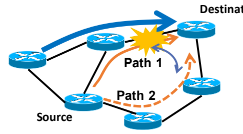
Traffic Engineering Based on Stochastic Model Predictive Control for Uncertain Traffic Change

Tatsuya Otoshi†, Yuichi Ohsita†, Masayuki Murata†
Yousuke Takahashi††, Keisuke Ishibashi††,
Kohei Shiomoto††, Tomoaki Hashimoto†††

† Osaka University, Japan
†† NTT Corporation, Japan
††† Osaka Institute of Technology, Japan

Traffic Engineering

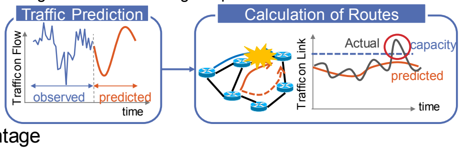
- Increasing the time variation of traffic in a backbone network
  - Deployment of streaming, cloud services, etc.
- Traffic Engineering(TE)
  - Periodical measurement of traffic and optimization of routes



Problems of existing TE
・Time lag of repose to traffic change
・Frequent route change caused by quick response
→ Network instability

Applying Traffic Prediction to TE

- Overview
  - Predicting the future traffic variation based on the observed traffic
  - Calculating a route considering the predicted traffic variation



- Advantage
  - Calculating routes in advance of a traffic change
  - Stable routes change by considering the future traffic

The prediction errors affects the TE performance

Objective and Approach

- Objective
  - Establishment of prediction based TE which achieves the both features
    - Proactive control to traffic changes
    - Robust control to prediction errors
- Approach

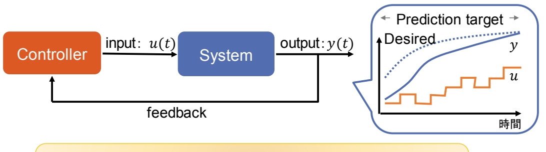
Stochastic Model Predictive Control (SMPC)[1]
- Considers future system behaviors
- Corrects the prediction by feedback
- Keeps the risk of wrong control low

Applying SMPC to TE
- Proactive control to traffic changes
- Robust control to prediction errors

[1] T. Hashimoto, "Probabilistic constrained model predictive control for linear discrete-time systems with additive stochastic disturbances," in Proceedings of IEEE 52nd Annual Conference on Decision and Control, Dec. 2013, p. 6434–6439.

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

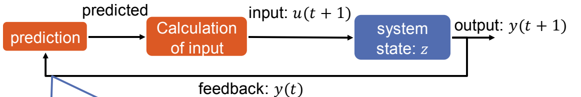


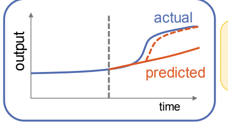
The prediction of output includes errors.
So, the setting of input must be robust to prediction error.

[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

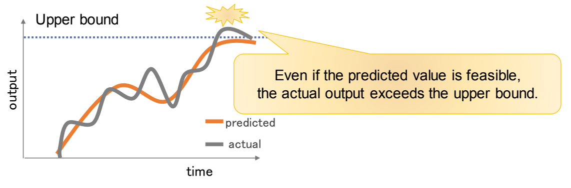




The increase of prediction error can be avoided.
However, influence of one step error still exists.

Influence of prediction error

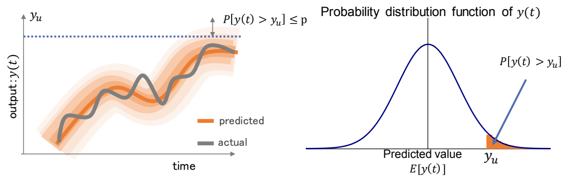
- System has some constraints about input and output
  - Physical limitation, Boundary condition, etc.
- Controller may break the constraints due to prediction errors



Stochastic Model Predictive Control（SMPC）

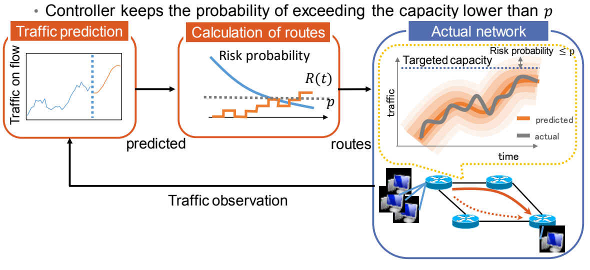
- Keeps the probability of wrong control under a certain level
  - Calculates the input value under $P[y(t) > y_u] \leq p$

y_u: upper bound of output
p: desired probability



Modeling TE control as SMPC

- Routes R is the input, and traffic on each link y is the output
- Accommodation of traffic under targeted capacity is objective
  - Controller keeps the probability of exceeding the capacity lower than p



SMP-TE（Stochastic Model Predictive TE）

- Formalization

Avoid large changes in route setting

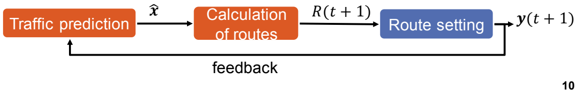
$$minimize : \sum_{k=t+1}^{t+h} ((1-w)||f(R(k))||^2 + w||R(k) - R(k-1)||^2)$$

$$subject\ to : \hat{y}(k) = G \cdot R(k) \cdot \hat{x}(k)$$
$$\forall p, \forall f, R_{p,f}(k) \in [0,1]$$
$$\textstyle\sum_{p \in \wp(f)} R_{p,f}(k) = 1$$
$$\forall l, P[y_l(k) > C_l] \leq p$$

Keep the risk of overcapacity under a certain level

w: weight for routes change
f: cost function
G: routing matrix
$\hat{x}$: predicted value of traffic on flow
C_l: targeted capacity of link l
p: desired probability
$\wp$: set of available paths
$\hat{y}$: predicted value of traffic on link
R: fraction ratio of routes allocation

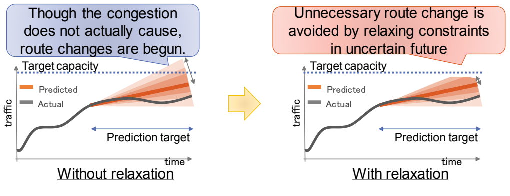
- Procedure



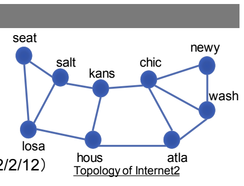
Relaxation of constraints in far future

- Unnecessary route change is caused by considering far future
  - Prediction errors increase as the prediction target becomes far
  - Stochastic constraints becomes strict with the increase in error
- Relaxing the constraints is useful to avoid the route change
  - Decreasing the probability to accommodate traffic as the target is far

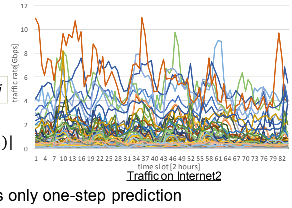
e.g. $q(t+k) = \max\left(0.5, (1-p)e^{-\frac{k-1}{\tau}}\right)$ τ: time constant



Evaluation environment



- Network
  - Topology : Internet2
  - traffic : actual trace data[3]（2012/2/6～2012/2/12）
- Prediction error
  - Gaussian distribution: $N(0, \sigma_j^2 t)$
  - $\sigma_j^2 = 0.3\ V[x_j^2]$[4]
- Metrics $V[x_j^2]$: variance of flow j
  - Queuing delay on bottleneck link
  - Route changes: $|R_p(t) - R_p(t-1)|$

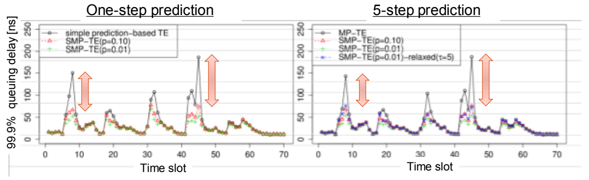


- Compared method
  - simple prediction-based TE : uses only one-step prediction
  - MP-TE : without considering the probability distribution of prediction error

[3] "Internet2 data," available from http://internet2.edu/observatory/archive/data-coll ections.html
[4] S. Han-Lin, et al., "Network traffic prediction by wavelet-based combined model," *Chinese Physics B*, vol. 18, no 5, pp. 1110-1124, Sep. 2005

Queueing delay on bottleneck link

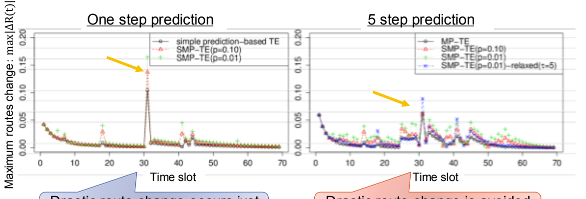
- SMP-TE keeps delay low even when the prediction error exists
- Other methods causes congestion due to the prediction error



99.9% queueing delay : the value of delay which 99.9% of packets experience delay lower than this value

Routes change

- Drastic change occurs when using only one step prediction
- TE considering multi-step future avoids the drastic change



Drastic route change occurs just before the congestion occurs

Drastic route change is avoided by proactive route change

Routes changes more frequently occurred when using multi-step prediction

Effect of relaxing stochastic constraints

- SMP-TE with relaxation avoids unnecessary route changes
  - Maximum routes change is slightly increased due to the delay of response
- Tuning τ balances the frequency and response delay

Route changes occurred in each method(p=0.01,h=5)

	average	maximum	frequency
MP-TE	0.074%	6.28%	33.3%
SMP-TE-relaxed($\tau = 5$)	0.10%	11.6%	52.2%
SMP-TE-relaxed($\tau = 20$)	0.11%	8.91%	62.3%
SMP-TE	0.12%	5.97%	78.2%

average : average of $|\Delta R_p(t)|$ on all time slots and paths
maximum: $\max_{p,t} |\Delta R_p(t)|$
frequency : ratio of time slots where $|\Delta R_p(t)| > 0.01$ on some paths

Summary and future work

- Summary
  - Proposition of SMP-TE
    - We introduce the idea of SMPC into TE
    - We propose a relaxation method of stochastic constraints
  - Evaluation of SMP-TE
    - We show that SMP-TE avoids the congestion even when prediction errors exist
    - We show that considering multi-step future avoids the drastic route change, while it causes unnecessary routes changes especially in SMP-TE
    - We show that relaxation of constrains reduce the unnecessary routes changes
- Future work
  - Decision of τ by considering the impact of route change in actual networks
  - Improving the scalability of SMP-TE by distributed control