints into evaluation for a realistic situation
    - E.g., node failure, resource competition, etc.

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