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Application of Attractor Selection to Adaptive Virtual Network Topology Control

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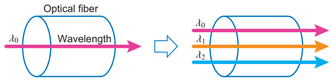
Background: wavelength division multiplexing

- Wavelength Division Multiplexing (WDM)
  - A technology that carries multiple wavelengths on a single optical fiber



- Enhances the capacity of existing optical backbone networks
- Is expected as a way to accommodate increasing Internet traffic

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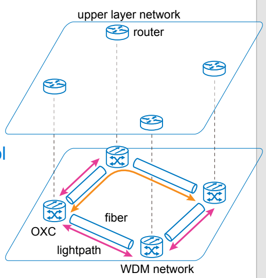
Background: virtual network topology control

- Wavelength-routed network
  - WDM network
    - Establish lightpaths
      - Optical transport channel
  - Virtual Network Topology (VNT)
    - consists of a set of lightpaths and electronic routers
  - Upper layer network (client network)
    - Transmit its traffic on the VNT
- Virtual Network Topology Control
  - Constructs an (sub-)optimal VNT by configuring lightpaths
  - To balance load or remove bottlenecks in the network
    - Effective transport of traffic
    - Efficient utilization of resources



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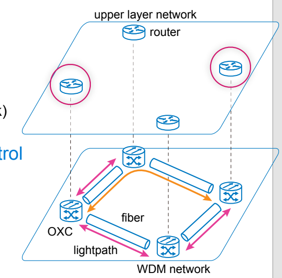

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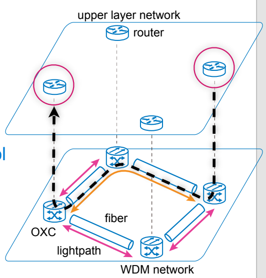

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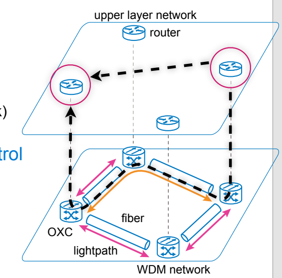

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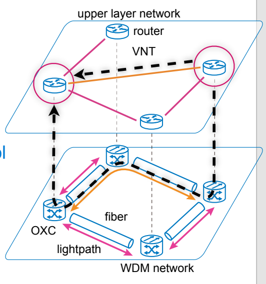


Needs to an adaptive network control to environmental changes

- Large environmental changes in network environments
  - e.g., interactions between traffic engineering and overlay routing
    - Cause large fluctuations in network environments
      - Traffic demand
      - Link load
- Environmental changes addressed in previous work
  - Periodical and gradual changes in traffic demand
- Various changes in environments
  - Changes in traffic demand
  - Link failures

To achieve an adaptive VNT control to various environmental changes, ⇒ we focus on ***attractor selection***.

Attractor selection

- Models for explaining adaptability of biological systems
  - e.g., E.coli cell [1], gene-metabolic network [2]
- Fundamental elements to determine behaviors of system
  - Noise
  - Programmed operation
  - Activity (condition of the system)

system behavior, activity, noise, programmed operation:

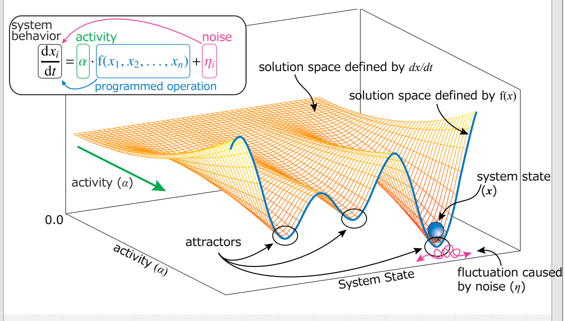
$$\frac{dx_i}{dt} = \alpha \cdot f(x_1, x_2, \ldots, x_n) + \eta_i$$

- Concept of attractor selection
  - Poor condition = low activity
    - Noise (η) dominates the system behavior
    - Search for other attractors where system condition is better by η
  - Good condition = high activity
    - $f(x)$ dominates the system behavior
    - Converge to the attractor by $f(x)$

Achieve adaptability to environmental changes by control $f(x)$ and η depending on the activity

[1] A. Kashiwagi, I. Urabe, K. Kaneko, and T. Yomo, "Adaptive response of a gene network to environmental changes by fitness-induced attractor selection," *PLoS ONE*, vol. 1, p. e49, Dec. 2006.
[2] C. Furusawa and K. Kaneko, "A generic mechanism for adaptive growth rate regulation," *PLoS Computational Biology*, vol. 4, p. e3, Jan. 2008.

Fundamental behavior of attractor selection



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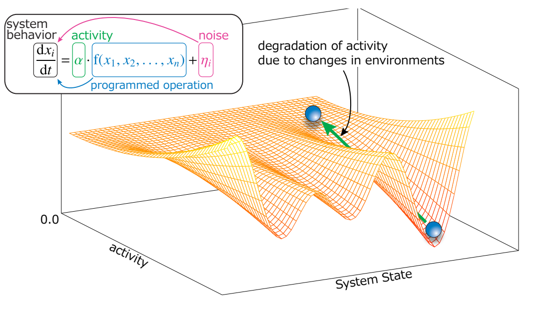

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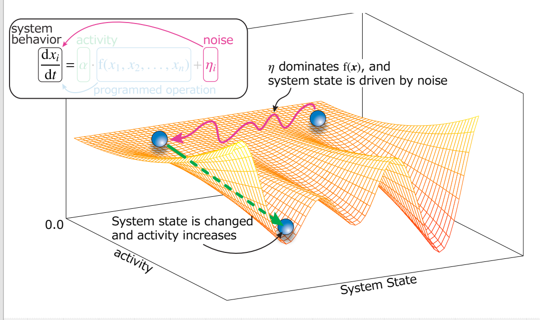

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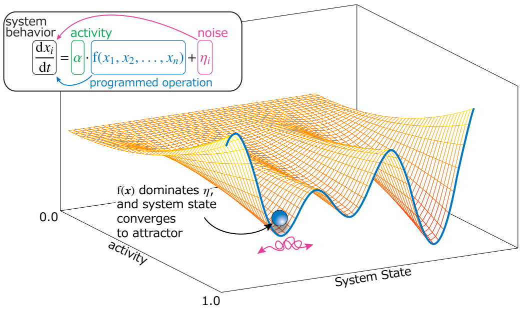
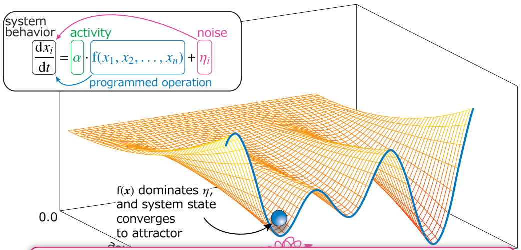
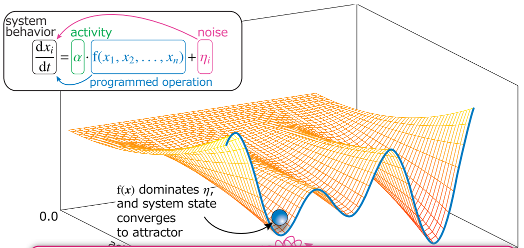


Fundamental behavior of attractor selection



- Since the system is driven by noise, attractor selection cannot guarantee the optimal performance.

Fundamental behavior of attractor selection

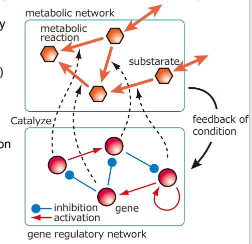


- Since the system is driven by noise, attractor selection cannot guarantee the optimal performance.
- However, since the system is driven without any assumptions on changes in environments, it has the potential capability of adapting various changes.

Attractor selection in a gene-metabolic network

- Layered structure
  - Metabolic reaction network
    - Generate vital substrates for cellular growth by metabolic reactions
    - Concentrations of the vital substrates is fed back to gene regulatory network as activity (α)
  - Gene regulatory network
    - Interactions of genes determine expression levels (x_i) of proteins on each gene
    - x_i controls the corresponding metabolic reaction
- Three elements of attractor selection
  - Programmed operation
    - Activation / inhibition between genes
  - Noise
  - Activity
    - Concentrations of vital substrates

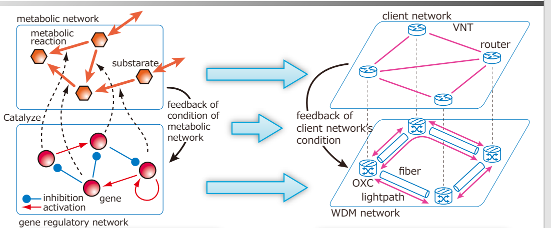
$dy_i/dt = \left(\sum_k \sum_j Con(k,j,i) \cdot x_j \cdot y_k - \sum_k \sum_j Con(i,j,k) \cdot x_j \cdot y_i\right) \cdot \varepsilon + D(Y_i - y_i)$



$dx_i/dt = \alpha \cdot \left(sig\left(\sum_j W_{ij} \cdot x_j - \theta\right) - x_i\right) + \eta$

$sig(z) = 1/(1 + \exp(-\mu z))$

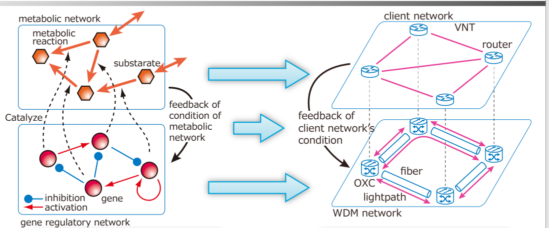
Applying attractor selection to VNT control



Gene-metabolic network | VNT control

- Achieve adaptability to environmental changes by using the noise and the feedback of the condition of the metabolic reaction network
- Achieve adaptability to environmental changes by using the noise and the feedback of the condition of the client network

Applying attractor selection to VNT control



Gene-metabolic network | VNT control

- Condition of metabolic network is poor
  - Search for other attractors where system condition is better by noise
- Condition of metabolic network is good
  - Converge to the attractor
- Condition of client network is poor
  - Search for other VNTs that accommodate client network's traffic better by noise
- Condition of client network is good
  - Converge to the attractor

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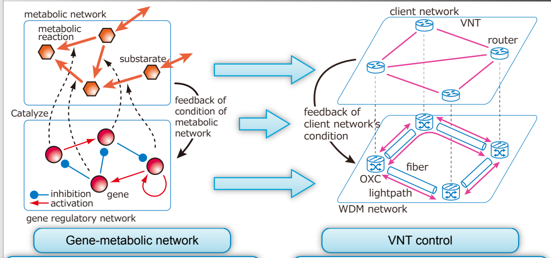
Applying attractor selection to VNT control



- The gene regulatory network controls the metabolic network adaptively to changes in environments
- The WDM network controls the client network adaptively to changes in environments

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VNT control based on attractor selection

- Challenges
  - Differences between VNT control and biological systems
    - Cannot apply attractor selection to VNT control directly
  - To realize an useful VNT control
    - Need an appropriate interpretation of attractor selection to VNT control
- Features
  - Adaptive network control to environmental changes
    - Do not assume a specific type of environmental changes
    - Achieve adaptability to various environmental changes by utilizing the noise
  - Effective network control with limited information

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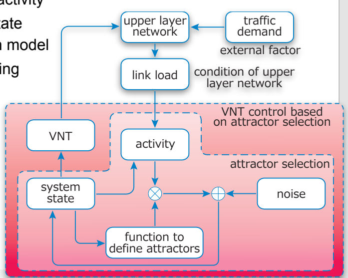
Behavior of VNT control based on attractor selection

- Behavior of our proposed method
  - Measure link load on the client network periodically
  - Convert link load to the activity
  - Determine the system state by the attractor selection model
  - Construct a VNT according to the system state



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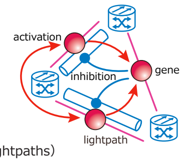
Interpretation of attractor selection to VNT control

- Gene-metabolic network ⇔ VNT control
  - Metabolic reaction network → client network
    - Use the maximum link utilization as the condition of the client network
  - Gene regulatory network → WDM network
    - Place genes to all node pairs (p_{ij})
    - Determine number of lightpaths on p_{ij} by the expression level (x_{pij}) on p_{ij}
      - Large x_{pij} → Many lightpaths
      - Small x_{pij} → Few lightpaths
    - Dynamics of the expression levels (x_{pij})



expression levels (for determining number of lightpaths)
function to define attractors noise

$$dx_{p_{ij}}/dt = \alpha \cdot \left(\mathrm{sig}\left(\sum_{p_{sd}} W(p_{ij}, p_{sd}) \cdot x_{p_{sd}} - \theta_{p_{ij}}\right) - x_{p_{ij}}\right) + \eta$$

system behavior activity interaction of genes (activation/inhibition)

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Policies to design attractors

expression levels (for determining number of lightpaths)
function to define attractors noise

$$dx_{p_{ij}}/dt = \alpha \cdot \left(\mathrm{sig}\left(\sum_{p_{sd}} W(p_{ij}, p_{sd}) \cdot x_{p_{sd}} - \theta_{p_{ij}}\right) - x_{p_{ij}}\right) + \eta$$

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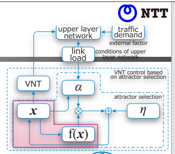

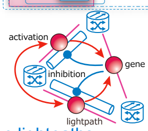

- Attractors are defined by
  - Activations and inhibitions between genes
    - Represented by $W(p_{ij}, p_{sd})$
    - p_{ij} activates p_{sd} → increases x_{psd} → increases the number of lightpaths on p_{sd}
    - p_{ij} inhibits p_{sd} → decreases x_{psd} → decreases the number of lightpaths on p_{sd}
- Encode the motivations to set up or tear down lightpaths
  - Adding lightpaths for effective transport of traffic
    - Activation
  - Establishing lightpaths for detouring traffic
    - Activation
  - Decreasing lightpaths due to resources being shared with other node pairs
    - Inhibition

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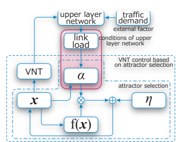
Activity

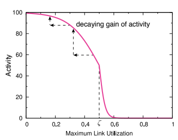
expression levels (for determining number of lightpaths)
function to define attractors noise

$$dx_{p_{ij}}/dt = \alpha \cdot \left(\mathrm{sig}\left(\sum_{p_{sd}} W(p_{ij}, p_{sd}) \cdot x_{p_{sd}} - \theta_{p_{ij}}\right) - x_{p_{ij}}\right) + \eta$$

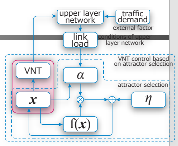
system behavior activity interaction of genes (activation/inhibition)



- Condition of the client network
  - The maximum link utilization (u_{max}) of the client network
    - Other metrics can be used
- Definition
  - u_{max} is higher than ζ → Poor condition
    - Decrease the activity drastically
    - Reconfigure VNTs by noise
  - u_{max} is lower than ζ → Good condition
    - Increase the activity gradually
    - Converge to an attractor with retaining the incentive to improve the condition of the client network



VNT construction



- Determine number of lightpaths
  - According to expression levels (x_{pij})
    - Assign resources in the WDM network according to x_{pij}
      - Number of transmitters (P_T) and recfeivers (P_R)
- Number of lightpaths G_{pij} on the node pair p_{ij}

$x_{p_{ij}}$ normalized by total x for all the node pairs that use the receiver on node j

convert to integers by the floor function

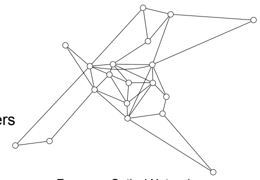
$$G_{p_{ij}} = \min\left(\lfloor P_R \cdot \frac{x_{p_{ij}}}{\sum_s x_{p_{sj}}} \rfloor, \lfloor P_T \cdot \frac{x_{p_{ij}}}{\sum_d x_{p_{id}}} \rfloor\right)$$

satisfy the constraints of both receivers and transmitters

  - Other constraints can be considered by adding x_{pij} normalized by total x for node pairs that share the common resource

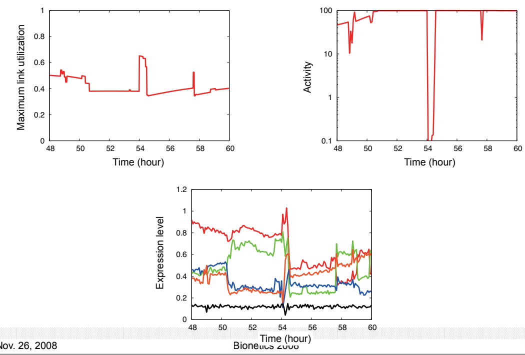
Simulation conditions

- Physical network
  - European Optical Network
    - 19 nodes, 39 links
- Physical constraints
  - Number of transmitters and receivers
    - 8 for each node
  - Number of wavelengths
    - Sufficient number on each fiber
- Environmental changes
  - Changes in traffic demand
    - Gradual and periodical changes
      - The cycle of changes: 24 hours
    - Sharp and sudden changes
      - Change traffic volume for every node pair randomly



European Optical Network

Behaviors of VNT control based on attractor selection



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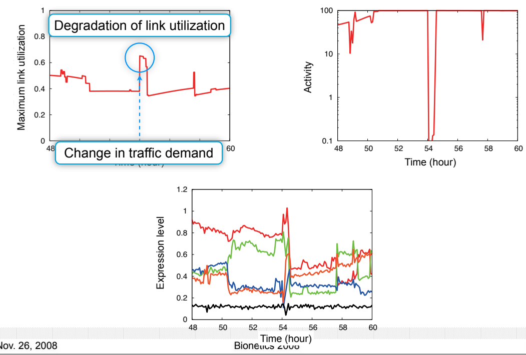

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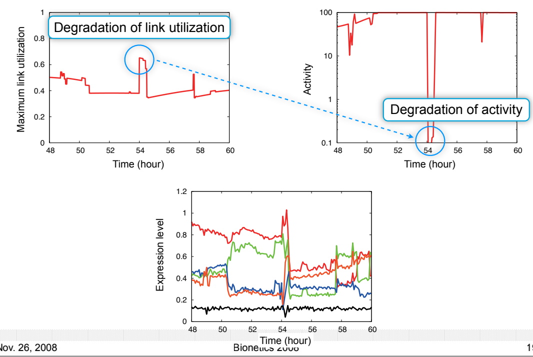

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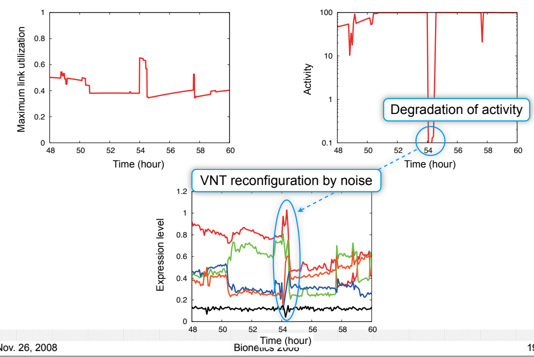

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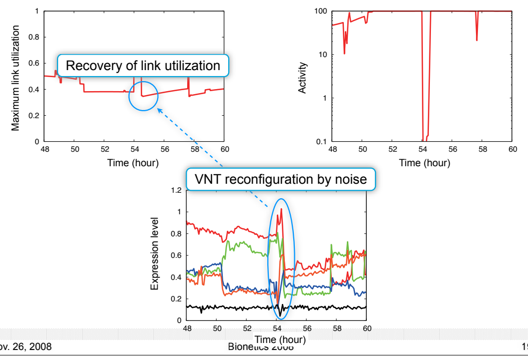

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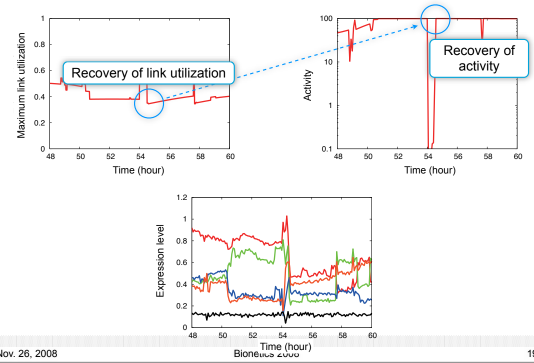

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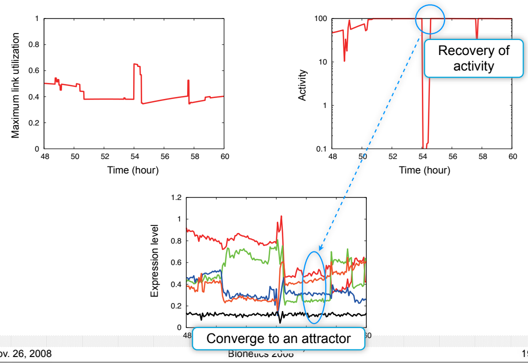

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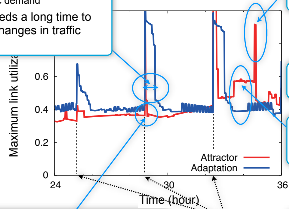
Adaptability to changes in traffic demand

Adaptation
- A heuristic method whose objective is adaptability to changes in traffic demand
- Assumes gradual and periodical changes in traffic demand

This approach needs a long time to adapts to sharp changes in traffic demand



Our method adapts to sharp changes in traffic demand quickly

Sharp changes in traffic demand

Since a fixed amount of noise has a constant influence on our method, the system state happens to drop out of an attractor.

Select a different attractor quickly

Our method cannot guarantee the achievable performance

The performance can be improved by using the appropriate amplitude of the noise for VNT control

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Conclusion and future work

- Large changes in network environments
  - Require an adaptive method of controlling VNTs
- Attractor selection
  - Is a model for explaining adaptability of biological systems
- Adaptive VNT control
  - Based on attractor selection in the gene and metabolic networks
  - Can adapt against
    - Various changes in traffic demand
- Future work
  - Determine the appropriate amplitude of the noise for VNT control

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