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Adaptability of Virtual Network Topology Control Based on Attractor Selection against Multiple Node Failures

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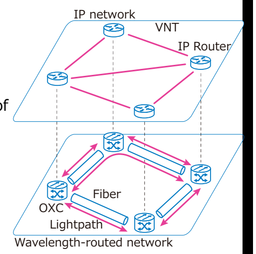
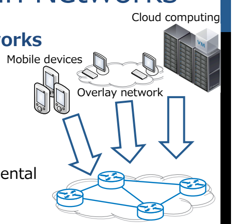
Virtual Network Topology Control

- **Wavelength-routed Networks**
  - WDM Network
    - Establish lightpaths
      - A lightpath is an optical transport channel
  - Virtual Network Topology (VNT)
    - A logical topology that consists of a set of lightpaths
  - IP Network
    - Transmits its traffic on the VNT
- **VNT Control**
  - Constructs an (sub-)optimal VNTs by configuring lightpaths
  - To achieve control objectives
    - E.g., effective transport of traffic, effective utilization of resources



Environmental Changes in Networks

- **Large environmental changes in networks**
  - Penetration of mobile devices
  - Emerging application layer technologies
    - E.g., Overlay networks, Cloud computing
- **Existing approaches to responding to environmental changes**
  - Assume a certain set of scenarios for environmental changes
    - Periodic and gradual changes in traffic
    - Single or a few number of node/link failures
  - Prepare countermeasures to those changes as algorithms



- Against these assumed environmental changes
  - → These approaches may guarantee optimal performance
- If unexpected changes occur
  - → They cannot achieve expected performance

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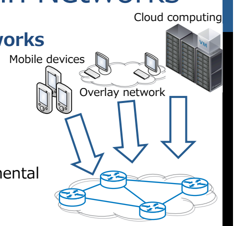


VNT control that adaptively responds to various environmental changes without priori knowledge of environmental changes is indispensable

To achieve adaptability of VNT control, we focus on the adaptability of biological systems (***attractor selection***).

Attractor Selection

- **Mathematical model to explain adaptive behaviors of biological systems**
  - E.g., E.coli cell, gene regulatory networks
- **Fundamental elements to determine behaviors of a system driven by attractor selection**
  - Noise
  - Programmed operation
  - Activity (condition of the system)
    - Good condition → High activity
    - Poor condition → Low activity

$$\frac{\mathrm{d}x_i}{\mathrm{d}t} = \alpha \cdot \mathrm{f}(x_1, x_2, \ldots, x_n) + \eta_i$$

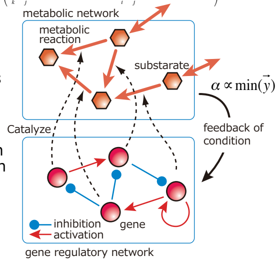
system behavior; activity; noise; programmed operation

- Achieve adaptability to environmental changes by controlling programmed operation ($\mathrm{f}(\boldsymbol{x})$) and noise ($\eta$) depending on the activity (α)

Attractor Selection in Gene Regulatory Network

- **Metabolic reaction network**
  - Generate vital substrates for cellular growth via metabolic reactions
  - Concentrations of the vital substrates is fed back to gene regulatory networks as activity (α)
- **Gene regulatory network**
  - Expression levels (x_i) of proteins on each gene is determined by attractor selection
    - Programmed operation
      - Interactions between genes
    - Activity
      - Condition of metabolic reaction network, i.e., concentrations of vital substrates
    - Noise
  - Expression levels control the corresponding metabolic reaction

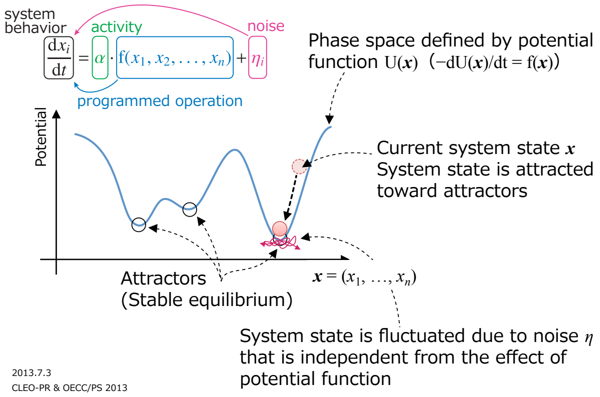
$$dy_i/dt = \left(\sum_k \sum_j \mathrm{Con}(k,j,i) \cdot x_j \cdot y_k - \sum_l \sum_j \mathrm{Con}(i,j,k) \cdot x_j \cdot y_i\right) \cdot \varepsilon + D(Y_i - y_i)$$



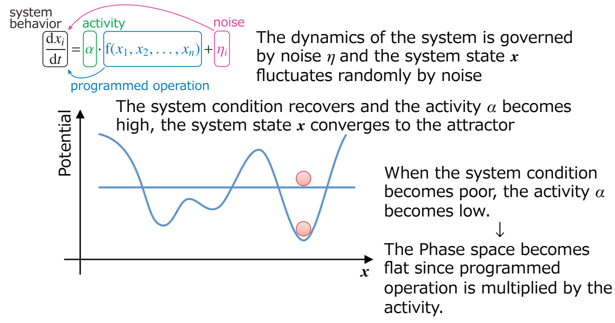
$$\frac{dx_i}{dt} = \alpha \cdot \left(\varsigma\left(\sum_j W_{ij}\, x_j\right) - x_i \right) + \eta$$

$$\varsigma(z) = \frac{1}{1+\exp(-\mu z)}$$

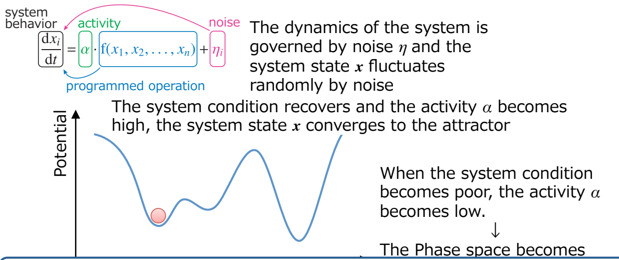
Fundamentals of Attractor Selection



Fundamentals of Attractor Selection

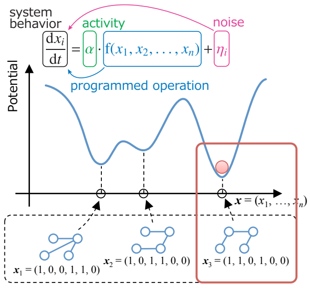


Fundamentals of Attractor Selection



- Attractor selection is a kind of mechanisms to search for a solution that is suitable for the current environment.
  - It cannot guarantee the optimality of the solution
    - It may find one of sub-optimal solutions
  - However, it has the potential capability of adapting various changes.

VNT Control Based on Attractor Selection



$x_i \in \{0, 1\}$: A binary variable to determine establishments of i-th lightpath

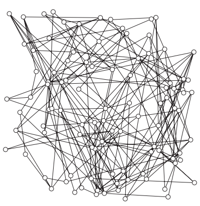
- $x_i = 1$: establish i-th lightpath
- $x_i = 0$: tear down i-th lightpath

A VNT (N nodes) is expressed with a N^2 dimensional vector $\boldsymbol{x} = (x_1, \ldots, x_{N2})$.
⇨ VNTs are mapped onto the N^2 dimensional phase space.

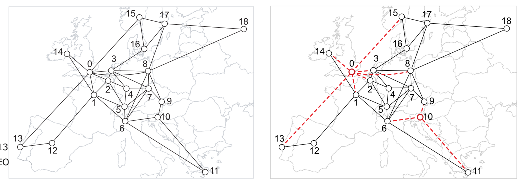
Drive the system with attractor selection and configure a VNT corresponding to the current system state $\boldsymbol{x} = (x_1, \ldots, x_{N2})$.

Simulation Model

- **Physical Network**
  - Random topology (100 nodes and 496 fibers)
- **Constraints for constructing VNTs**
  - Each node has 16 transmitters and receivers of optical signals
- **Environmental changes in the network**
  - Random node failures
    - Lightpaths that are pass through failed nodes are also failed
    - Failed lightpaths are always unavailable during node failure

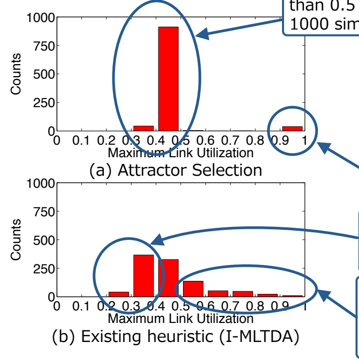


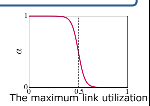
Random topology



Distribution of the maximum link utilization during node failures

Our proposed method constructs VNTs, having the maximum link utilization less than 0.5 in 955 out of 1000 simulation trials.





In a few cases, our proposed method fail to construct good VNTs

In some cases, heuristic method constructs VNTs better than our proposed method

The heuristic method also constructs VNTs that have higher link utilization than our proposed method

Conclusion and Future Work

- **We propose an adaptive VNT control method against various environmental changes**
  - It is inspired by the adaptive behavior of gene regulatory networks
- **Our proposed method is highly adaptive**
  - It adaptively responds to node failures in more than 95% of simulation trials when 20% of nodes in the physical network fail simultaneously
- **Future Work**
  - Extending our approach for other virtualization-based networks
    - E.g., network virtualization or OpenFlow