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

Masaya Murakami
Osaka University, Japan

Jan. 5, 2017

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

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
  \[ p(d) = e^{\beta d^4} \]
  - \( \beta \): summation constant, \( d \): parameter

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\cite{4} 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

Construction of VS-Layer

- Generate virtual links between modules (Inter-VLs)
  - Each pair can have multiple Inter-VLs
  - Form an Inter-VL following $p'(d_{ab})$
    - $p'(d_{ab}) = \exp(-d_{ab}/\alpha)$
    - $d_{ab}$: normalized distance between modules, $\alpha$: parameter within $[0, 1]$
  - 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

- Types of VS-Layer
  - EDR model
    - Proposed method with $p'(d_{ab}) = \exp(-d_{ab}/\alpha)$
  - Random model
  - Modules connected at random
  - BA model\cite{4}
    - New node $j$ is connected to node $i$ with probability $p_i = k_i/\sum k_i$
    - $k_i$ is the degree of node $i$
  - 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

- 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

<table>
<thead>
<tr>
<th>Evaluation of structural properties on $N = 4000$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min-Link</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>APL [m]</td>
</tr>
<tr>
<td>AHC</td>
</tr>
<tr>
<td>WC [T/Sq]</td>
</tr>
<tr>
<td>Modularity</td>
</tr>
</tbody>
</table>

References:
Comparison of Different Scales

- Divided results of $N = 4000$ by those of $N = 2000$
- Evaluate effect of scaling the number of modules

EDR showed good performance
- Reduction of increase on APL and WC
- Suppression of AHC

Our method proposes high scalability when the number of modules increased

<table>
<thead>
<tr>
<th></th>
<th>Min-Link</th>
<th>EDRL = AHC</th>
<th>EDRL = AHC</th>
<th>Random</th>
<th>BA</th>
<th>Full-Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>APL</td>
<td>2.52</td>
<td>1.29</td>
<td>1.39</td>
<td>1.47</td>
<td>1.48</td>
<td>1.38</td>
</tr>
<tr>
<td>AHC</td>
<td>2.54</td>
<td>3.11</td>
<td>1.10</td>
<td>1.12</td>
<td>1.10</td>
<td>1.03</td>
</tr>
<tr>
<td>WC</td>
<td>1.37</td>
<td>2.28</td>
<td>2.59</td>
<td>2.58</td>
<td>2.60</td>
<td>2.63</td>
</tr>
</tbody>
</table>

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 $L$
  - III. Random Shape model
    - Randomly rewire inter-module connections of $L$

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

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.