Dynamic Content Allocation for Cloud-assisted Service of Periodic Workloads

György Dán

Royal Institute of Technology (KTH)

Niklas Carlsson

Linköping University

LiU EXPANDING REALITY

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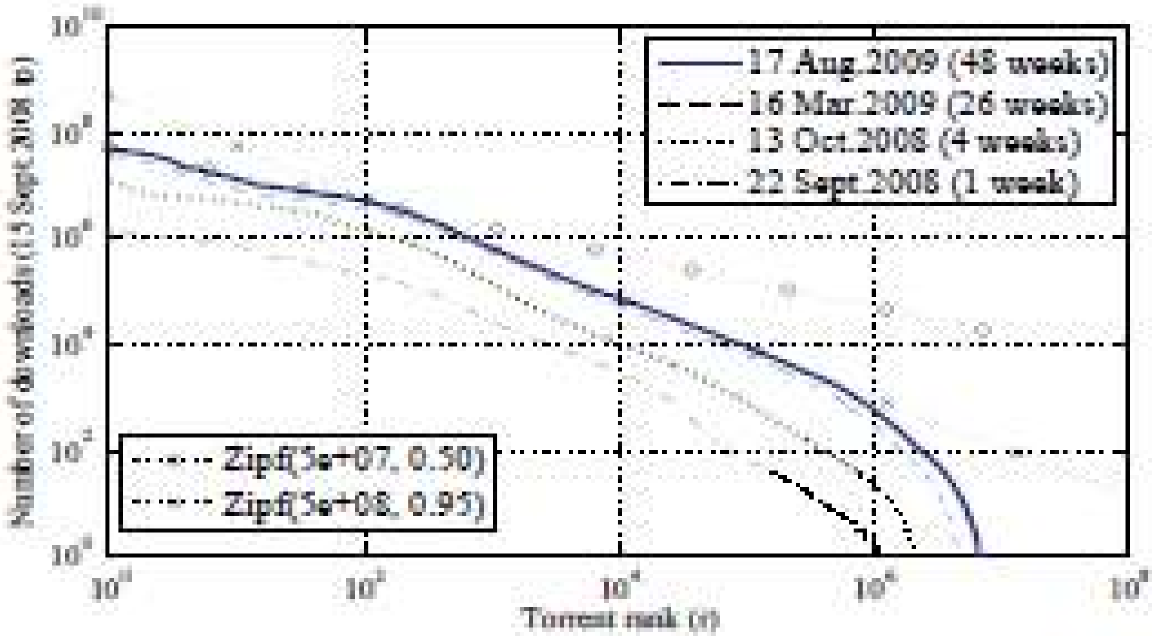
Internet Content Delivery



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- Large amounts of data with varying popularity
- Multi-billion market ($8B to $20B, 2012-2015)
  - Goal: Minimize content delivery costs
- Migration to cloud data centers
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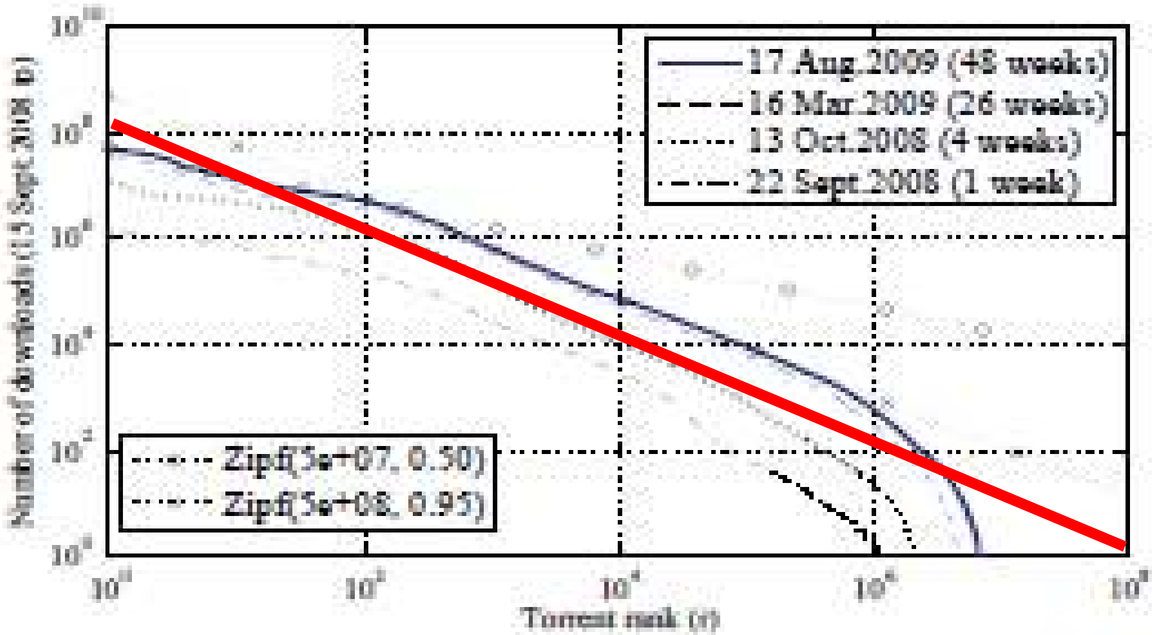

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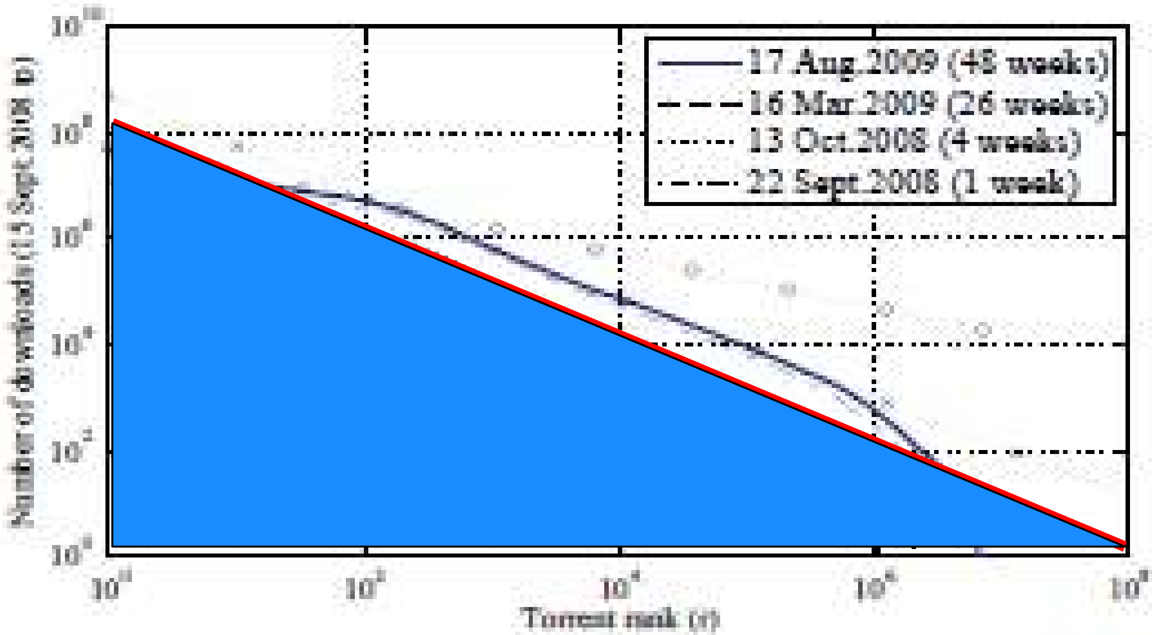

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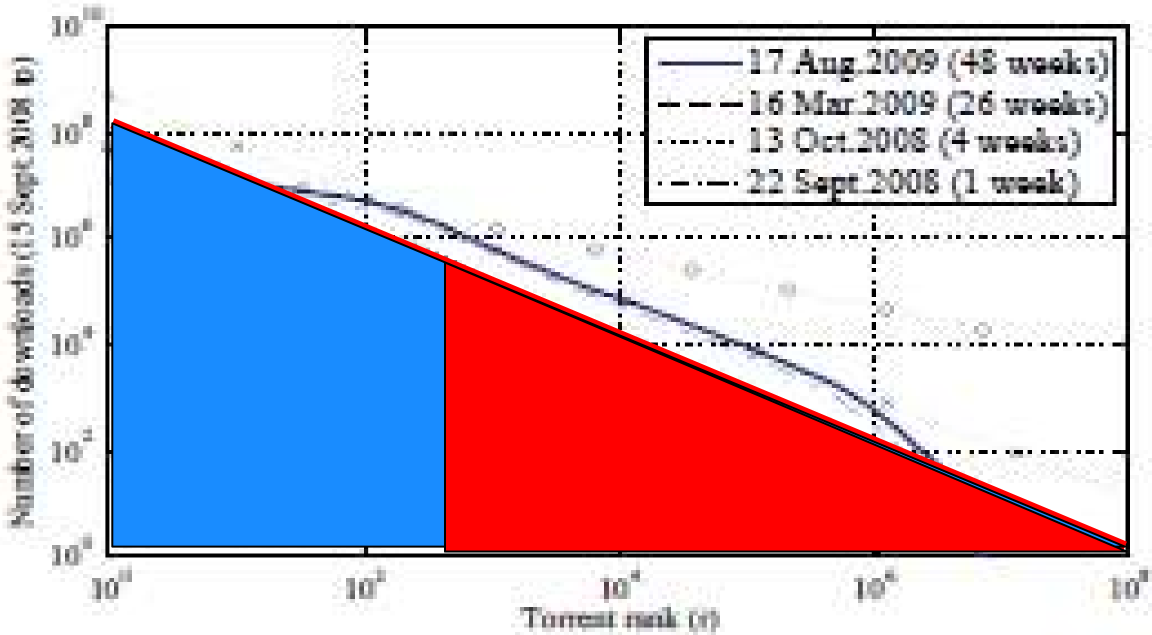

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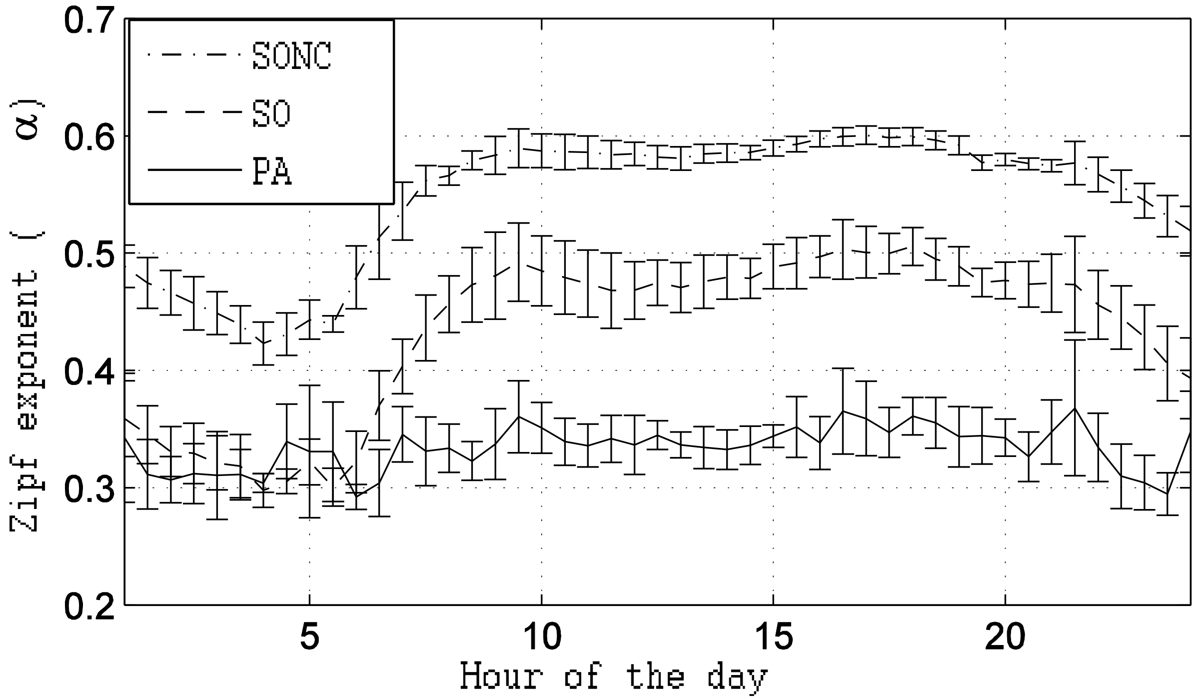
Periodic Workloads

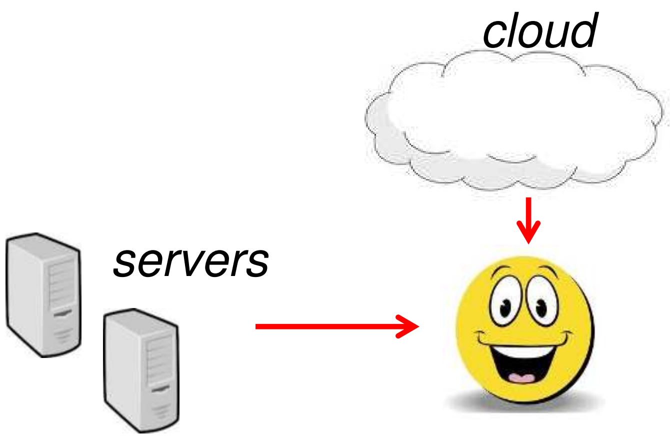
- Characterization of Spotify traces
- In addition to diurnal traffic volumes …
- … we found that also the Zipf exponent vary with time-of-day



Content Delivery

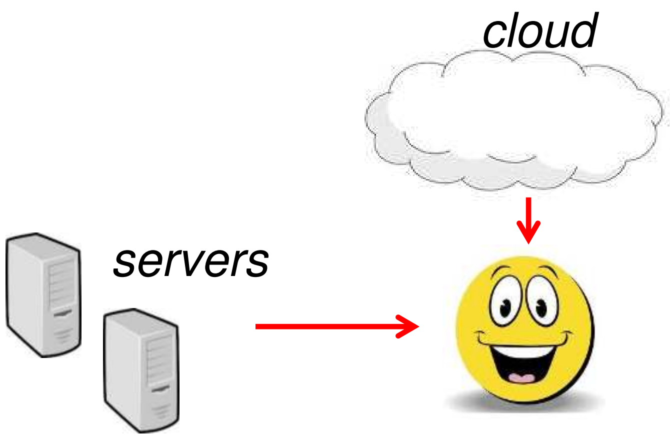
- Cloud-based delivery

- Dedicated infrastructure



Content Delivery

- Cloud-based delivery
  - Flexible computation, storage, and bandwidth
  - Pay per volume and access
- Dedicated infrastructure
  - Limited storage
  - Capped unmetered bandwidth
  - Potentially closer to the user



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Cloud bandwidth elastic; however, flexible comes at premium …

High-level problem

- Minimize content delivery costs

	Bandwidth	Cost
Cloud-based	Elastic/flexible	$$$
Dedicated servers	Capped	$

-

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How to get the best of two worlds?

High-level problem

- Minimize content delivery costs

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  - Improved workload models and prediction enables prefetching …
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High-level problem

- Minimize content delivery costs

	Bandwidth	Cost
Cloud-based	Elastic/flexible	$$$
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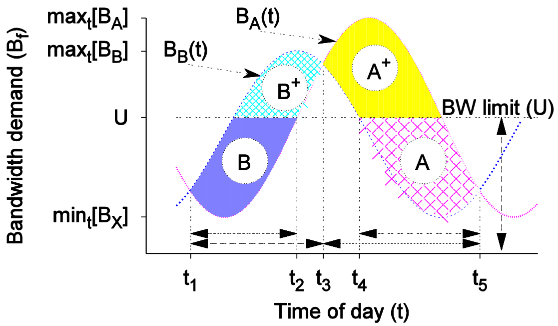
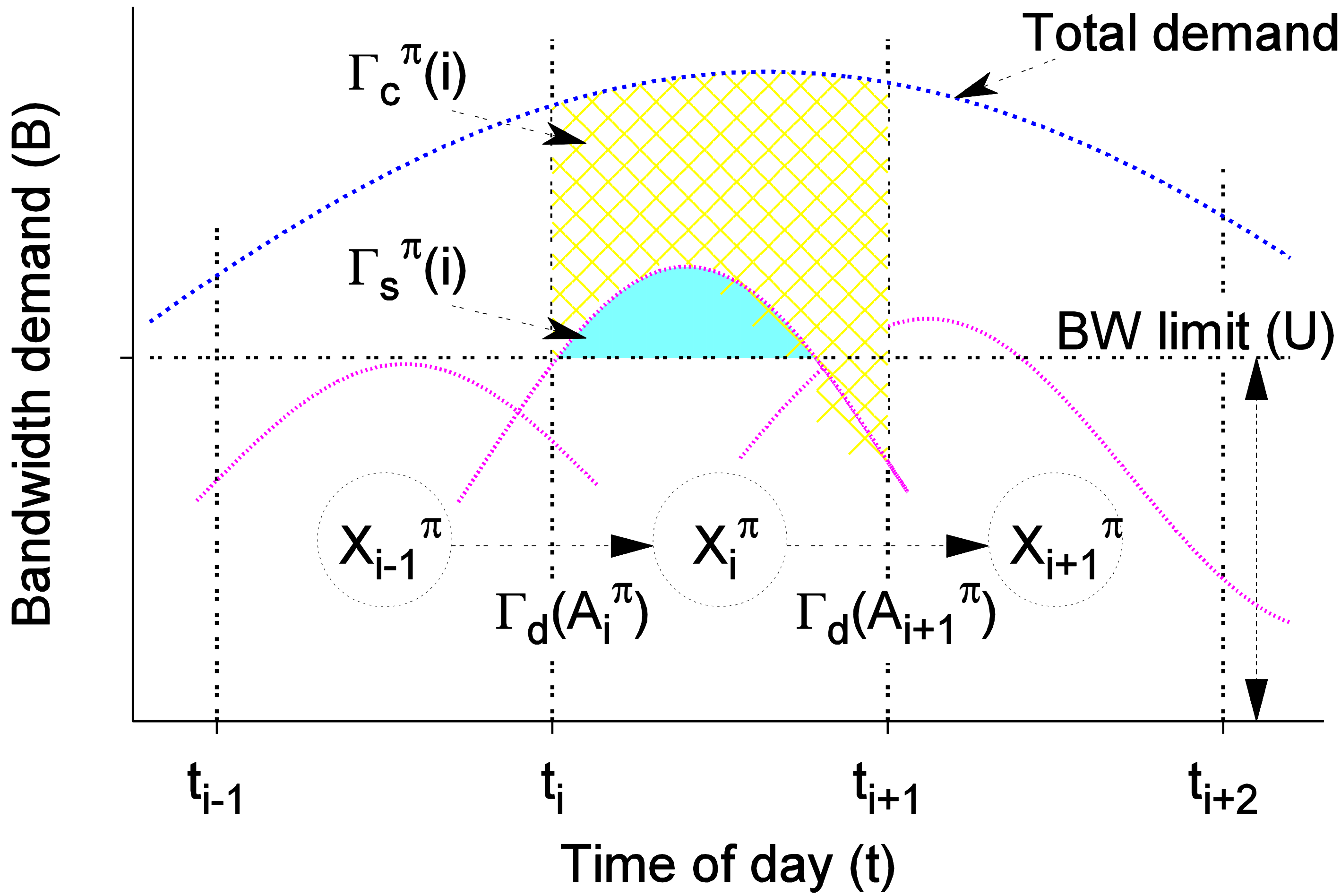
- How to get the best out of two worlds?
  - Improved workload models and predcition enables prefetching …
- Dynamic content allocation
  - Utilize capped bandwidth (and storage) as much as possible
  - Use elastic cloud-based services to serve “spillover”
-

Dynamic Content Allocation Problem



- Formulate as a finite horizon dynamic decision process problem
- Show discrete time decision process is good approximation
- Define exact solution as MILP
- Provide computationally feasible approximations (and prove properties about approximation ratios)
- Validate model and policies using traces from Spotify

Cost minimization formulation



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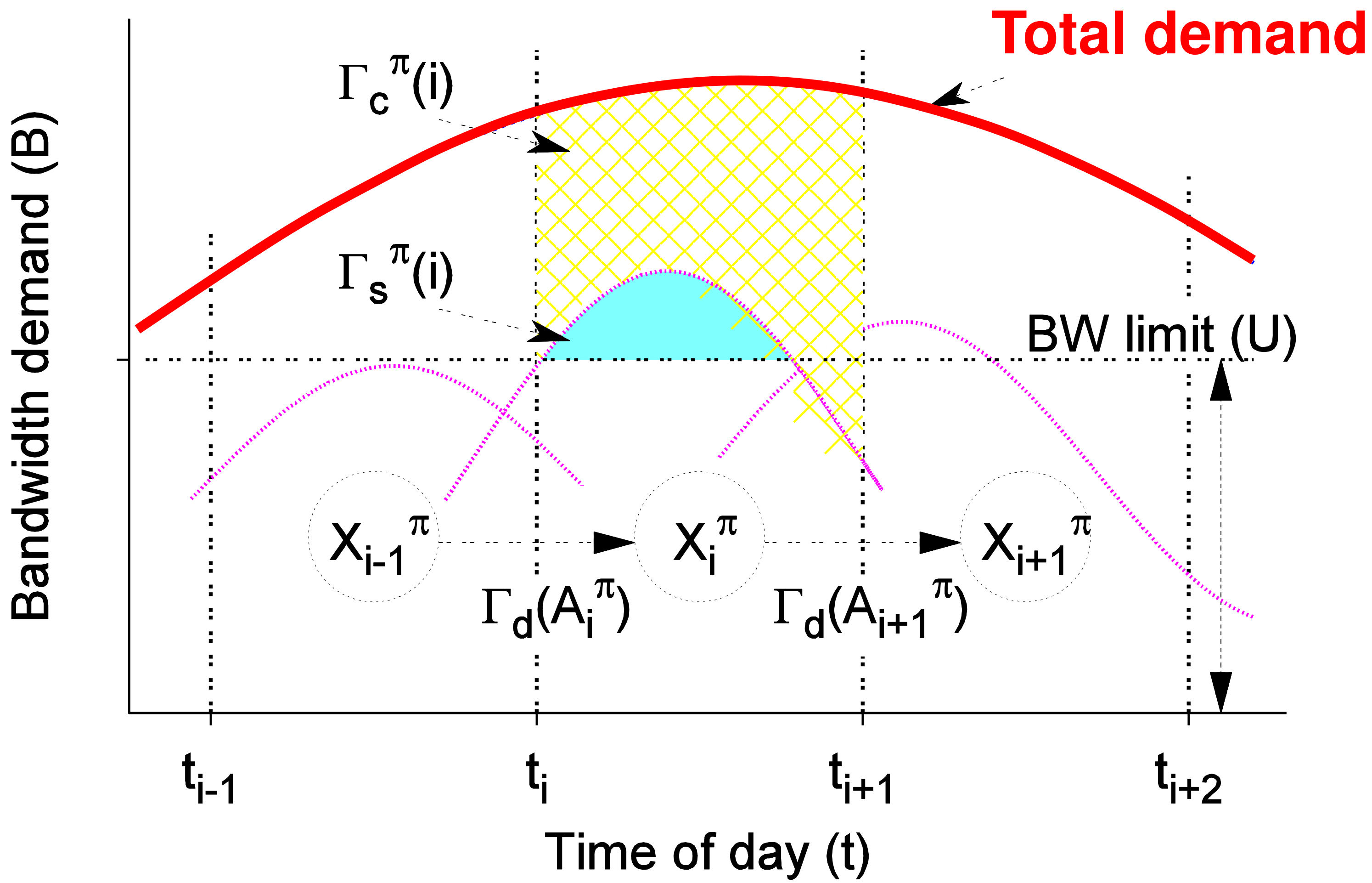

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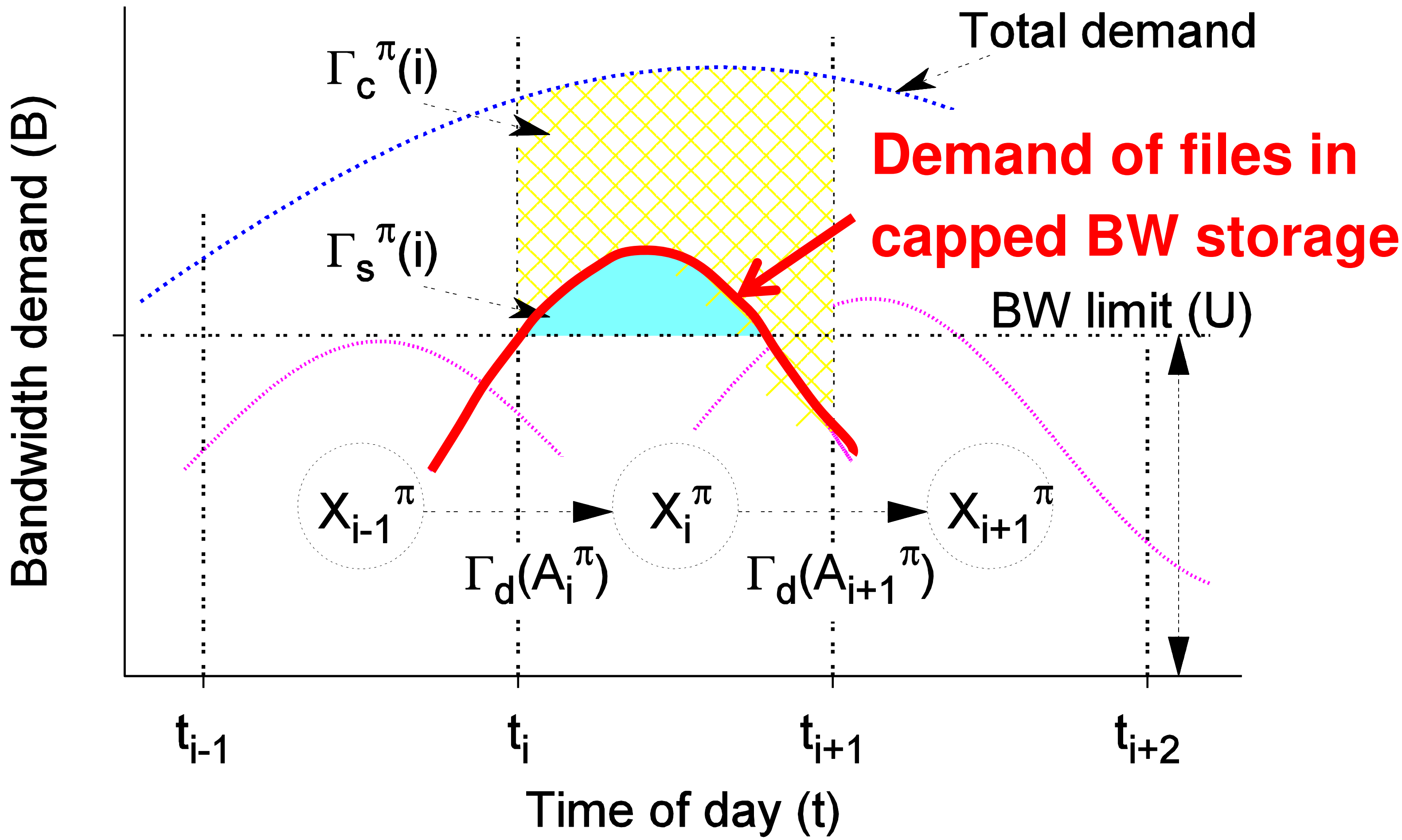

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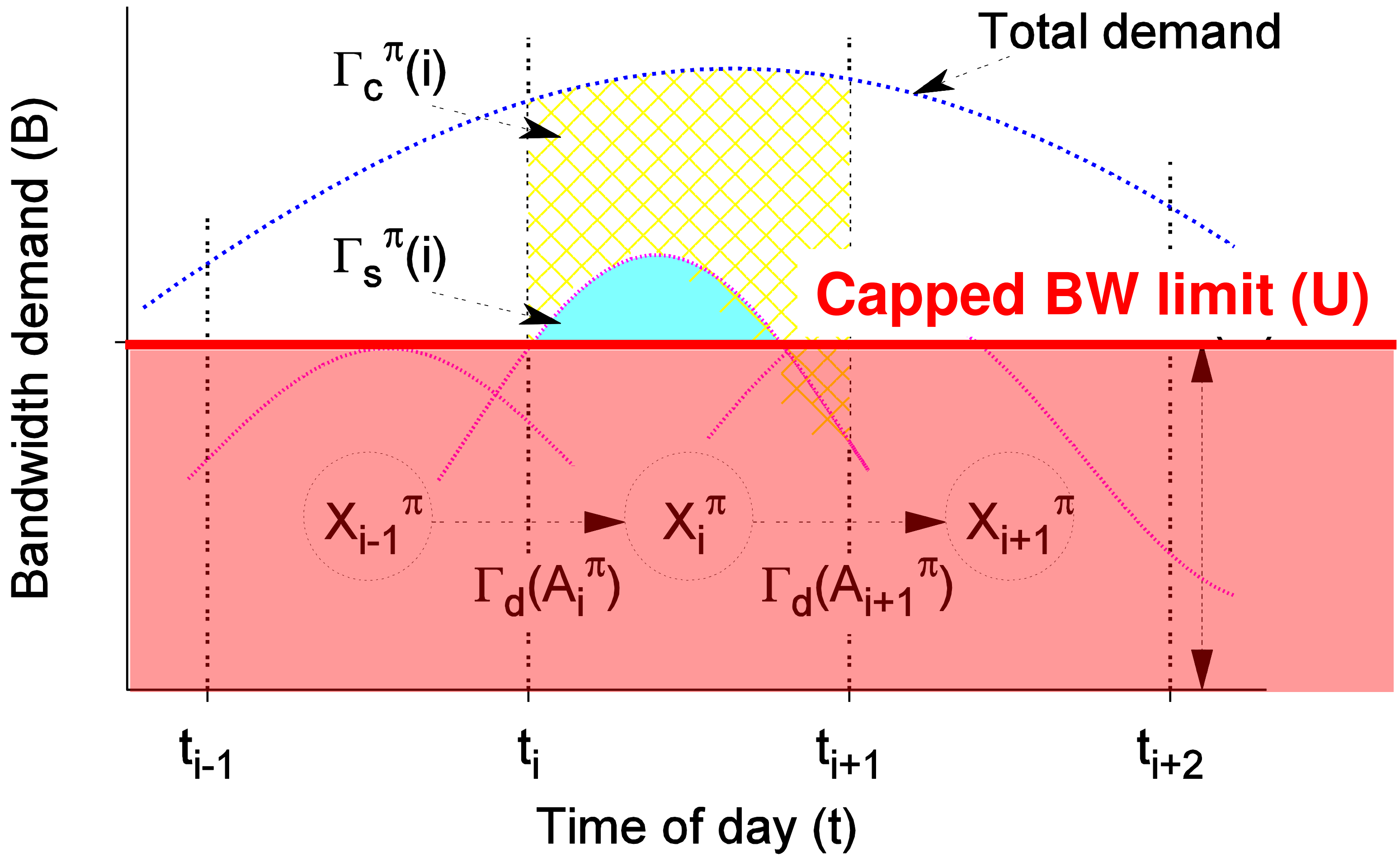

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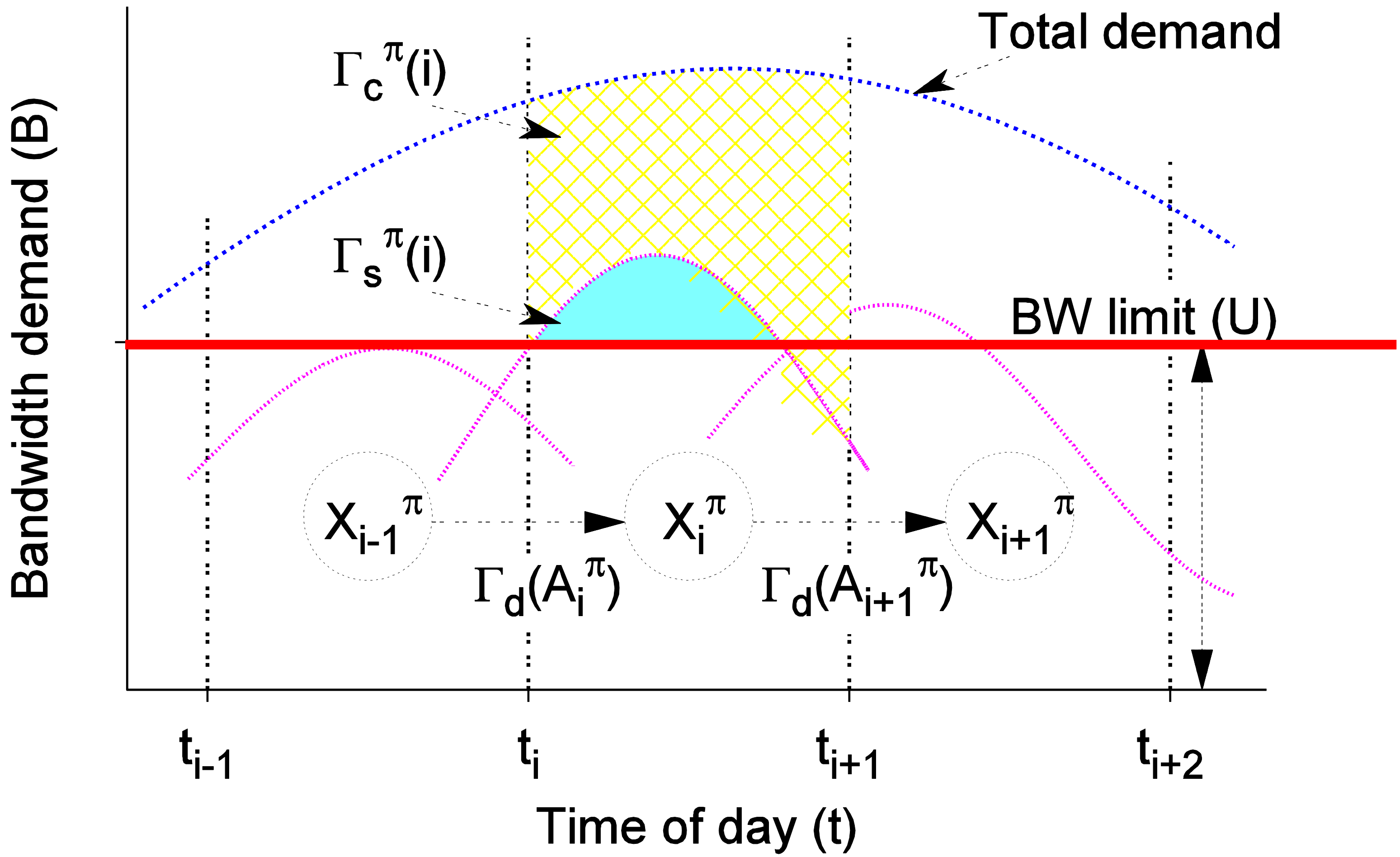

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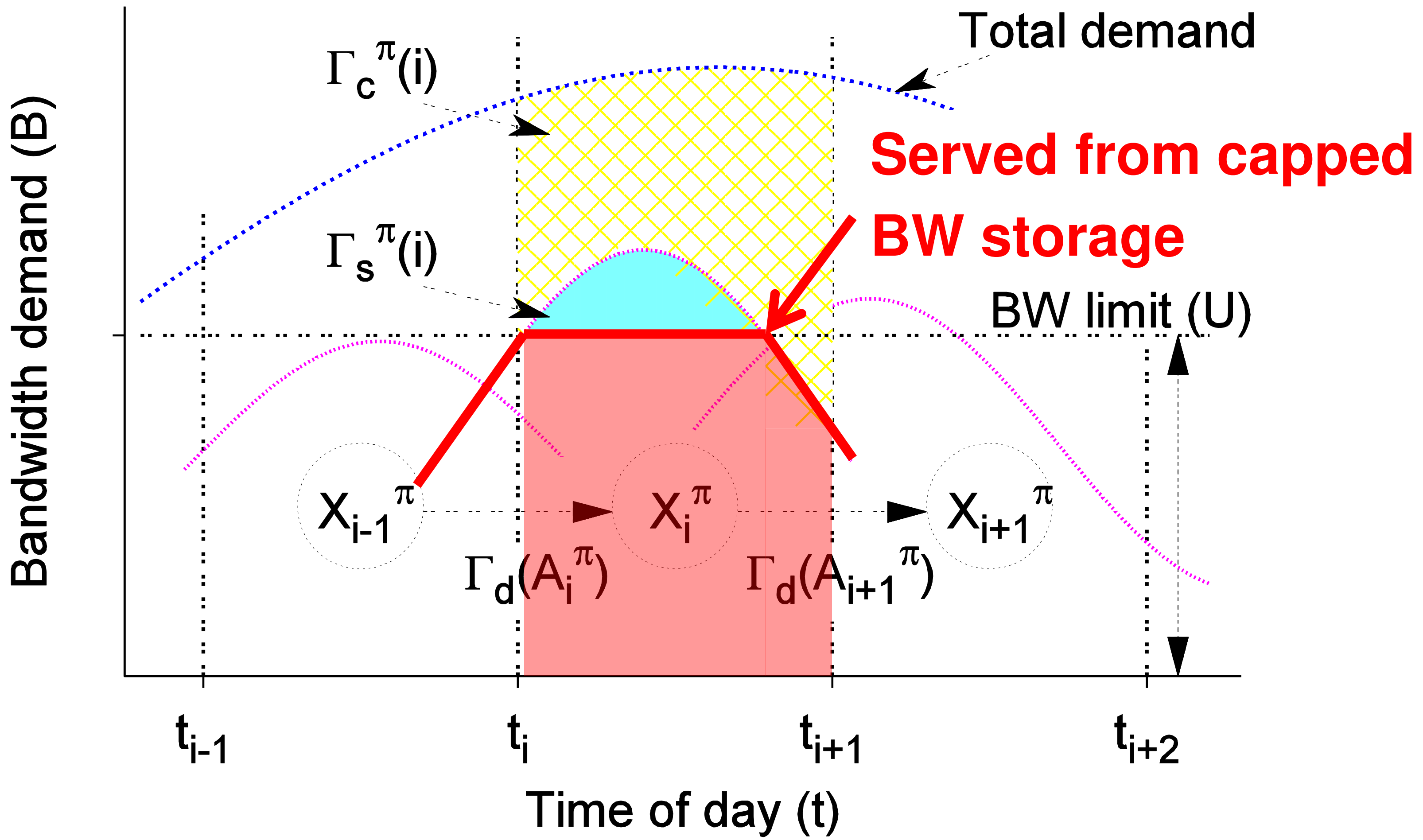

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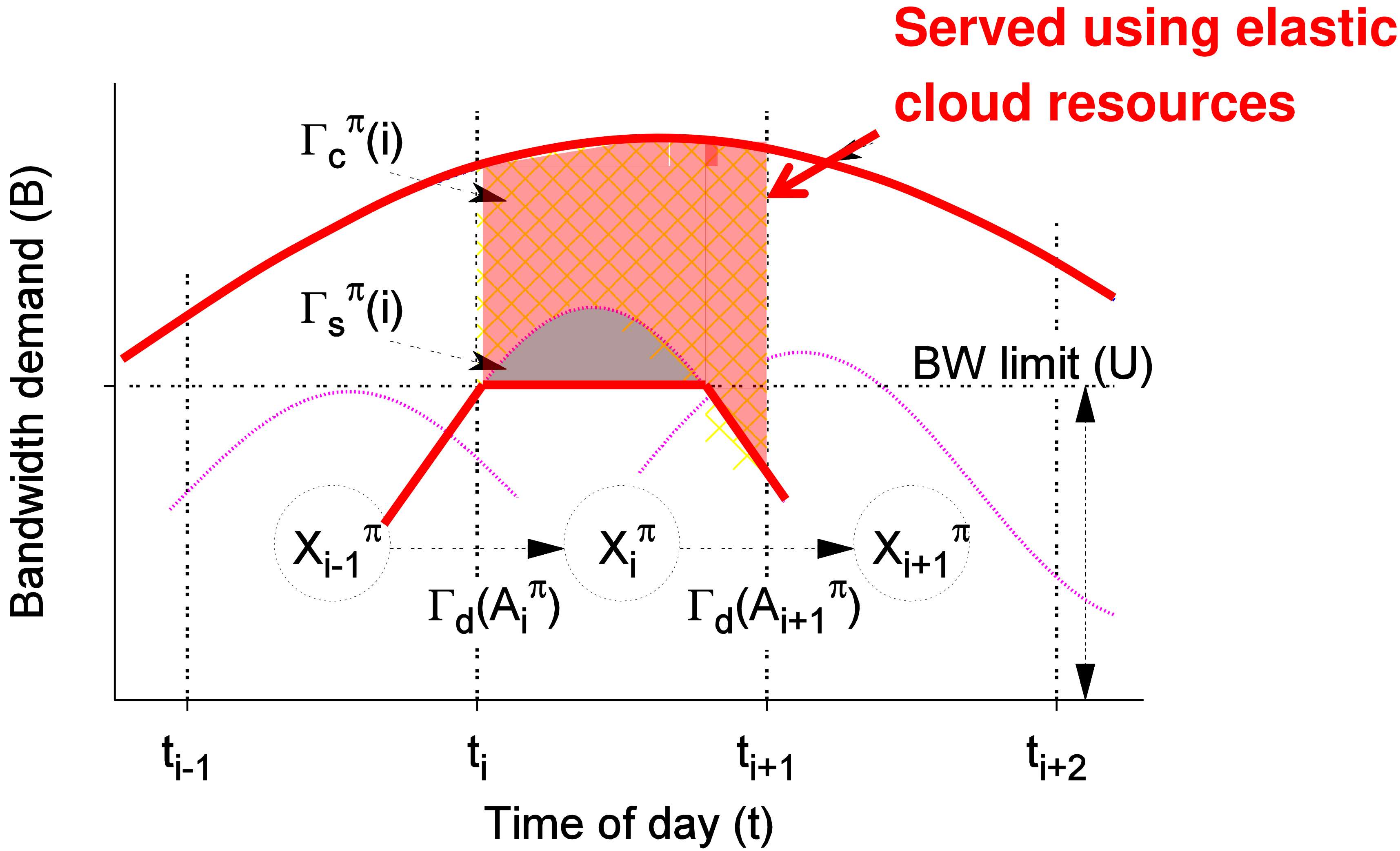

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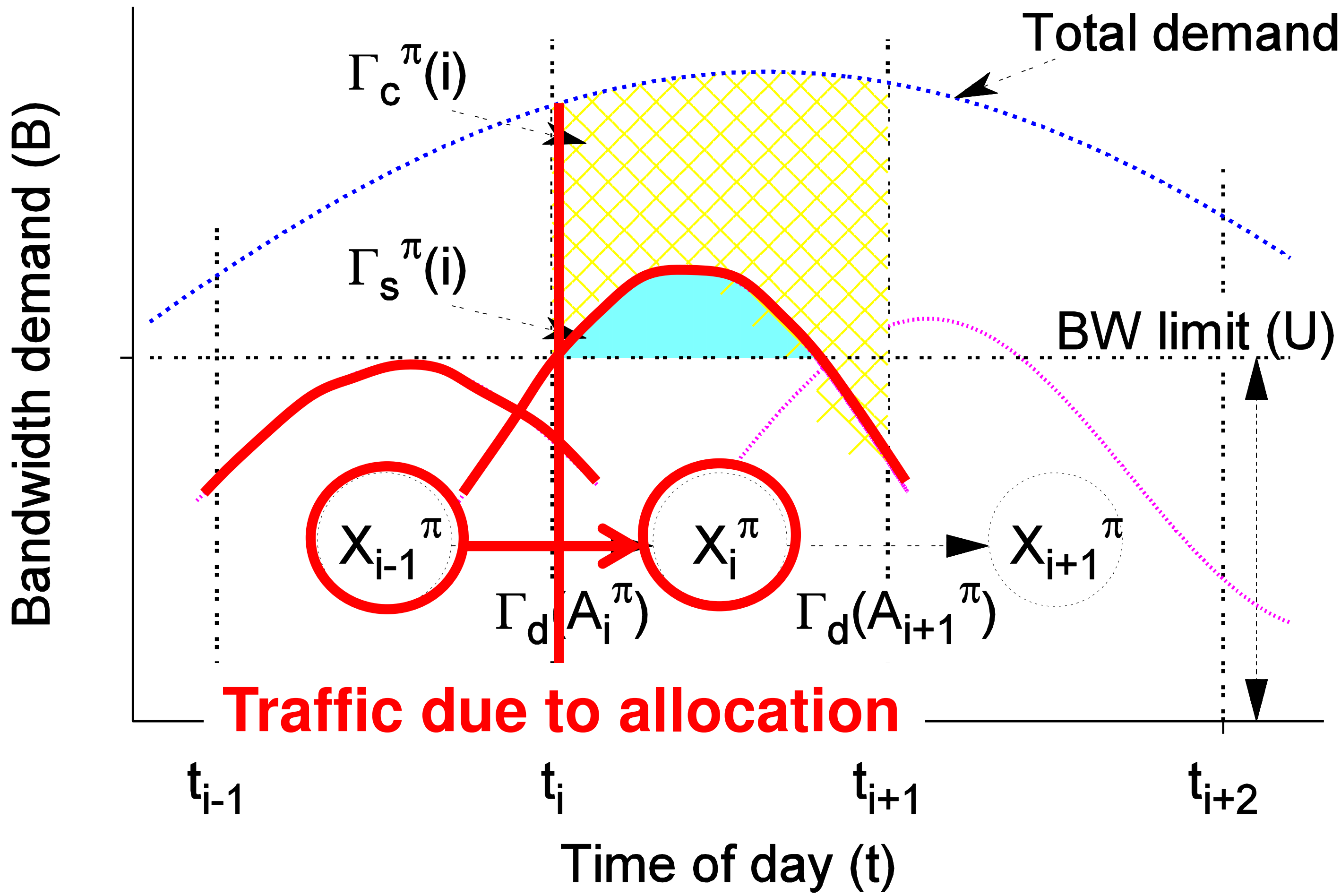

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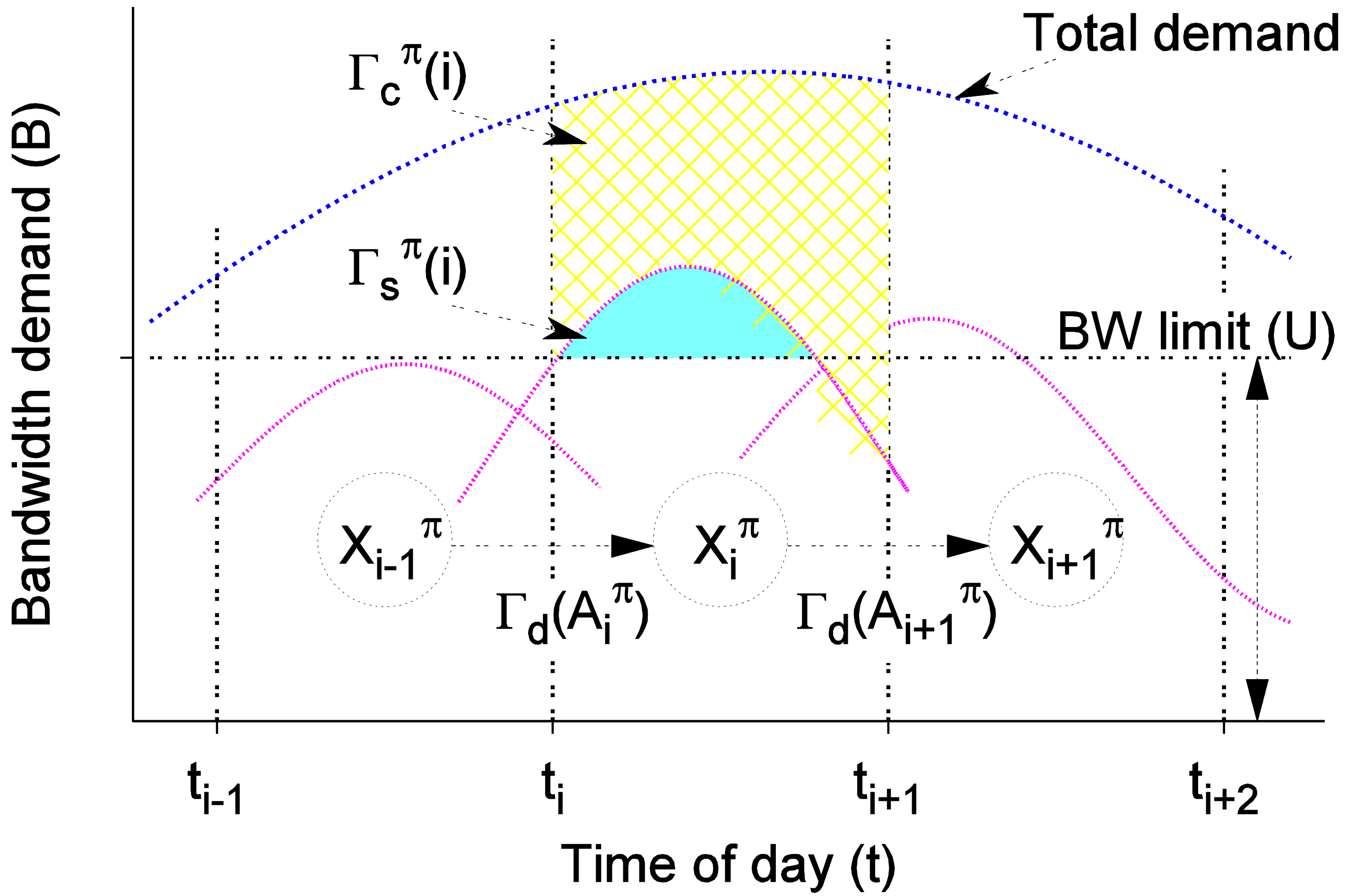

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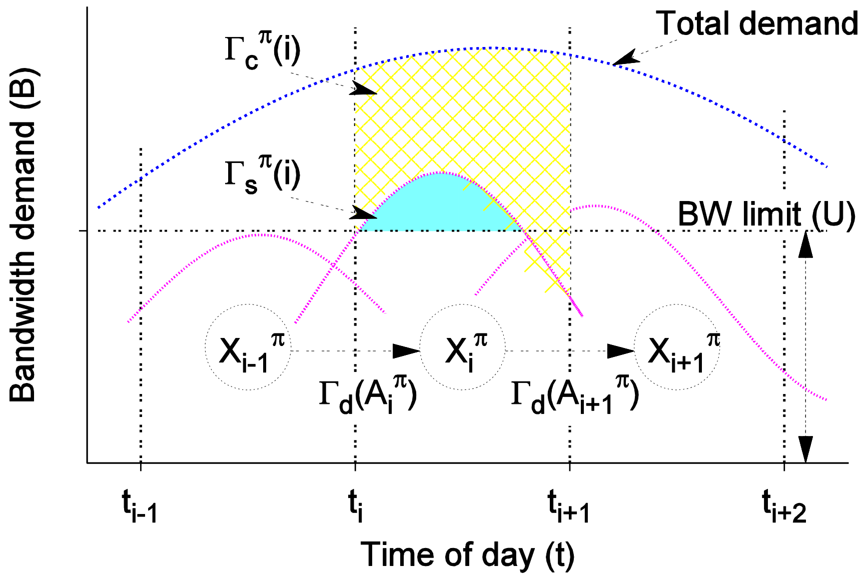

- Traffic of files only in cloud

$$\Gamma_c^{\pi}(i) = E\left[\int_{t_i^{\pi}}^{t_{i+1}^{\pi}} \sum_{f \notin \mathcal{X}_i^{\pi}} B_f(t)\right]$$

- Spillover traffic

$$\Gamma_s^{\pi}(i) = E\left[\int_{t_i^{\pi}}^{t_{i+1}^{\pi}} \left(\sum_{f \in \mathcal{X}_i^{\pi}} B_f(t) - U\right)^{+} dt\right]$$

- Traffic due to allocation

$$\Gamma_d^{\pi}(A_i^{\pi}) = \sum_{f \in A_i^{\pi}} L_f$$

- Total expected cost

$$J^{\pi}(T, \mathcal{X}_0) = \gamma \times \sum_{i=0}^{I^{\pi}} \left\{\Gamma_d^{\pi}(A_i^{\pi}) + \Gamma_c^{\pi}(i) + \Gamma_s^{\pi}(i)\right\}$$

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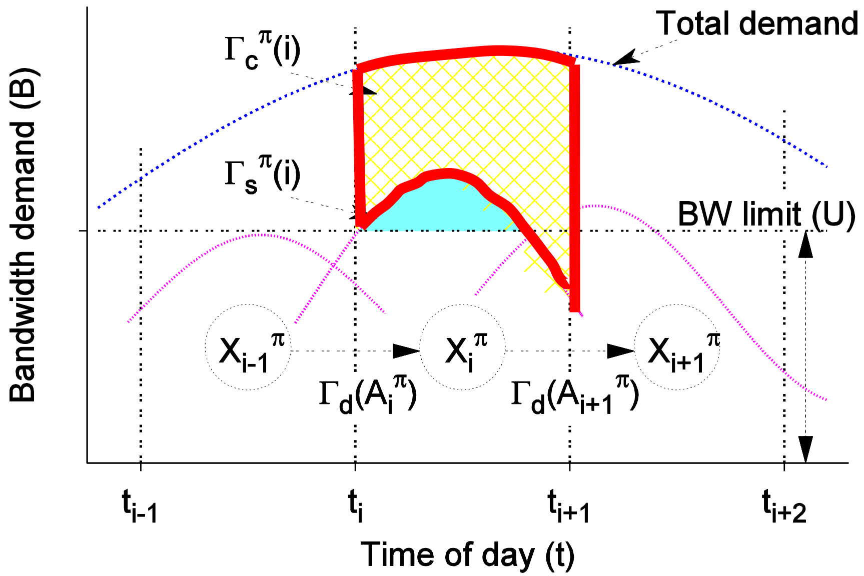

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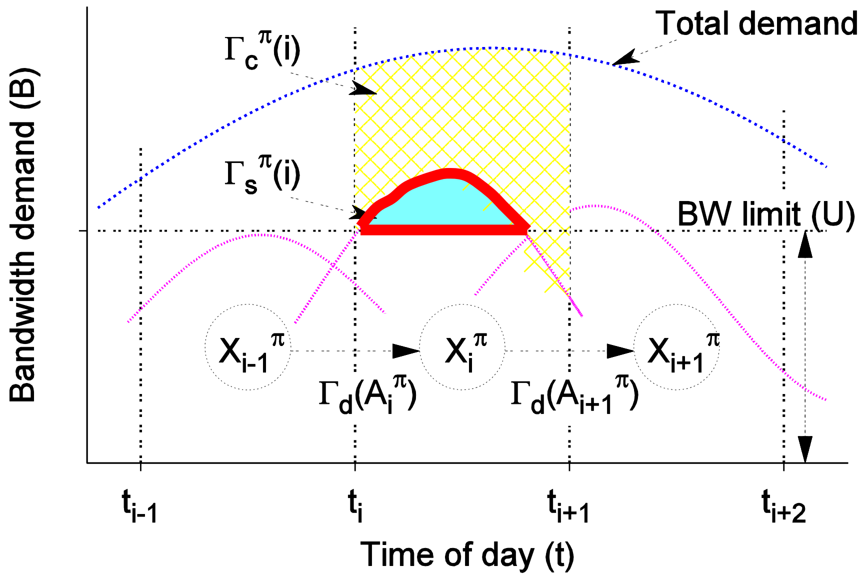

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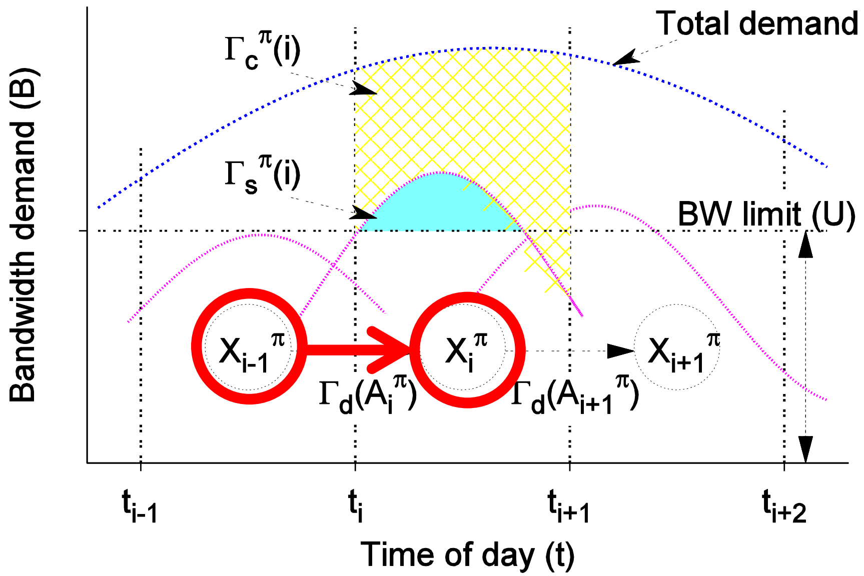

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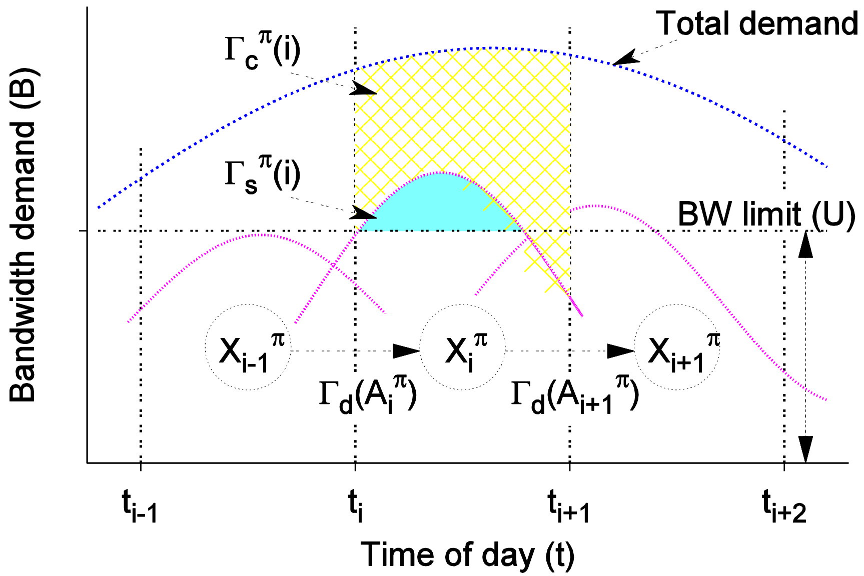

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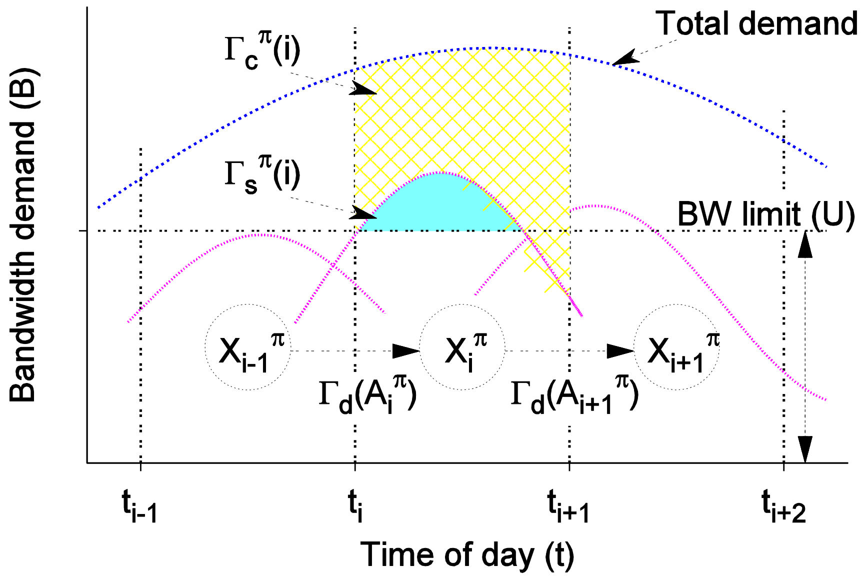

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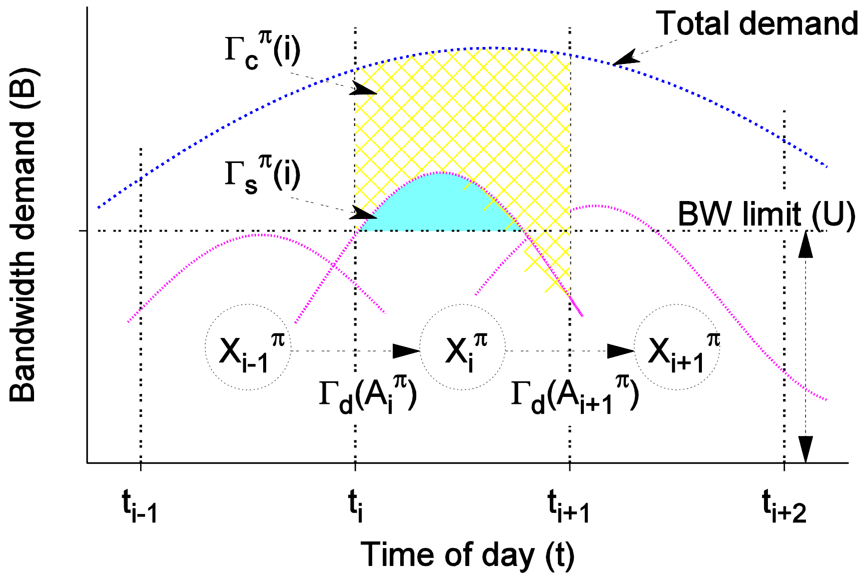

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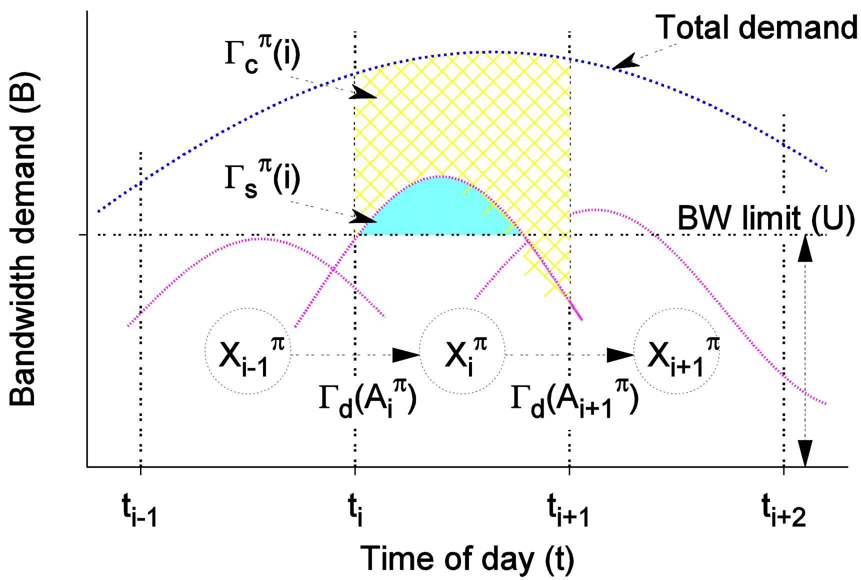

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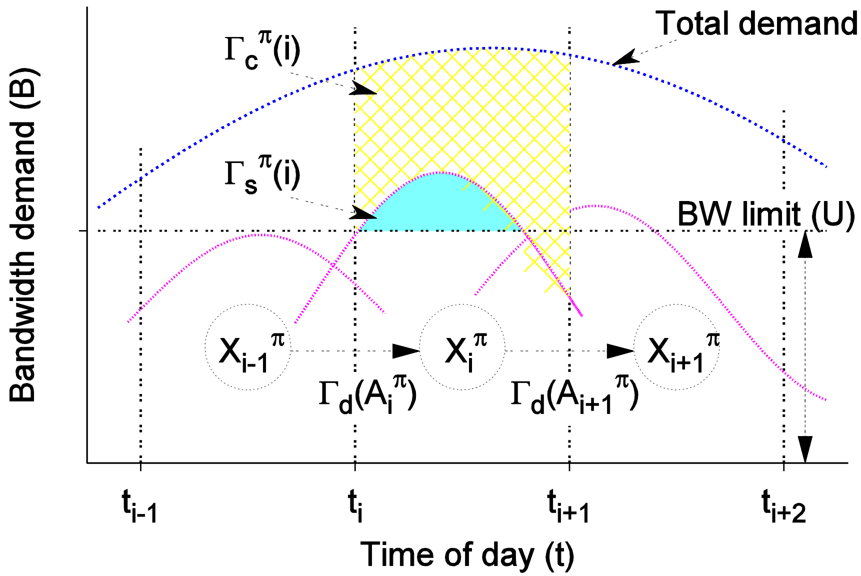
Utilization maximization
~~Cost minimization formulation~~



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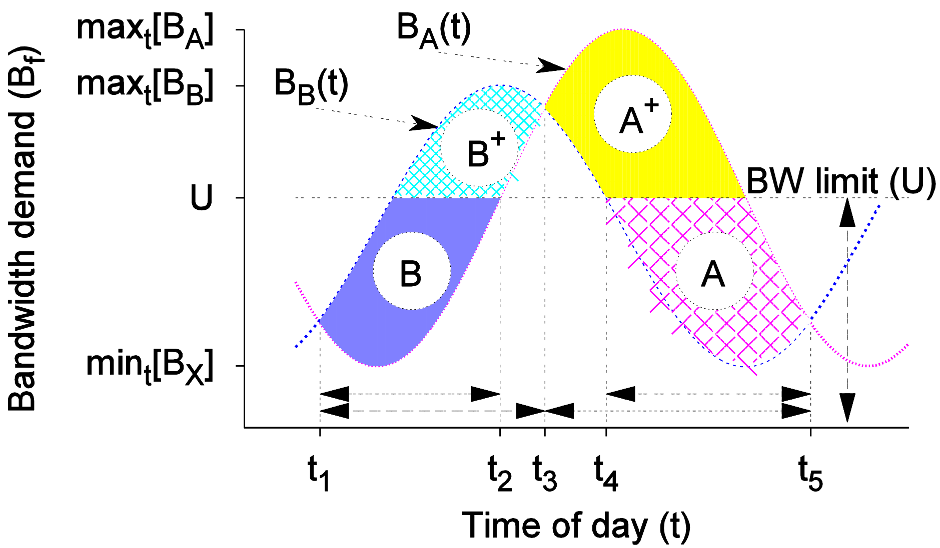

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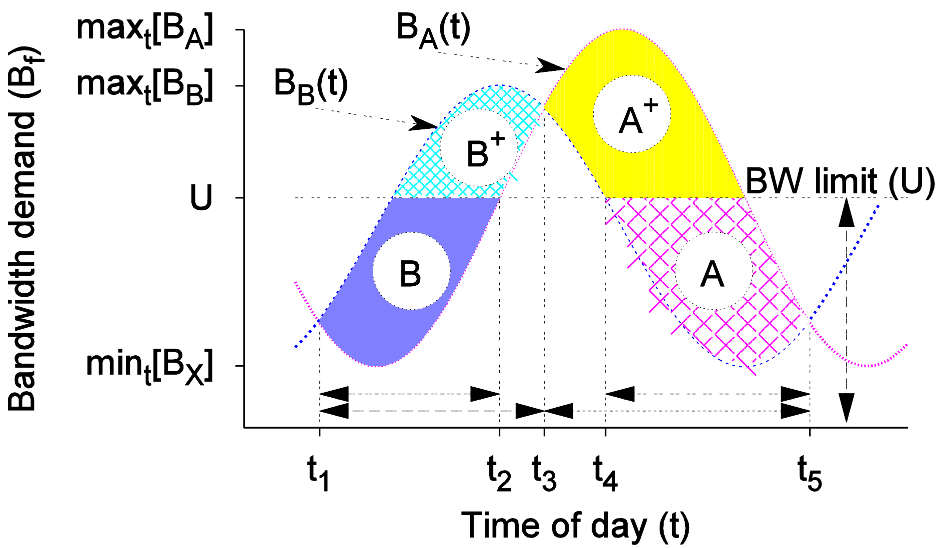

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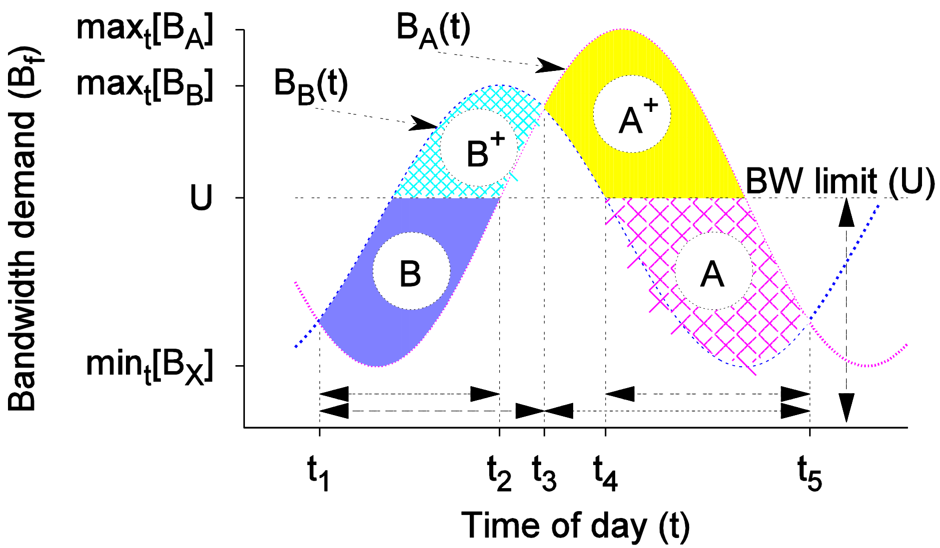

Two file example

- Equivalent formulation

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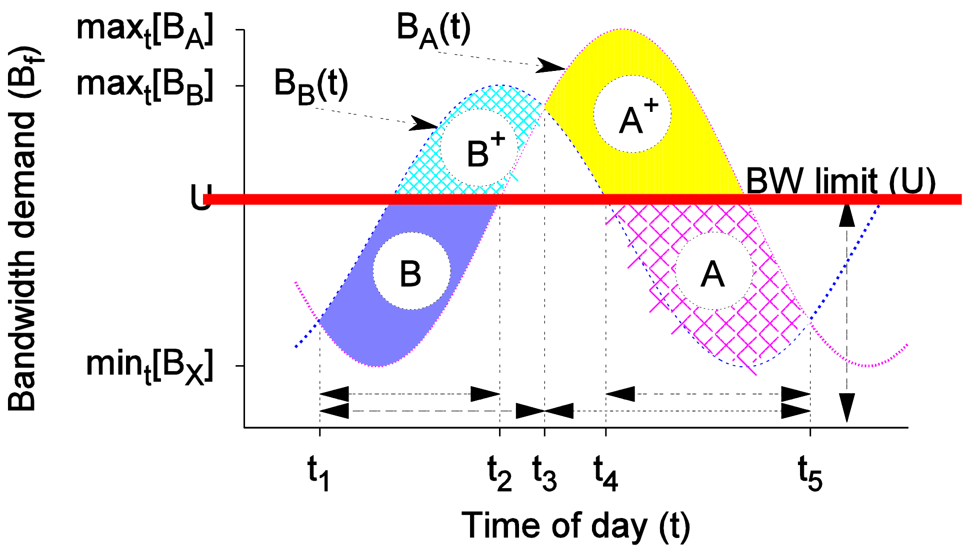

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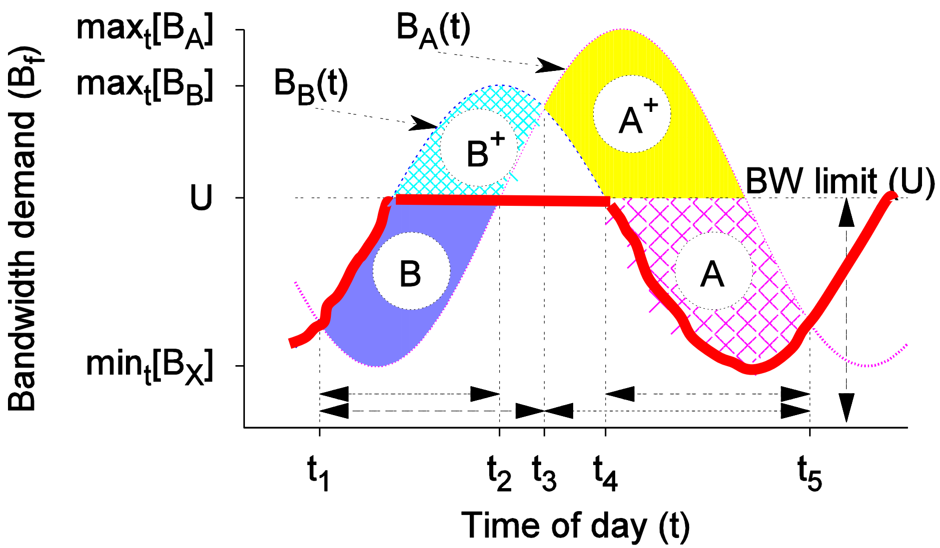
Optimal policy $\pi^* = \arg\max_{\pi \in \Pi} U^{\pi}(T, \mathcal{X}_0)$

Utilization maximization

~~Cost minimization formulation~~



Two file example

- Equivalent formulation

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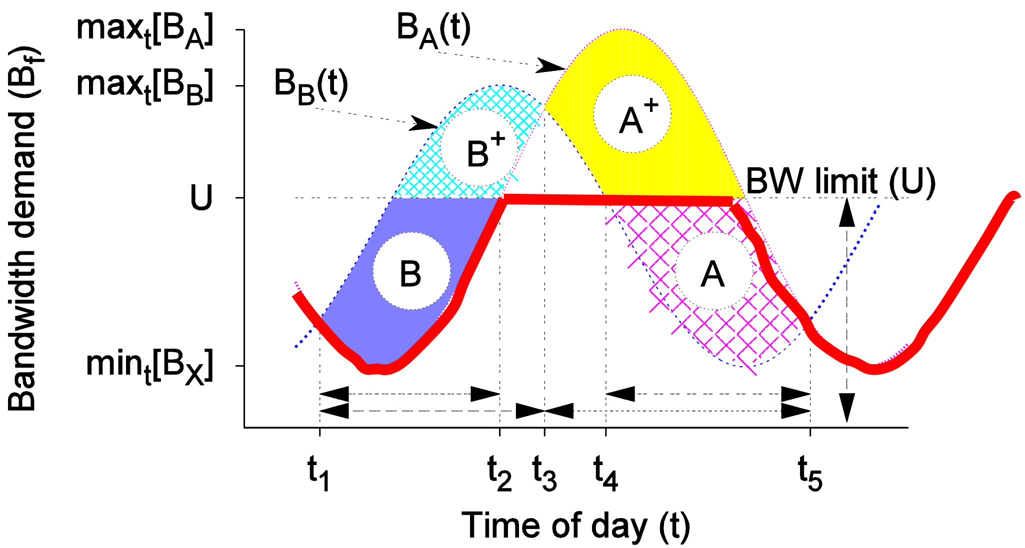

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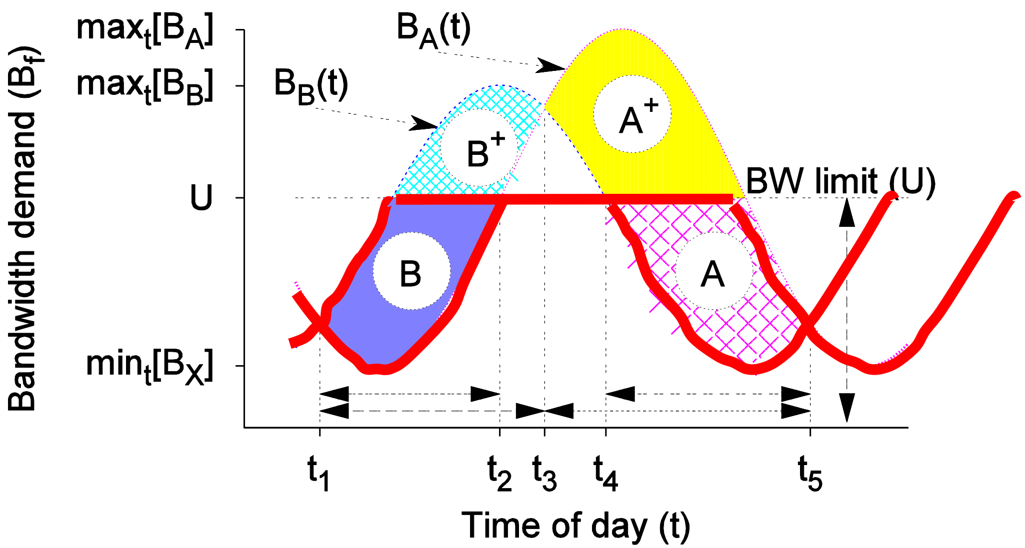

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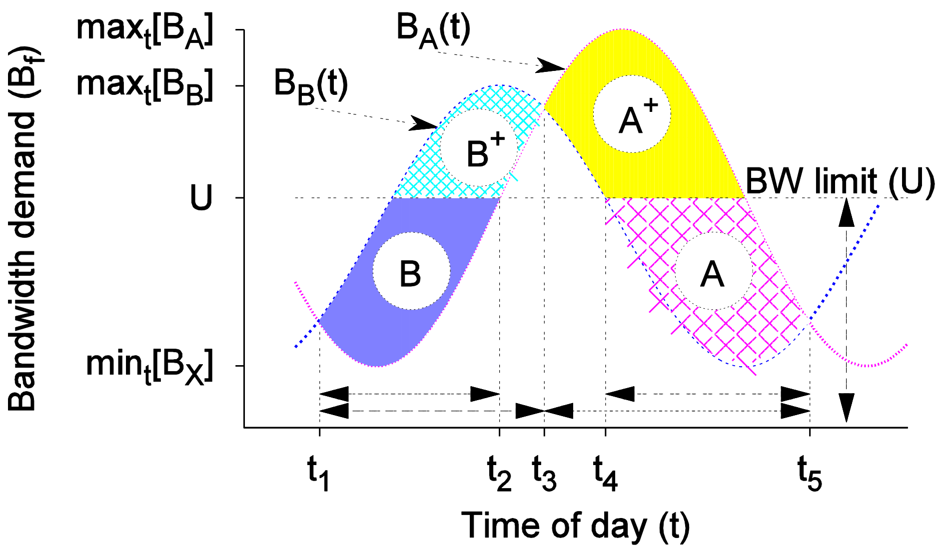
Discrete-time Decision Problem



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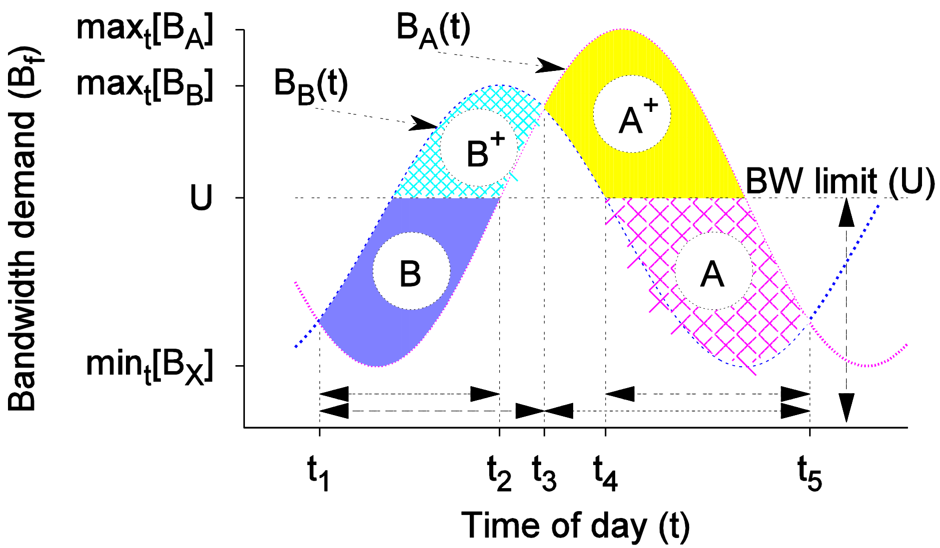

- Approximation

$$\sum_{f\in\mathcal{X}(t)} B_f(t) \approx \sum_{f\in\mathcal{X}_i} \overline{B}_f^i \text{ for } t_i \le t < t_{i+1}$$

$P(\sum_{f\in\mathcal{X}} B_f(t) \le U)$ *decrease exponentially*

- Finite horizon decision

$$U^{\pi^*}([t_i, t_{I+1}], \mathcal{X}_{i-1}) = \max_{\mathcal{X}_i} \{\overline{\Gamma}_s(i) - \Gamma_d(A_i) + U^{\pi^*}([t_{i+1}, t_{I+1}], \mathcal{X}_i)\}$$

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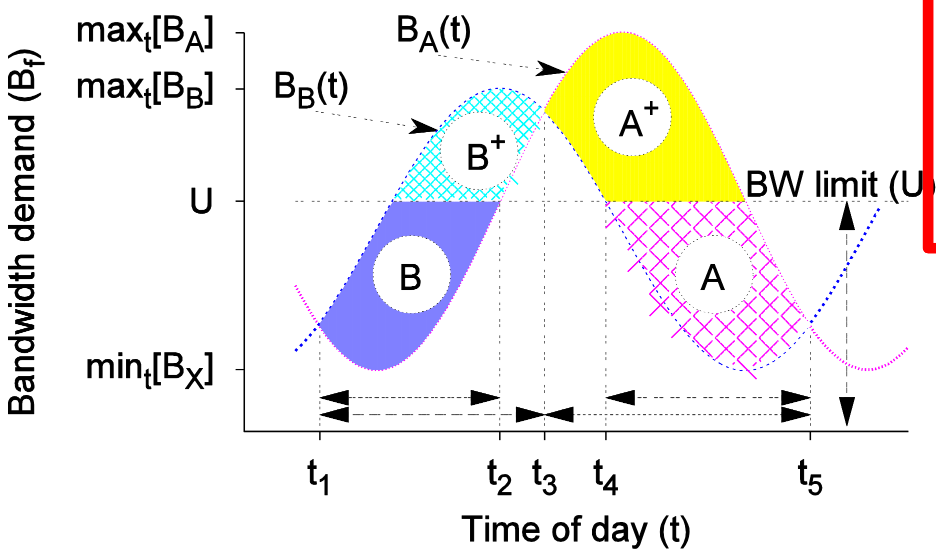

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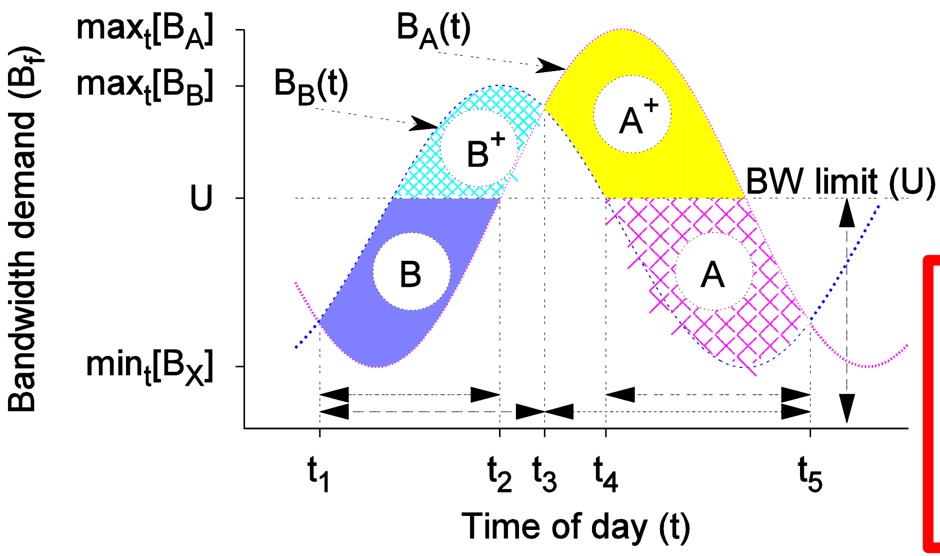

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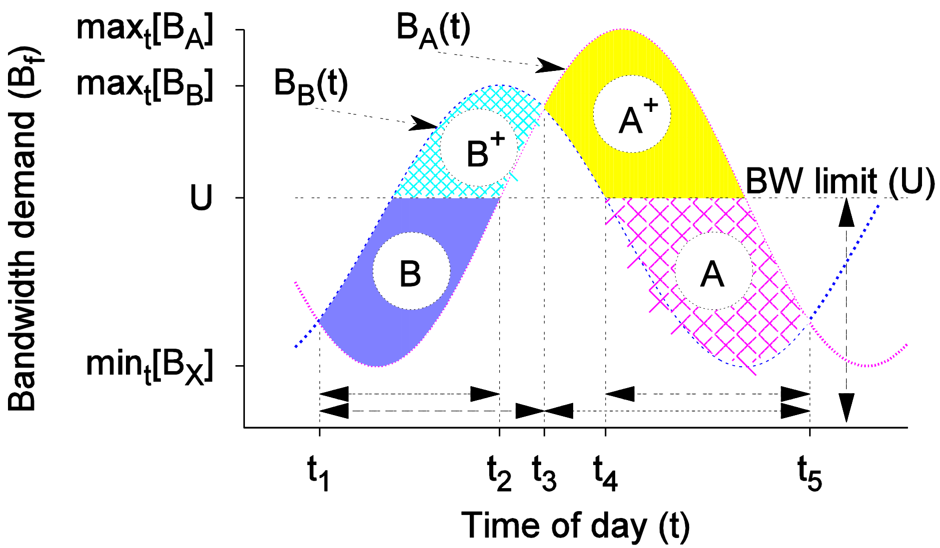

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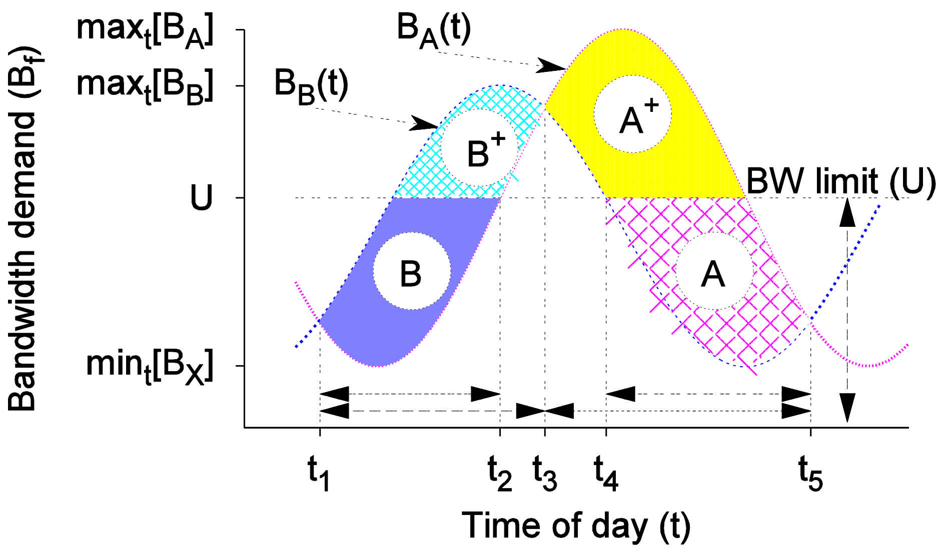

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Theorem: *Exact solution as a MILP*

Let $\Delta_i = t_{i+1} - t_i$. Every solution of the MILP

$$\max \sum_{i=1}^{I} \left\{ \Delta_i \left(\sum_{f\in\mathcal{F}} \overline{B}^i_f x_{i,f} - s_i \right) - \sum_{f\in\mathcal{F}} L_f b_{i,f} \right\}$$

s.t.

$$\sum_{f\in\mathcal{F}} \overline{B}^i_f x_{i,f} - s_i \le U, \quad \forall 1 \le i \le I \qquad (1)$$

$$x_{i,f} - x_{i-1,f} - b_{i,f} \le 0, \quad \forall 1 \le i \le I, f \in \mathcal{F} \qquad (2)$$

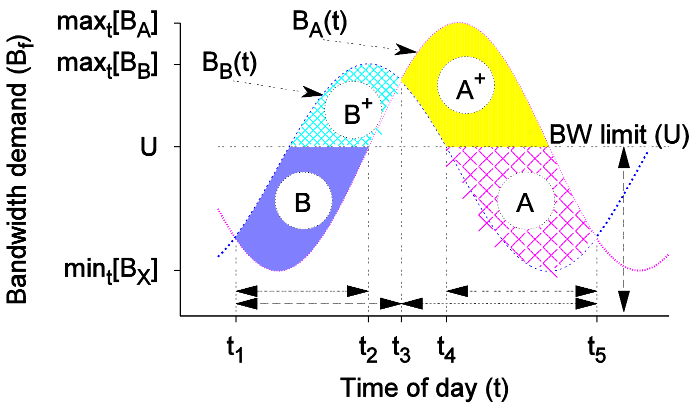
$$\sum_{f\in\mathcal{F}} L_f x_{i,f} \le S, \quad \forall 1 \le i \le I \qquad (3)$$

$$b_{i,f} \ge 0, \quad x_{i,f} \in \{0,1\}, \quad \forall 1 \le i \le I, f \in \mathcal{F} \qquad (4)$$

$$s_i \ge 0, \quad \forall 1 \le i \le I, \qquad (5)$$

is an optimal policy π^*.

Policy: No Download Cost (NDC)



- Consider next interval only

$$\chi_i^{NDC} = \arg\max_{\chi_i} \overline{\Gamma}_s^{\pi}(i)$$

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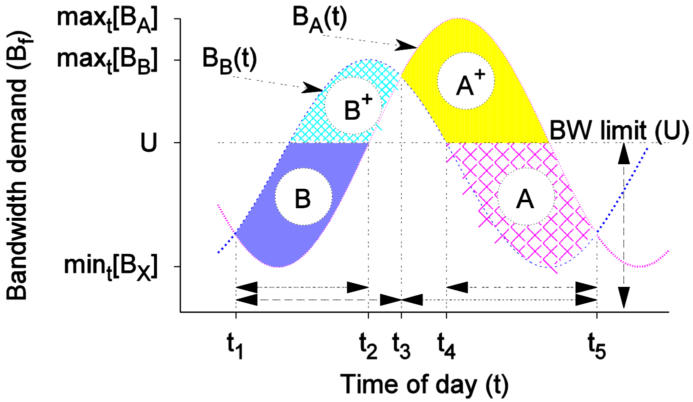

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$$\frac{J^{NDC}}{J^{\pi^*}} = \frac{1+\epsilon}{1.5\epsilon} \Rightarrow \lim_{\epsilon\to 0} \frac{J^{NDC}}{J^{\pi^*}} = \infty$$

- Proposition 2: Approximation bound

The approximation ratio of NDC is $\frac{J^{NDC}}{J^{\pi^*}} \leq 1 + IS/J^{\pi^*}$.

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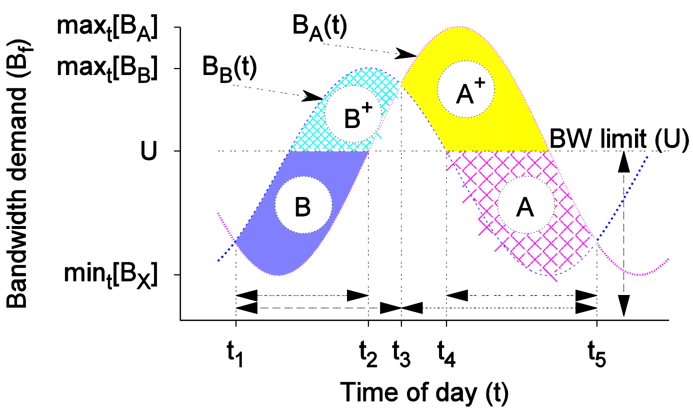

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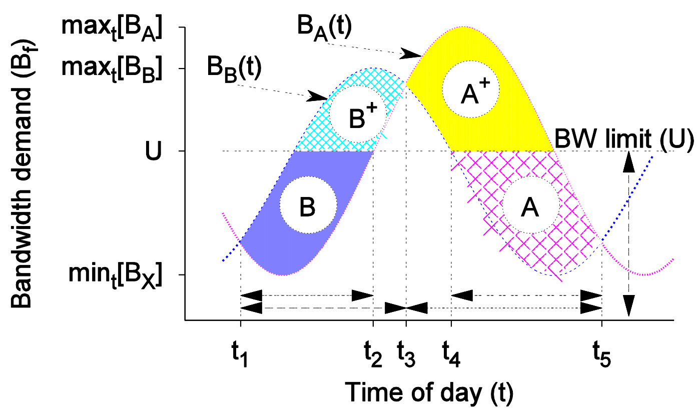

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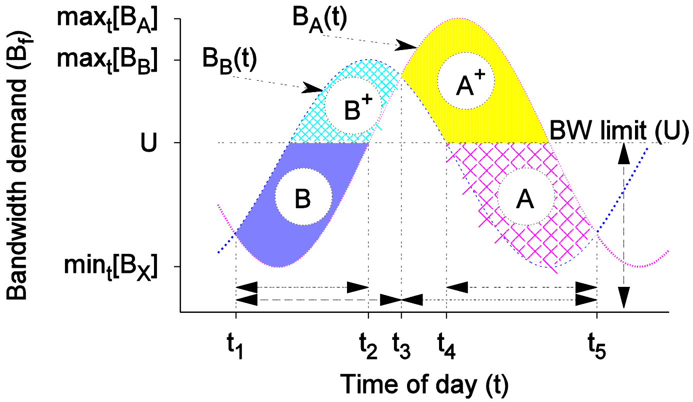

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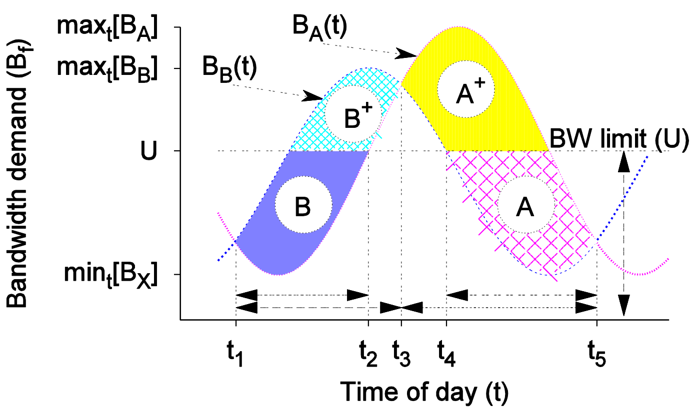
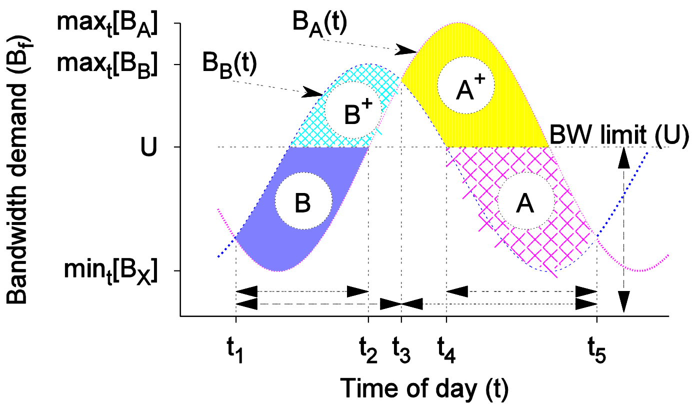
Policy: k-Step Look Ahead (k-SLA)



- Consider k next intervals

$$\chi_i^{1-SLA} = \arg\max_{\chi_i} \left\{ \overline{\Gamma}_s^{\pi}(i) - \Gamma_d^{\pi}(A_i) \right\}$$

Policy: k-Step Look Ahead (k-SLA)



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$$\mathcal{X}_i^{1-SLA} = \arg\max_{\mathcal{X}_i} \left\{ \overline{\Gamma}_s^{\pi}(i) - \Gamma_d^{\pi}(A_i) \right\}$$

- Proposition 3: Unbounded approximation ratio

$$\frac{J^{1-SLA}}{J^{\pi^*}} = \frac{1+\epsilon}{3\epsilon} \Rightarrow \lim_{\epsilon \to 0} \frac{J^{1-SLA}}{J^{\pi^*}} = \infty$$

- Proposition 4: Approximation bound

Assume the average demand of each file inserted into the dedicated storage by an optimal policy π^* is lower bounded by a factor $\rho > 0$ such that the demand of each such file satisfies $\rho \frac{1}{I} \sum_{i=0}^{I} \overline{B}_f^i \Delta_i \geq L_f$. Then, for $k > \frac{\rho I}{I - \rho}$ the approximation ratio of k-SLA is

$$\frac{J^{k-SLA}}{J^{\pi^*}} \leq \frac{1}{1 - \frac{\rho}{k}(1 + \frac{k}{I})}. \qquad (6)$$

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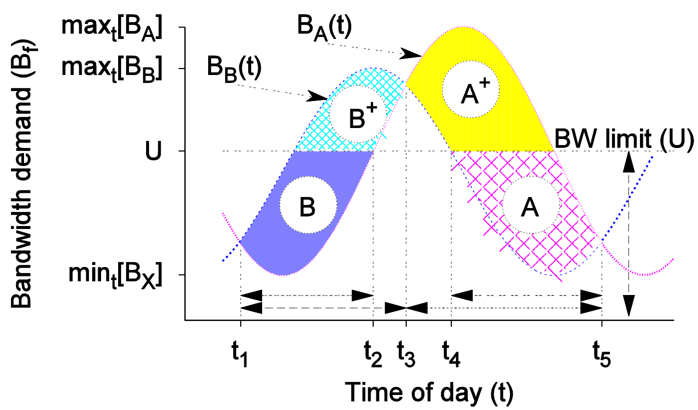

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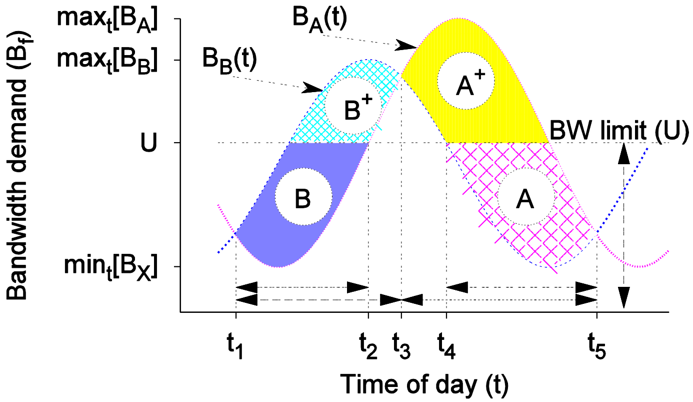

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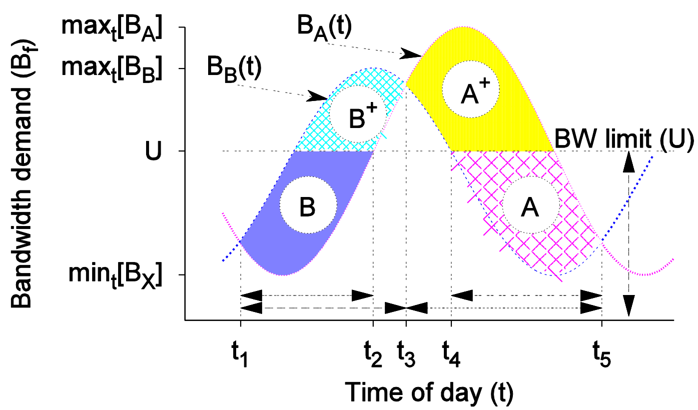

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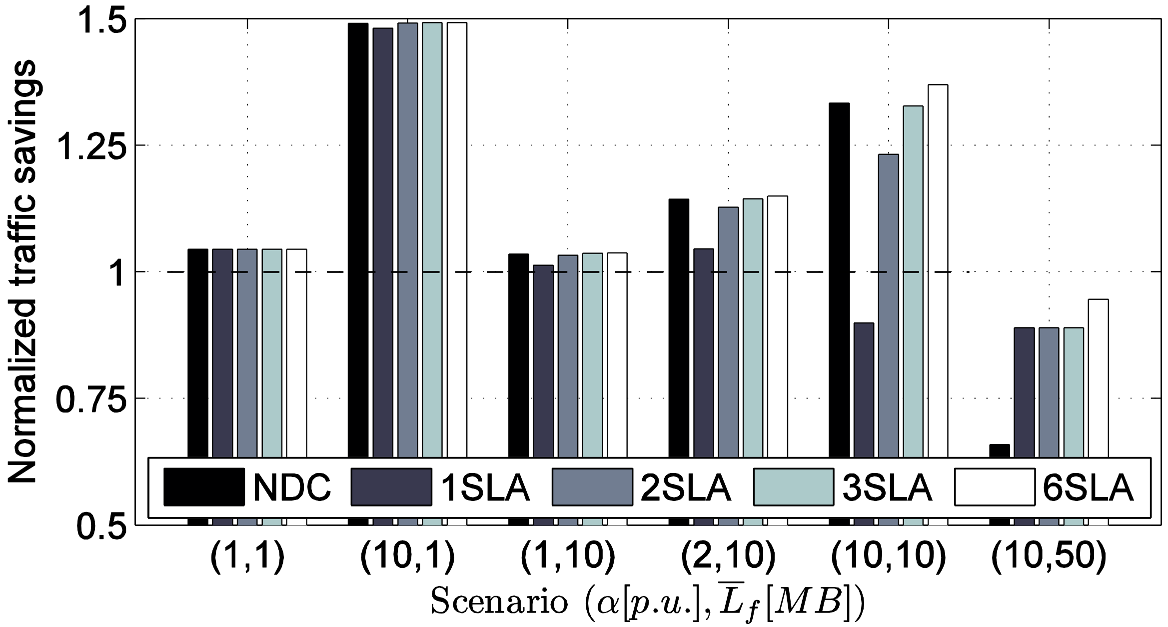
Trace-based analysis (Synthetic)

- Normalized traffic savings

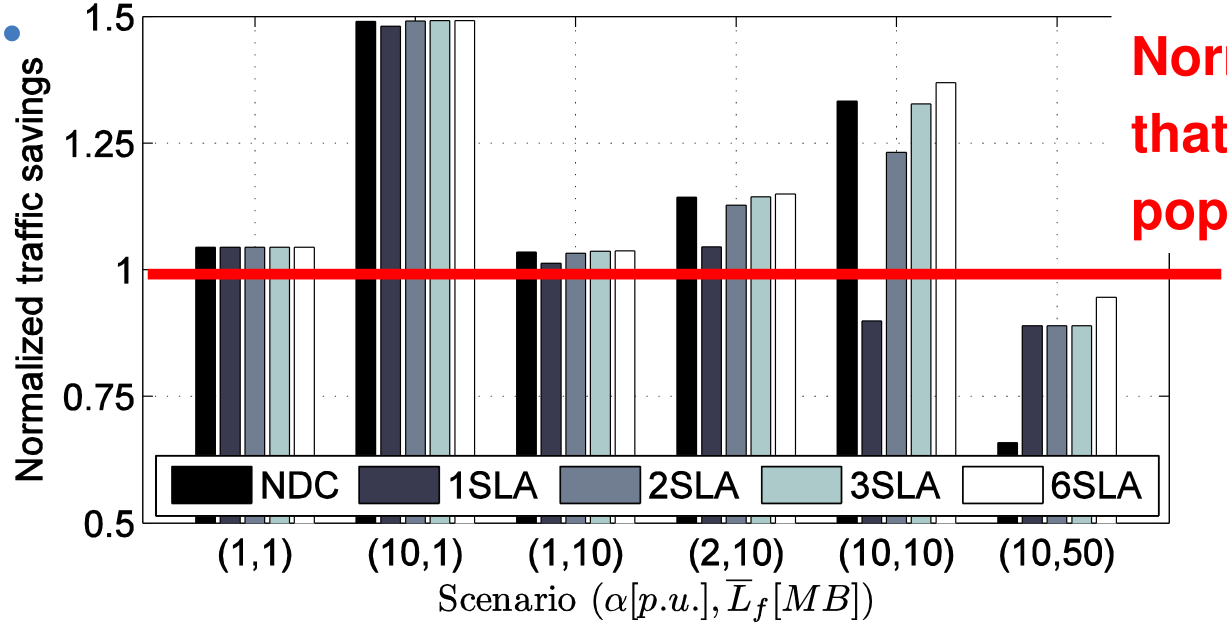


Based on Spotify trace characterization

- Workload: 3 groups of 1000 files; peaks N(0,2) offset by 8h for each group; sinusoid with 24h period; min/max ratio N(0.075,0.075), file sizes U(L/2,3L/2), bandwidth demand Bounded Pareto (B_{min}, B_{max}, α)

Trace-based analysis (Synthetic)

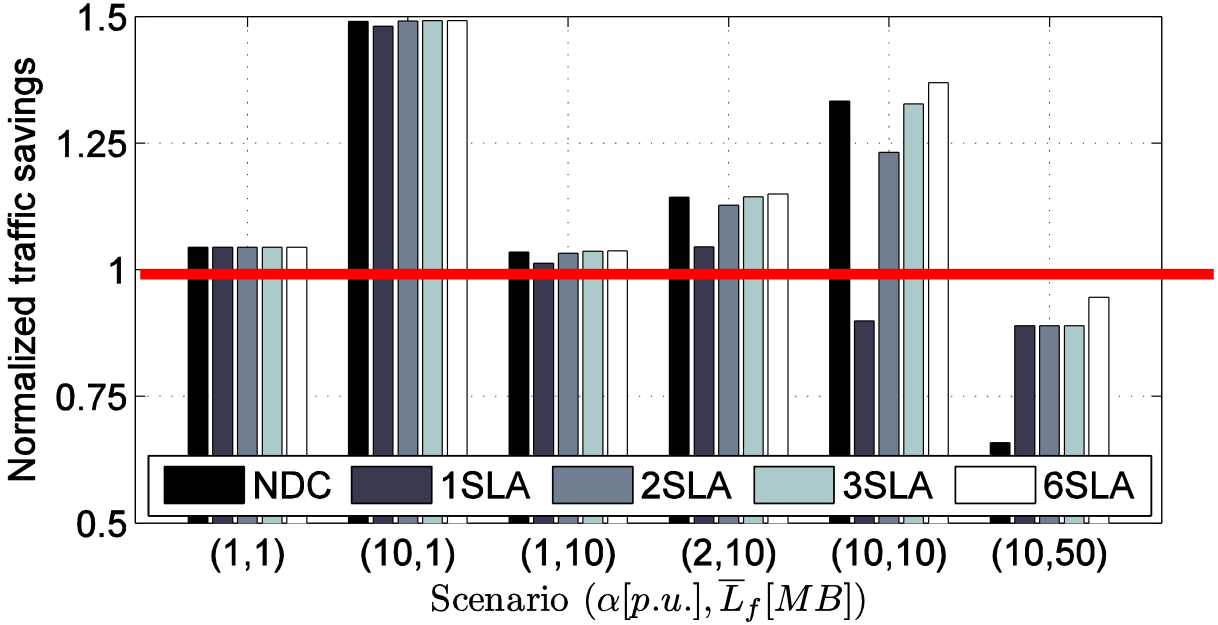
- Normalized traffic savings
-



Normalize against policy that stores the most popular files

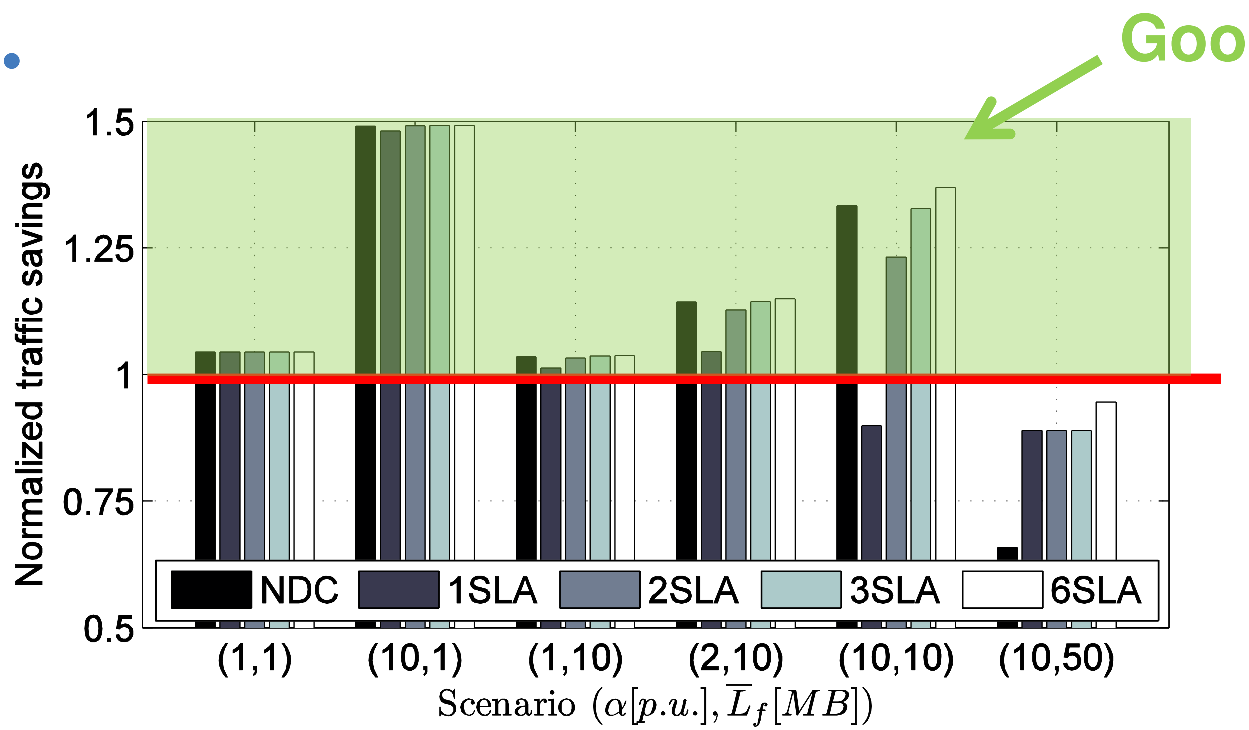
Trace-based analysis (Synthetic)

- Normalized traffic savings
-



Trace-based analysis (Synthetic)

- Normalized traffic savings
-



Trace-based analysis (Synthetic)

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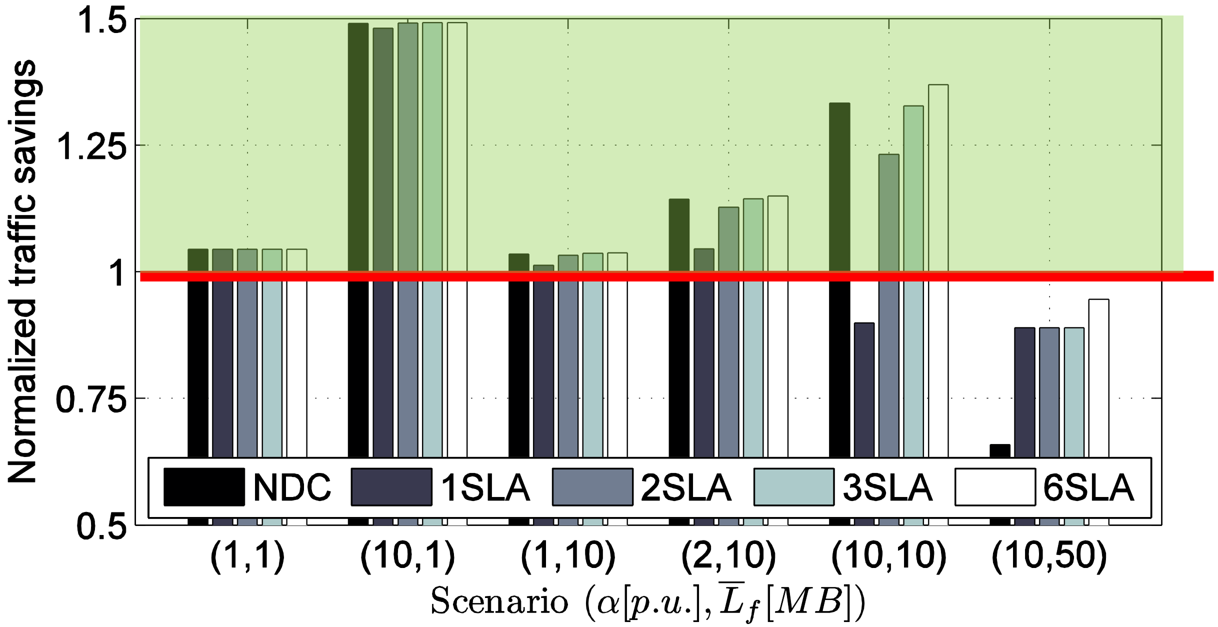
-



- Modest gains when Zipf-like (α≈1) rank popularity
- Significant gains when more uniform (α≈10)
- NDC fails for larges sizes (6-SLA still works well)

Trace-based analysis (Synthetic)

- Normalized traffic savings
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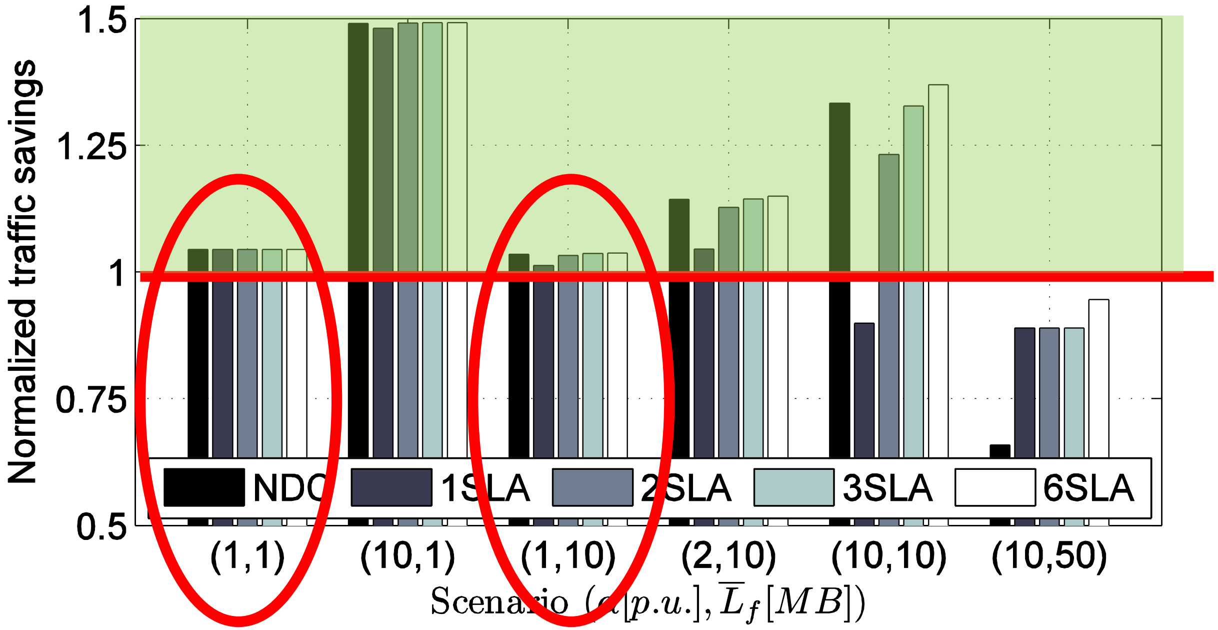

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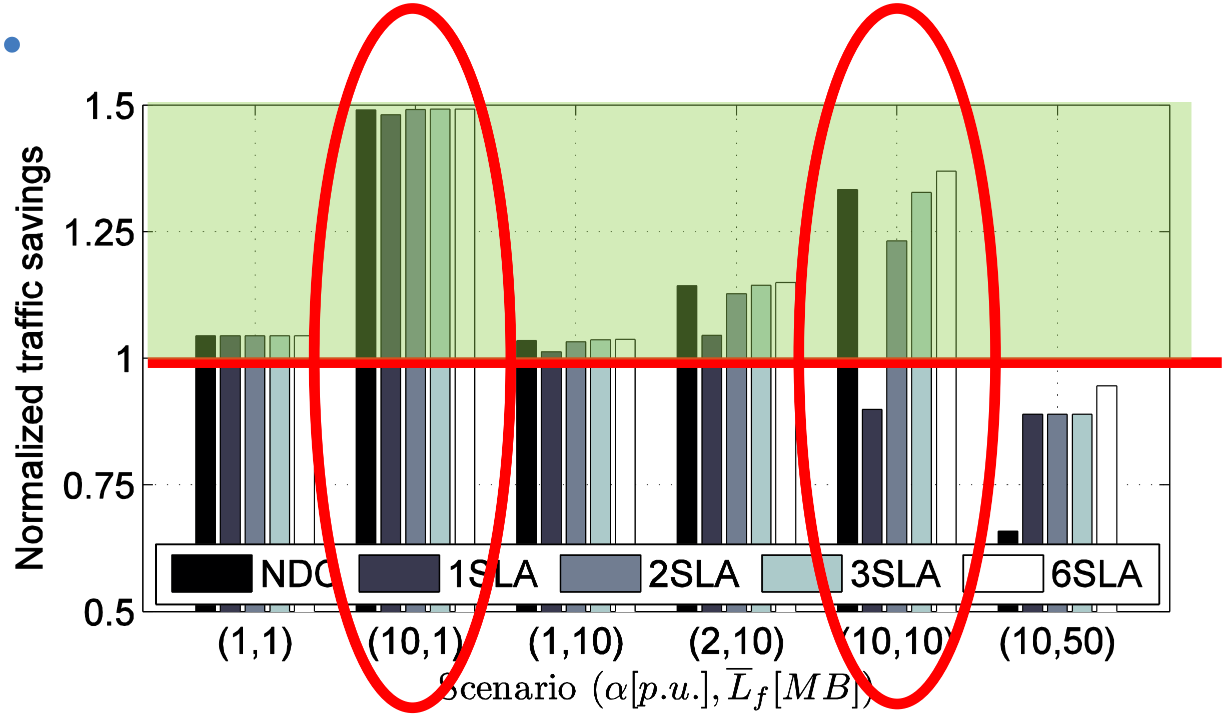

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Trace-based analysis (Synthetic)

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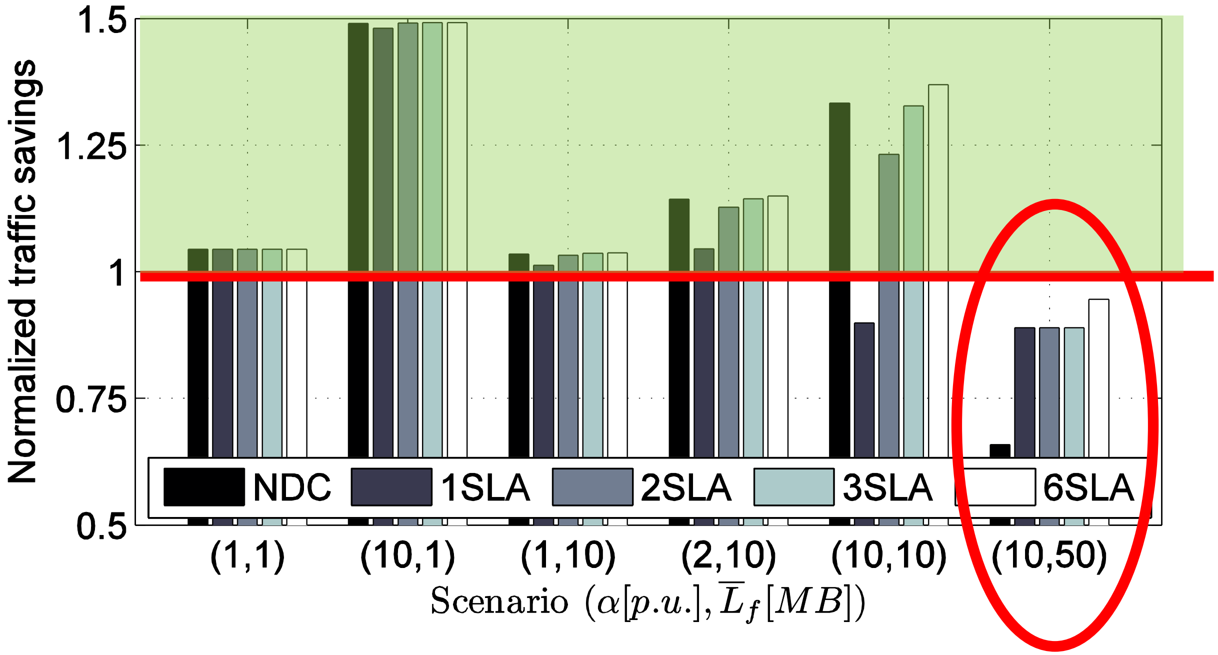
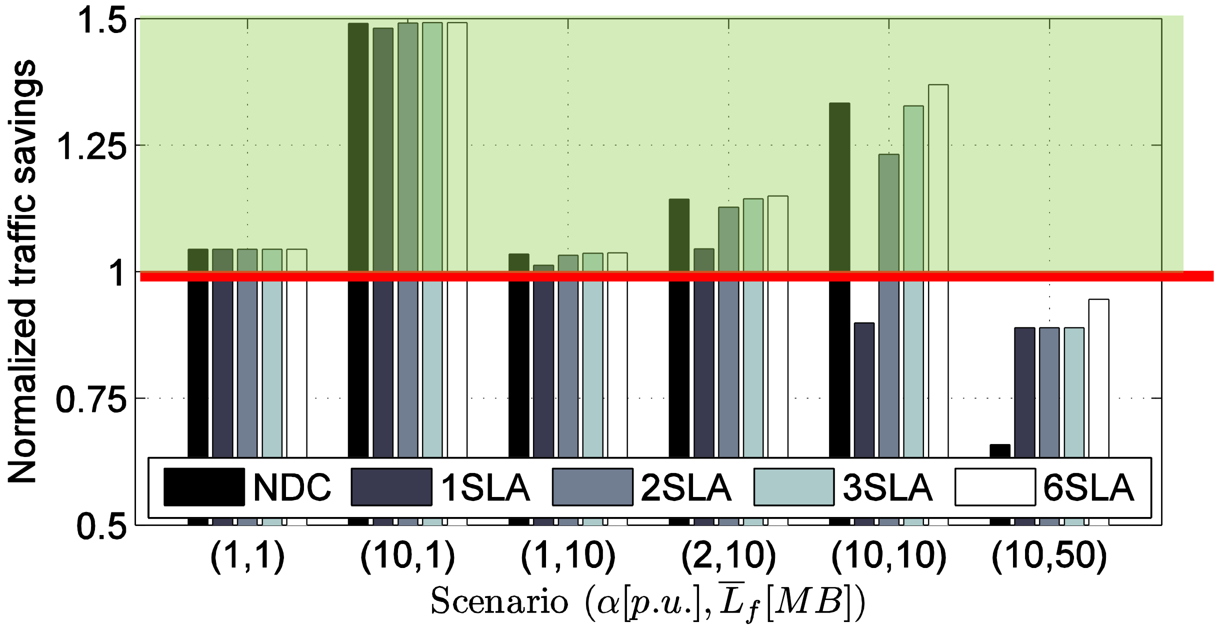


- Modest gains when Zipf-like ($\alpha \approx 1$) rank popularity
- Significant gains when more uniform ($\alpha \approx 10$)
- NDC fails for larges sizes (6-SLA still works well)

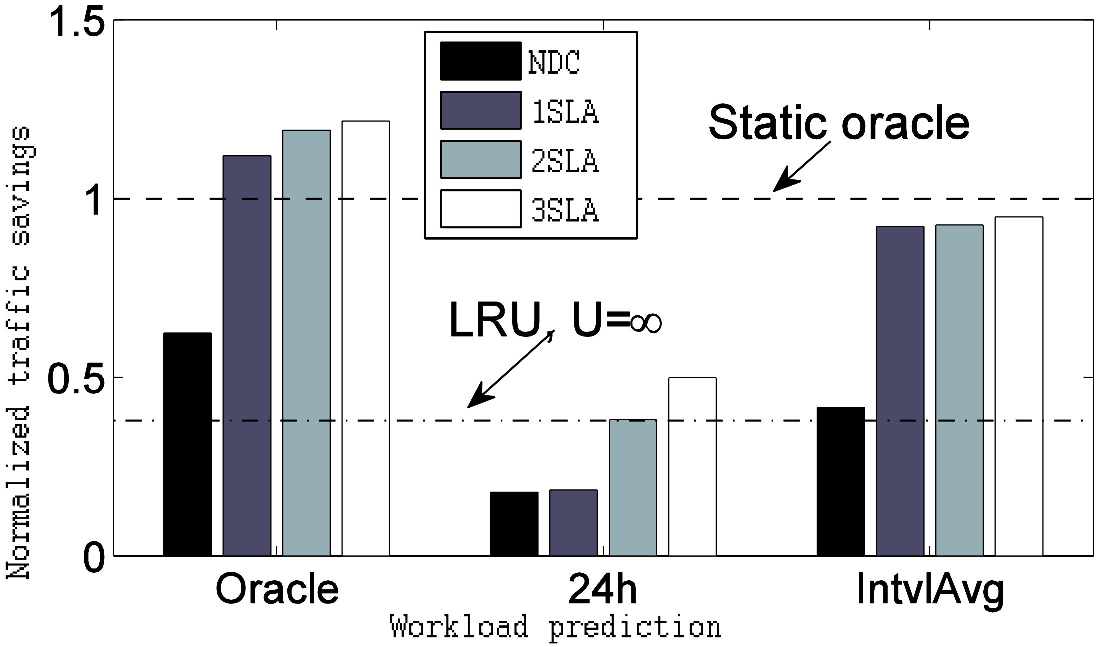
Trace-based analysis (Synthetic)

- Normalized traffic savings
-



- Modest gains when Zipf-like ($\alpha\approx1$) rank popularity
- Significant gains when more uniform ($\alpha\approx10$)
- NDC fails for larges sizes (6-SLA still works well)

Trace-based Analysis

- Spotify traces (all requests for 1M random tracks; 1 week)
- Prediction policies: (i) "oracle", (ii) 24h, (iii) interval average
- 

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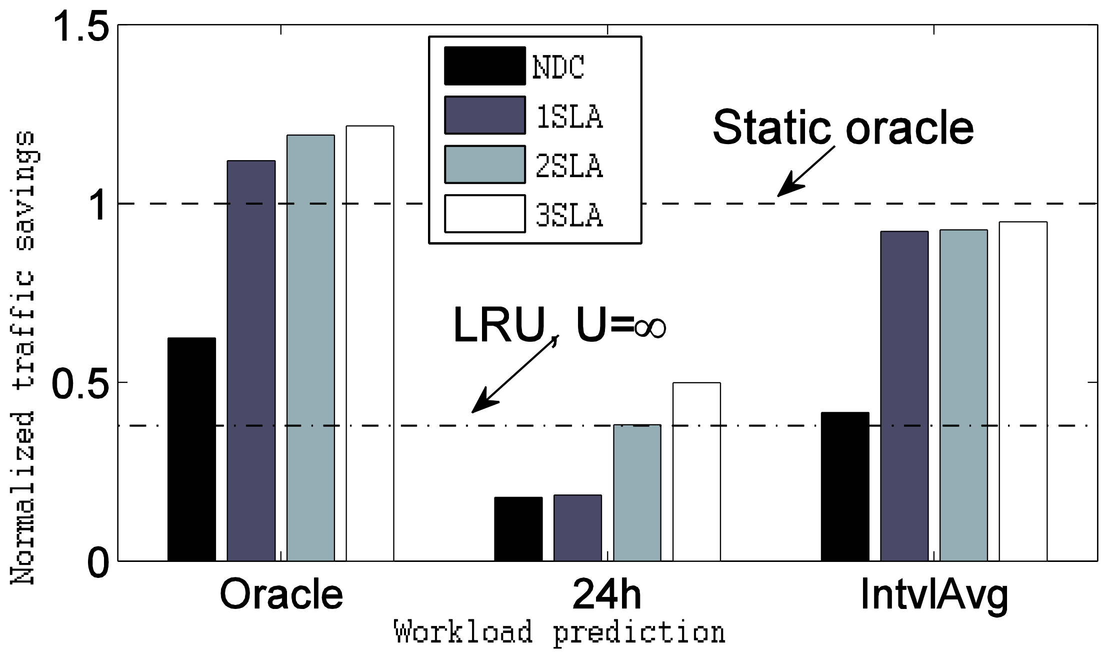
- 

  - NDC fails; 3-SLA works reasonably well
  - Dynamic allocation with k-SLA outperform LRU by far

Trace-based Analysis

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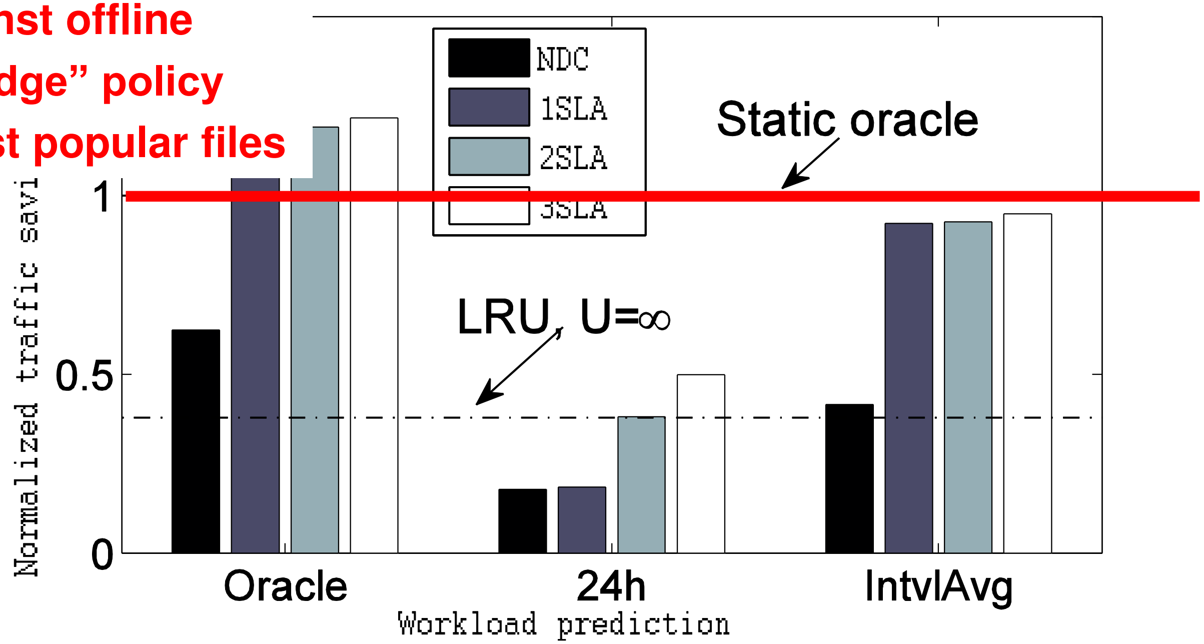
- Prediction policies: (i) “oracle”, (ii) 24h, (iii) interval average

Normalize against offline “global knowledge” policy that stores most popular files



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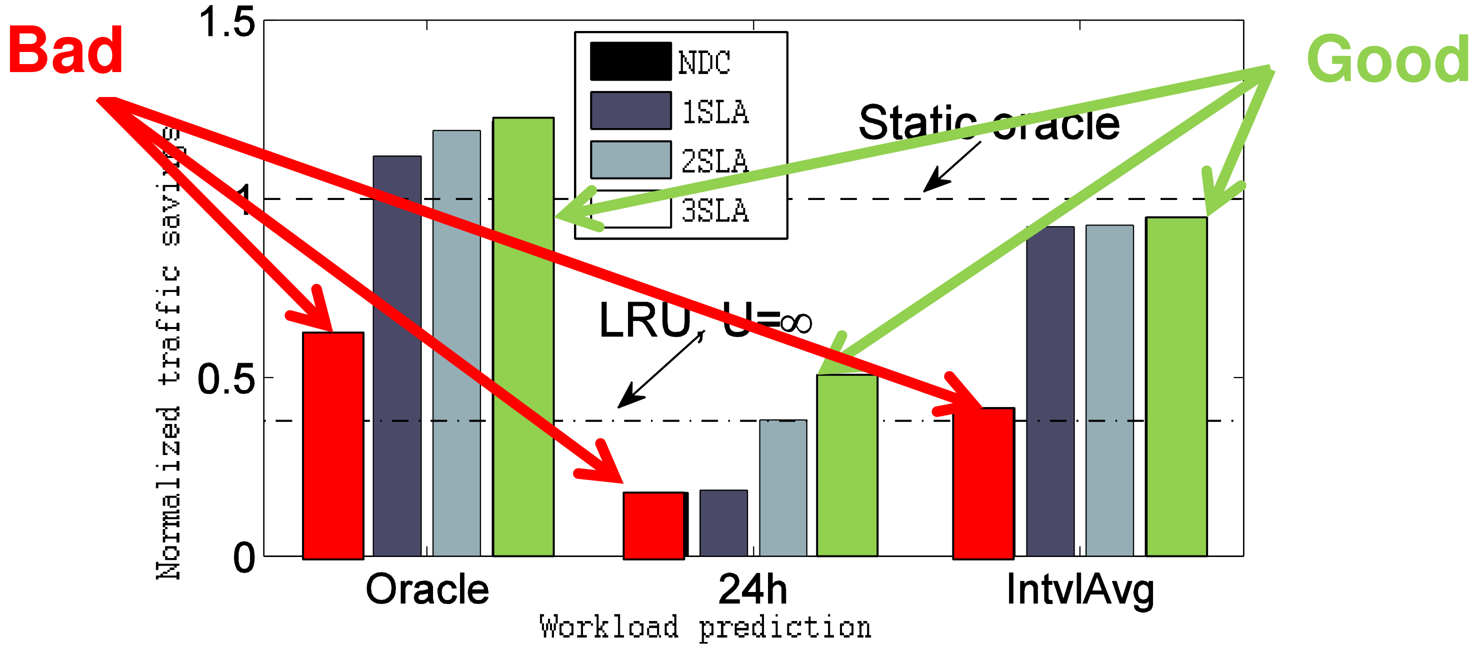
- 

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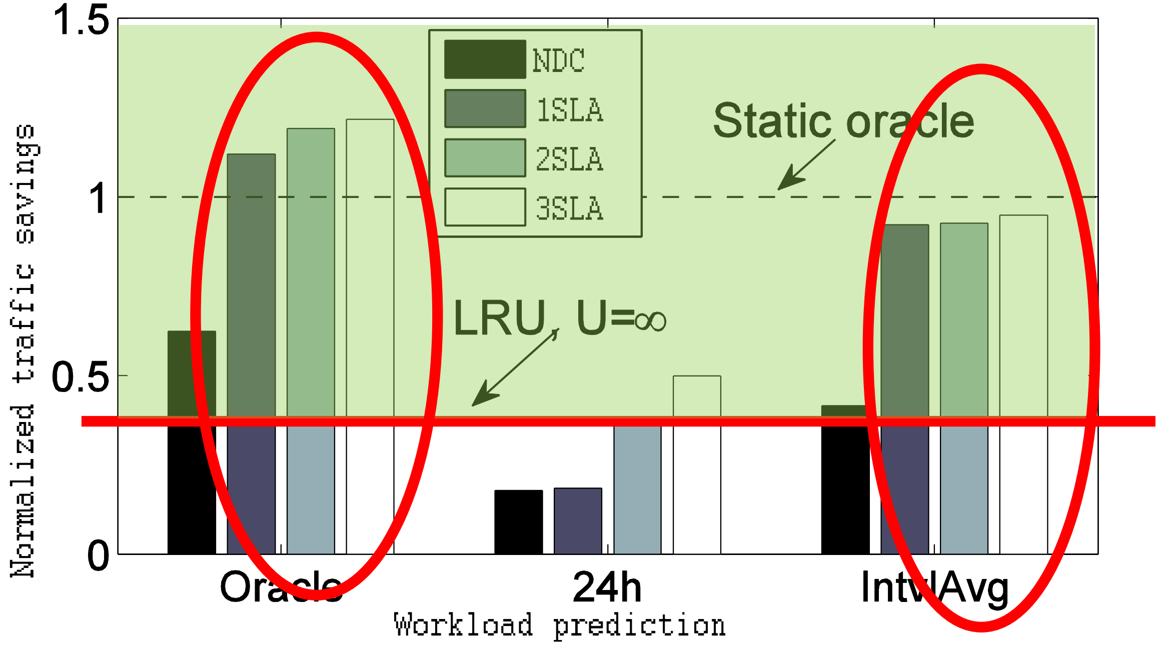
- 

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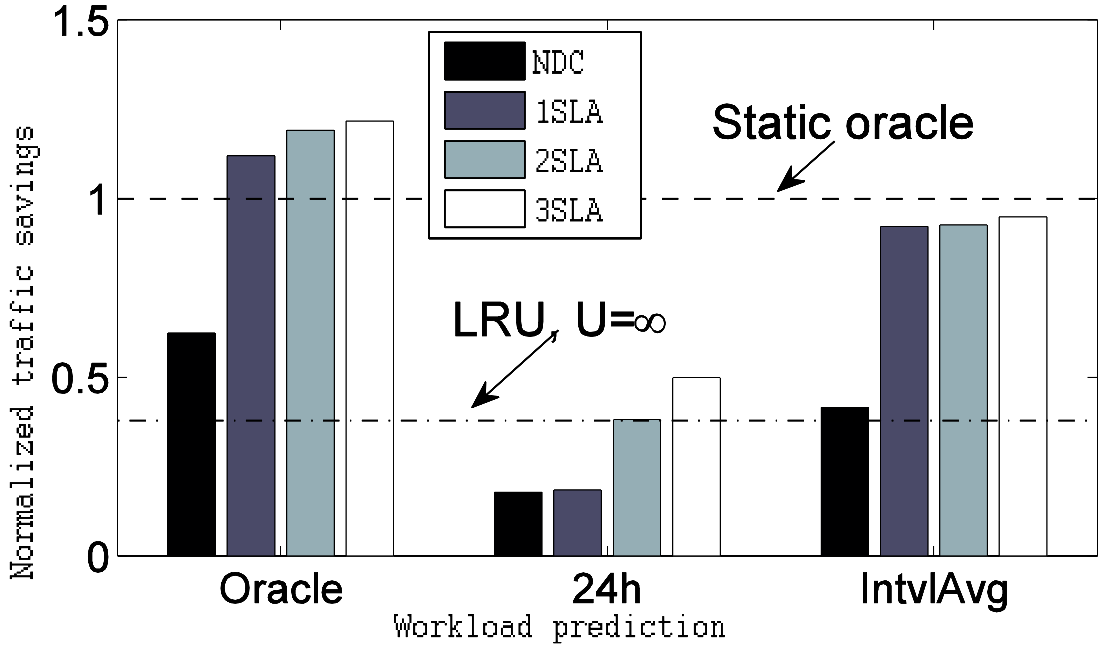
- 

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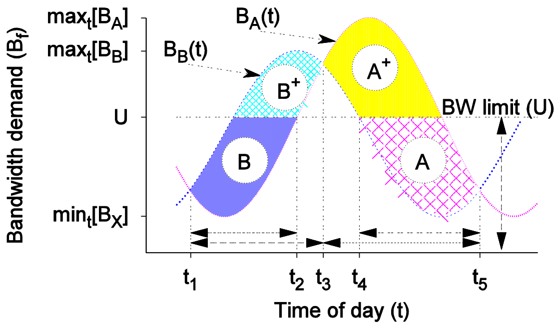
Dynamic Content Allocation Problem



- Finite horizon dynamic decision problem
- Discrete mean-value approximation
- Exact solution as MILP
- Computationally feasible approximations (e.g., k-SLA) with performance bounds
- Validate model and policies using traces from Spotify

LiU EXPANDING REALITY

Dynamic Content Allocation for Cloud-assisted Service of Periodic Workloads

György Dan (KTH) and Niklas Carlsson (LiU)

Thank you!

Niklas Carlsson (niklas.carlsson@liu.se)
www.ida.liu.se/~nikca/papers/infocom14.pdf