Hierarchical Traffic Engineering Based on Model Predictive Control

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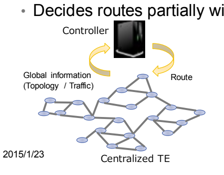
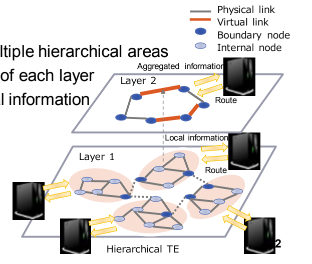
Hierarchical Traffic Engineering

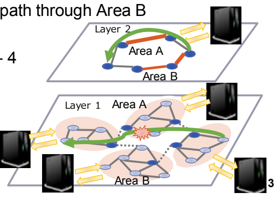
- Lack of scalability in the centralized Traffic Engineering (TE)
  - Gathering whole information and changing routes to avoid congestion
  - Messaging and computation costs increase with the size of network
- Hierarchical TE
  - Divides the whole network into multiple hierarchical areas
  - Deploys a controller on each area of each layer
  - Decides routes partially with partial information





Route Oscillation in Hierarchical TE

- Route Oscillation
  - Routes change in one layer changes global network state
  - The new state induces further routes change in other layer
- Example
  1. Controller in Layer 2 selects the path through Area A
  2. Congestion occurs in Area A
  3. Controller in Layer 2 selects the path through Area B
  4. Congestion occurs in Area B
  5. Routes oscillate by repeating 1 – 4

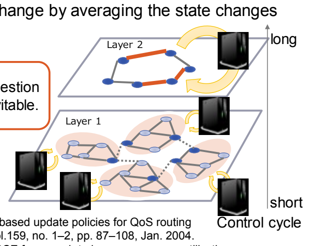


Existing Solution to Route Oscillation

- Setting long control interval in upper layer[1,2,etc.]
  - Routes in lower layer converge when the routes in upper layer are fixed
  - Upper layer avoid unnecessary change by averaging the state changes

Problem of existing method

Long time is required to mitigate the congestion when the inter-area routes change is inevitable.



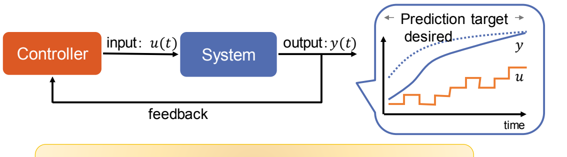
[1] B.-J. Chang and R.-H. Hwang, "Distributed cost-based update policies for QoS routing on hierarchical networks," Information Sciences, vol.159, no. 1–2, pp. 87–108, Jan. 2004.
[2] M. Chamania, et al., "An adaptive inter-domain PCE framework to improve resource utilization and reduce inter-domain signaling," Optical Switching and Networking, vol. 6, no. 4, pp. 259–267, Dec. 2009.

Objective and Approach

- Objective
  - Establishment of new hierarchical TE which achieves the followings
    - All Layers operate in a same time interval to avoid the response delay
    - Each layer avoids the routes oscillation even with the same time interval
- Approach
  - Introducing Model Predictive Control (MPC) to the hierarchical TE
    - Predicting other controllers' behavior helps the cooperation between layers
    - Avoiding the impact of prediction errors with reducing drastic route change
    - Correcting the prediction using newly observed data as a feedback

Model Predictive Control (MPC)[2]

- Inputs setting to a system to make the output close to desired
- Considers how output will change to calculate input values

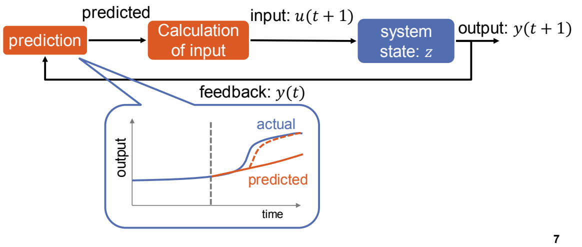


The prediction of output includes errors.
So, the setting of input must be robust to prediction error.

[2] S. J. Qin and T. A. Badgwell, "A survey of industrial model predictive control technology," Control Engineering Practice, vol. 11, no. 7, pp. 733–764, Jul. 2003.

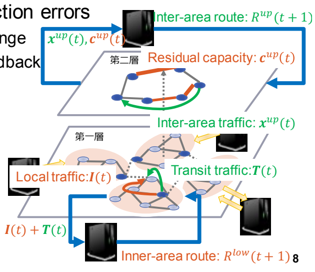
Correction of prediction error by feedback

- Controller corrects the prediction by observing the output
- Controller recalculates the inputs with the corrected prediction
- Controller avoids the drastic change of the input



Hierarchical Model Predictive TE (MP-TE)

- Inter-layer cooperation by predicting other controllers' behavior
  - Upper layer predicts the residual capacity of each area in lower layer
  - Lower layer predicts how much traffic upper layer delegates to the area
- Avoiding the impact of prediction errors
  - Reducing the drastic routes change
  - Correcting the prediction by feedback



Controller in Upper Layer

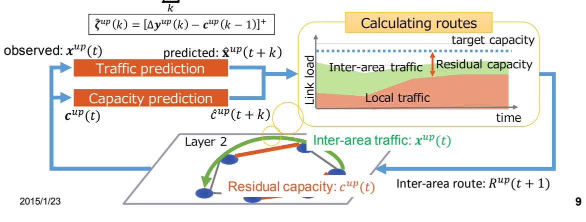
c_i^{low}: target capacities of links in lower layer
y_i^{low}: loads of links in lower layer
y_i^{up}: loads of links in upper layer
w^{up}: weight of routes change in upper layer

- Prediction
  - Predicting the future inter-area traffic and residual capacities in areas
- Calculation of routes
  - Minimizing the congestion among border-nodes with small routes changes

$c_{i,j}^{up}(t) = \sum_{p:i\to\cdots\to j} \min_{l\in p}\left(c_l^{low}(t) - y_l^{low}(t)\right)$

$$minimize: \sum_k \{(1-w^{up})|\zeta^{up}(k)|^2 + w^{up}|\Delta R^{up}(k)|^2\}$$

$\zeta^{up}(k) = [\Delta y^{up}(k) - c^{up}(k-1)]^+$



Controller of Each Area in Lower Layer

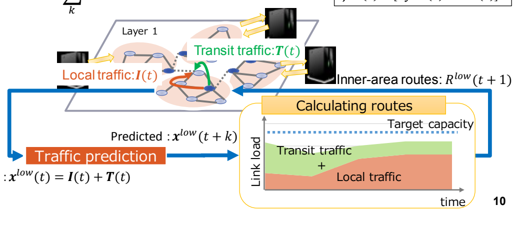
w^{low}: weight for routes change in lower layer

- Prediction
  - Predicting the inner-area traffic summing local and transit traffic
- Calculation of route
  - Minimizing the congestion within the area with small routes changes

$x^{low}(t) = I(t) + T(t)$

$$minimize: \sum_k \{(1-w)|\zeta^{low}(k)|^2 + w^{low}|\Delta R^{low}(k)|^2\}$$

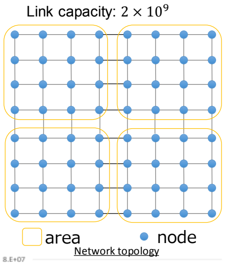
$\zeta^{low}(k) = [\Delta y^{low}(k) - c^{low}(k)]^+$



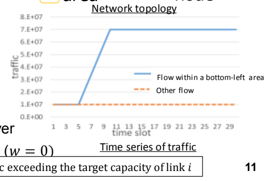
Evaluation Environment

- Network
  - Topology: lattice
  - Partitioning: shown in the right figure
  - Traffic: increasing in a certain area
- Prediction
  - Simple line fitting to past time series
- Metrics
  - Routing convergence time
  - Congestion level: $\max_i \zeta_i(k)$
- Compared method
  - Simple TE with same prediction
    - Setting large control interval at upper layer
    - Without avoiding drastic routes changes ($w = 0$)

Link capacity: 2×10^9



Network topology

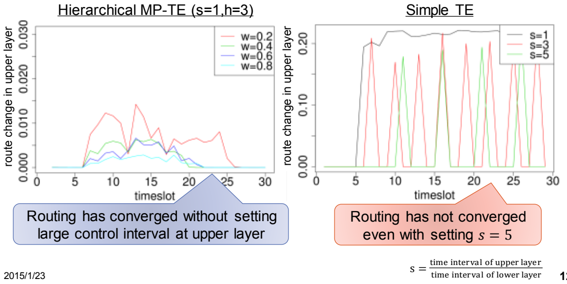


Time series of traffic

$\zeta_i(k)$: amount of traffic exceeding the target capacity of link i

Route Convergence

- MP-TE achieves the routing convergence
- Simple TE is insufficient to complete convergence

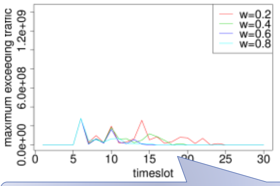


$s = \frac{\text{time interval of upper layer}}{\text{time interval of lower layer}}$

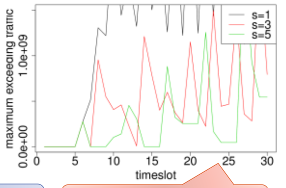
Congestion Level

- MP-TE keeps congestion level low even during the convergence
- Simple TE causes large congestion because of the oscillation

Hierarchical MP-TE (s=1,h=3)



Simple TE



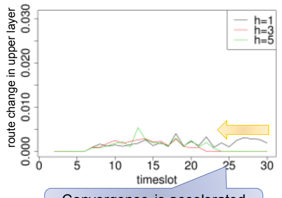
Congestion is kept low during the routing convergence, and solved after convergence

Large congestion is induced by route oscillation

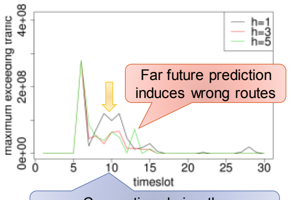
Impact of Predictive Horizon Length in MP-TE

- Considering further future accelerates the convergence
- Too far future prediction misleads with prediction error

Routes change



Congestion level



Convergence is accelerated by setting s=3,5 than s=1

Congestion during the convergence is reduced with s=3,5

$s = 1, w = 0.8$

Summary and Future Work

- Summary
  - Proposition of hierarchical MP-TE
    - Controllers corroborate by predicting other controllers' behavior
    - Each controller avoid the impact of prediction errors
  - Evaluation of hierarchical MP-TE
    - MP-TE converges routes properly with same time intervals at all layers
    - Far future prediction accelerates the routing convergence, but may mislead
- Future work
  - Developing a more sophisticated prediction method
    - Including the prediction of which information should be exchanged by controllers
  - Investigating the area partitioning method with arbitrary given topology