Predictive Delay-Aware Network Selection in Data Offloading

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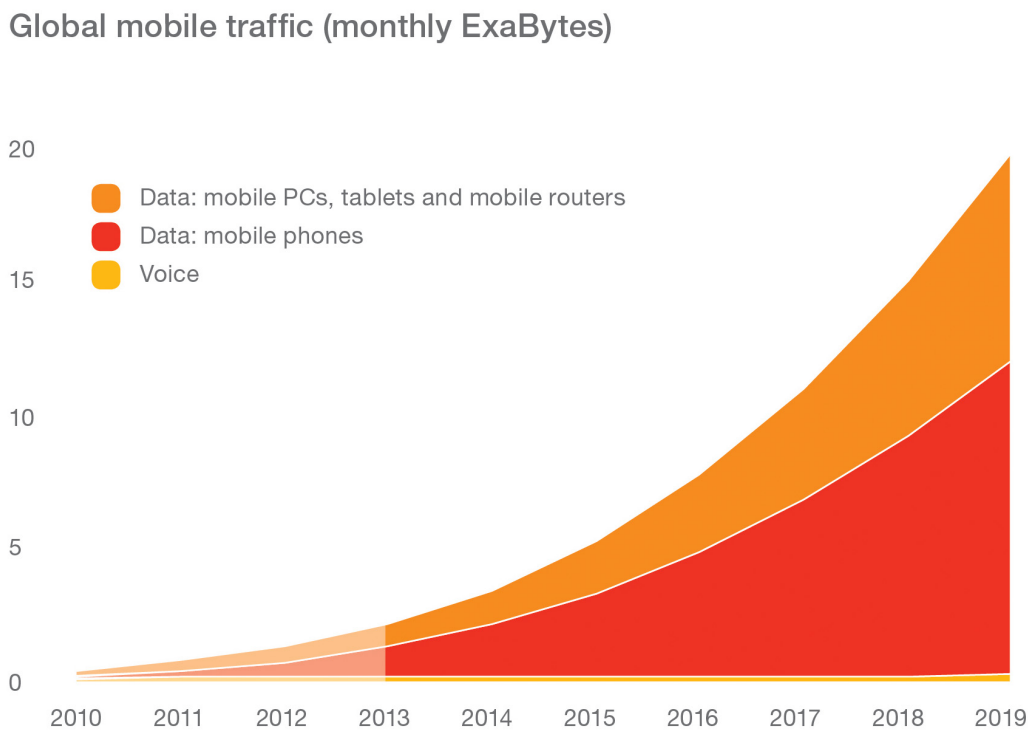
Mobile Traffic Explosion



Global Mobile Data Traffic Growth till 2019 (©Ericsson)

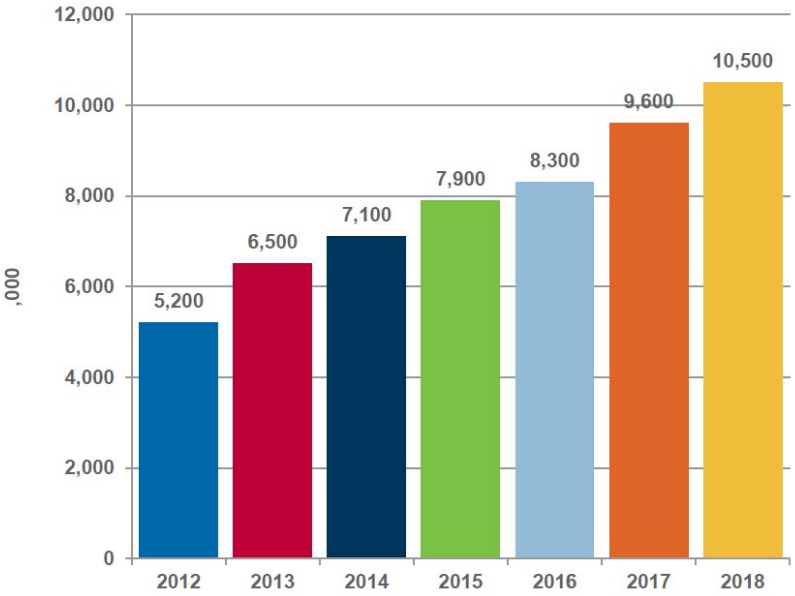
- Annual grow rate $\sim$ 45%
  - A 10-fold increase between 2013 and 2019

Mobile Traffic Explosion

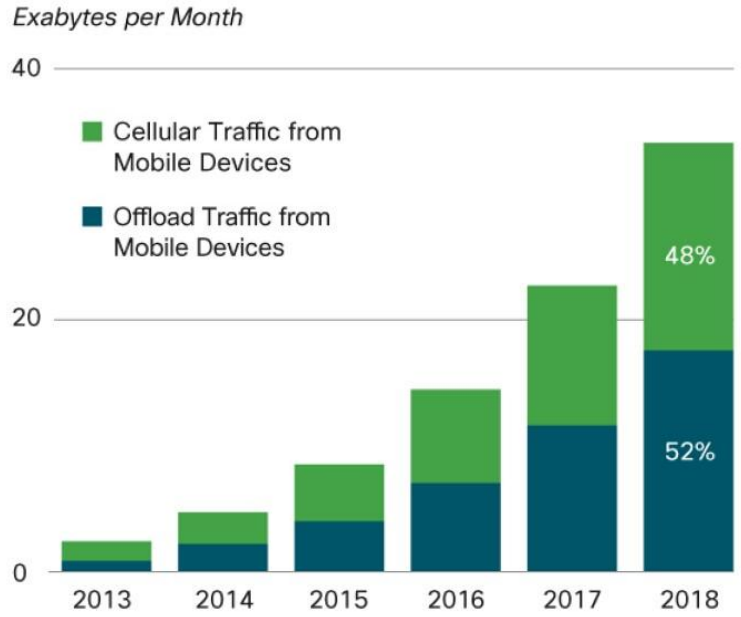
- Traditional ways to expand the network capacity
  - Acquiring new spectrum bands
  - Building more cell sites
  - Upgrading technologies (*e.g.*, 3G $\rightarrow$ 4G)
  - ...
- Problems: time-consuming and costly
- Question: How to expand the network capacity in a cost and time-efficient manner?
- One answer: Data offloading

Mobile Data Offloading

- Data offloading: deliver cellular traffic to other complementary networks (*e.g.*, Wi-Fi, femtocell)
  - Wi-Fi deployment rate is increasing (10.5 million by 2018)
  - More than half traffic will be offloaded (52% by 2018)



New Carrier-Grade Wi-Fi Per Year (©WBA)



Percentage of Offloaded Traffic (©Cisco)

Mobile Data Offloading

- Type 1: User-initiated offloading
  - Users decide which network (*e.g.*, cellular or Wi-Fi) to connect
- Type 2: Operator-initiated offloading (this work)
  - Mobile operator makes the network selection decision
  - Advantages: seamless switch, optimize revenue and QoE

Problem Description

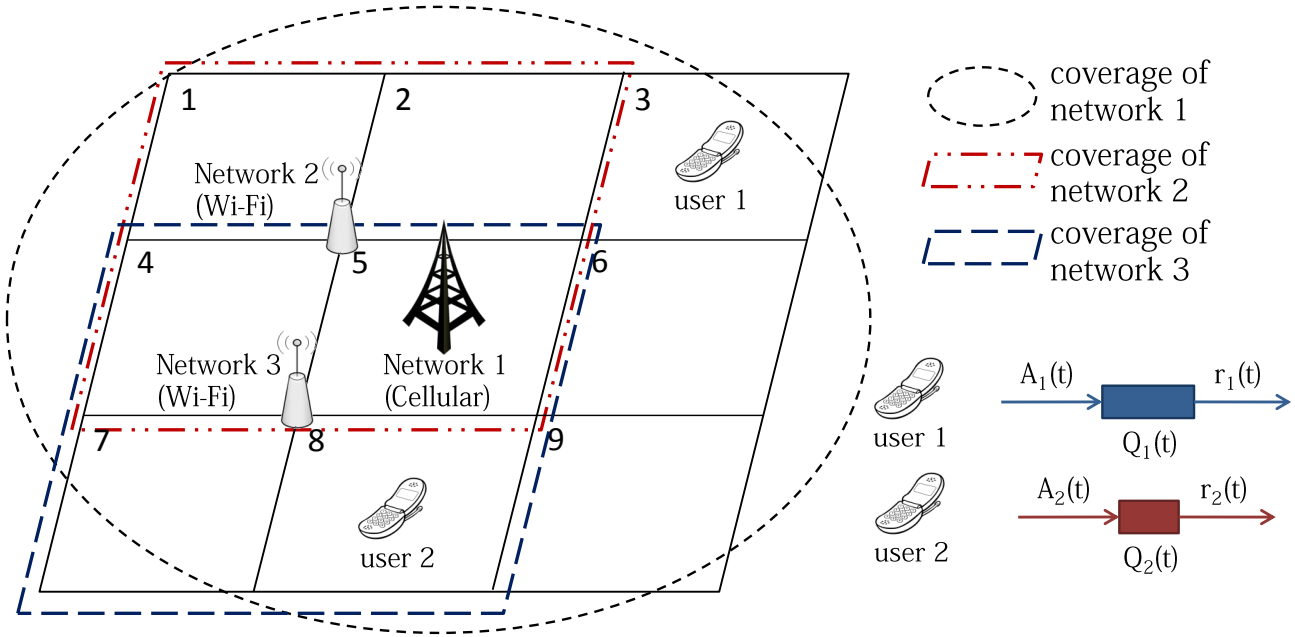
- Major concerns
  - Operation cost: networks have heterogeneous operation costs
  - Traffic delay: delaying traffic causes users' dissatisfaction

- Question: How does operator dynamically select networks for users so that the long-term operation cost and traffic delay is well balanced?

Problem Description

- Challenge: limited information on system randomness
  - Users' traffic demand and network availability
- Case 1: Only have current slot information
  - Algorithm: Lyapunov optimization $\rightarrow$ **DNS**
- Case 2: Have both current and predicted future information
  - Algorithms: a novel frame-based Ly. opt. $\rightarrow$ **P-DNS, GP-DNS**

System Model



- Single operator
- Multiple networks, locations, and users
  - Network availability is location-dependent
  - Users randomly move across the locations with random traffic arrivals

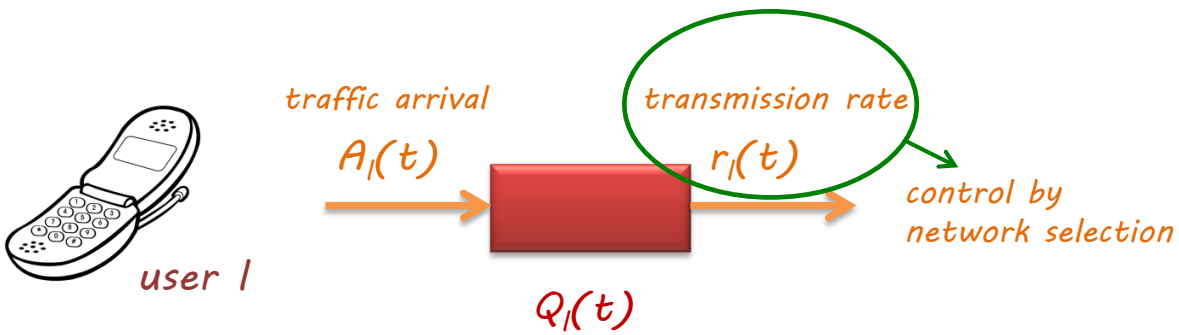
Notations

- System settings
  - Slotted system, $t \in \{0, 1, 2, \cdots\}$
  - Set of locations, $\mathcal{S} = \{1, 2, \cdots, S\}$
  - Set of users, $\mathcal{L} = \{1, 2, \cdots, L\}$
  - Set of networks, $\mathcal{N} = \{1, 2, \cdots, N\}$
  - Location-dependent availability: $\mathcal{N}_s \subseteq \mathcal{N}$, networks available at $s \in \mathcal{S}$
- System randomness
  - User $l \in \mathcal{L}$'s traffic arrival at t, $A_l(t)$
  - User $l \in \mathcal{L}$'s location at t, $S_l(t)$
- Operator's online decision
  - Network selection for l at t, $\alpha_l(t)$
  - Determine: User l's transmission rate at t, $r_l(\boldsymbol{\alpha}(t))$
  - Determine: Total operation cost at t, $c(\boldsymbol{\alpha}(t))$

Queueing Dynamics

- Users' data queues
  - User l's unserved traffic at t, $Q_l(t)$

$$Q_l(t+1) = \max\left[Q_l(t) - r_l\left(\boldsymbol{\alpha}(t)\right), 0\right] + A_l(t)$$



Case 1: Only Current Network Information

- At time t, operator only observes
  - Traffic arrivals, $\boldsymbol{A}(t)$ (random variable)
  - Users' locations, $\boldsymbol{S}(t)$ (random variable)
  - Data queues, $\boldsymbol{Q}(t)$ (determined by historical arrival and transmission)
- Propose **DNS** algorithm to make online decision on $\boldsymbol{\alpha}(t)$

Delay-Aware Network Selection (DNS)

Delay-Aware Network Selection (DNS) Algorithm

At each time slot t, the operator:

- Chooses the network selection vector $\boldsymbol{\alpha}^*(t)$ that solves

$$\textbf{minimize} \quad \left[-\sum_{l=1}^{L} Q_l(t) r_l(\boldsymbol{\alpha}(t))\right] + V c(\boldsymbol{\alpha}(t))$$

$$\textbf{variables} \quad \alpha_l(t) \in \mathcal{N}_{S_l(t)} \cup \{0\}, \ \forall l \in \mathcal{L}.$$

- Updates the queueing vector $\boldsymbol{Q}(t+1)$ accordingly.

- Intuition:
  - When $Q_l(t)$ is large, suspending service incurs severe delay.
    Strategy: serve user l immediately even with a high operation cost
  - When $Q_l(t)$ is small, suspending service does not lead to severe delay.
    Strategy: wait till enter Wi-Fi area

Performance of DNS

Performance of DNS

Under mild assumption on capacity region, for i.i.d. randomness:

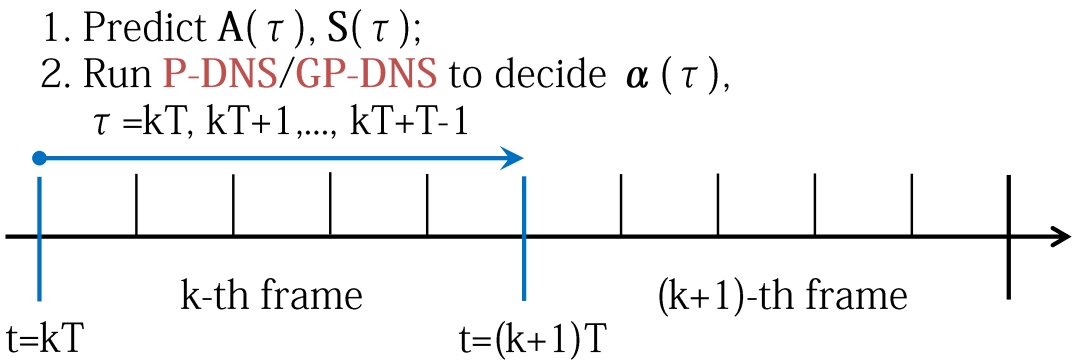
$$c_{av}^{\mathrm{DNS}} \triangleq \limsup_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}\{c(\boldsymbol{\alpha}(\tau))\} \leq c_{av}^{*} + \frac{B}{V},$$

$$Q_{av}^{\mathrm{DNS}} \triangleq \limsup_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \sum_{l=1}^{L} \mathbb{E}\{Q_l(\tau)\} \leq \frac{B+Vc_{\max}}{\eta}.$$

- $[O(1/V), O(V)]$ cost-delay tradeoff (V: control parameter)
  - Time average operation cost is within $O(1/V)$ of the optimality
  - Time average traffic delay is bounded by $O(V)$
  - Conclusion: The operation cost can be pushed arbitrarily close to the optimal value, but at the expense of an increase in the traffic delay
- **DNS** has similar cost-delay tradeoff under Markovian randomness

Case 2: Current and Future Information

- Question: how to improve **DNS** with predictable future information?
- Frame-based prediction and network selection structure
  - Frame size, T (prediction capability)
  - k-th frame, $\mathcal{T}_k \triangleq \{kT, kT+1, \ldots, kT+T-1\}$



Predictive Delay-Aware Network Selection (P-DNS)

Predictive Delay-Aware Network Selection (P-DNS) Algorithm

At time slot $t = kT$, $k \in \{0, 1, \ldots\}$, the operator:

- Chooses the network selection vectors $\{\boldsymbol{\alpha}^*(\tau)\}$, $\tau \in \mathcal{T}_k$, that solve

$$\textbf{minimize} \quad \sum_{\tau=kT}^{kT+T-1} \left(\sum_{l=1}^{L} Q_l(\tau)\left(A_l(\tau) - r_l\left(\boldsymbol{\alpha}(\tau)\right) + \theta\right) + V c\left(\boldsymbol{\alpha}(\tau)\right) \right)$$

$$\textbf{subject to} \quad Q_l(\tau), \tau \in \mathcal{T}_k, \text{ follows queueing dynamics}$$

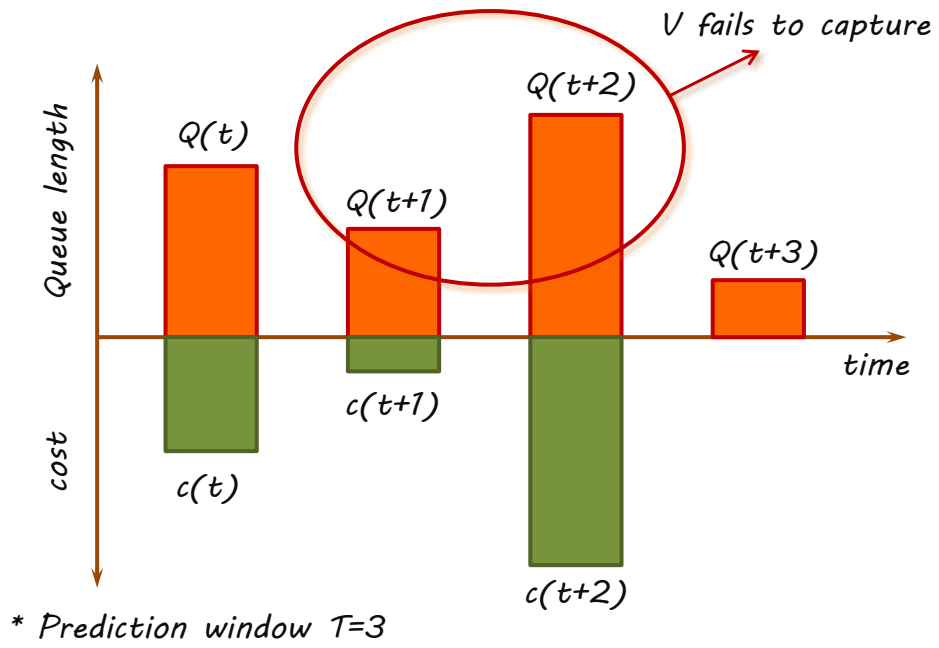
$$\textbf{variables} \quad \alpha_l(\tau) \in \mathcal{N}_{S_l(\tau)} \cup \{0\}, \ \forall l \in \mathcal{L}, \tau \in \mathcal{T}_k.$$

- Updates the queueing vector $\boldsymbol{Q}(kT + T)$ accordingly.

- Besides V, we add another positive control parameter θ

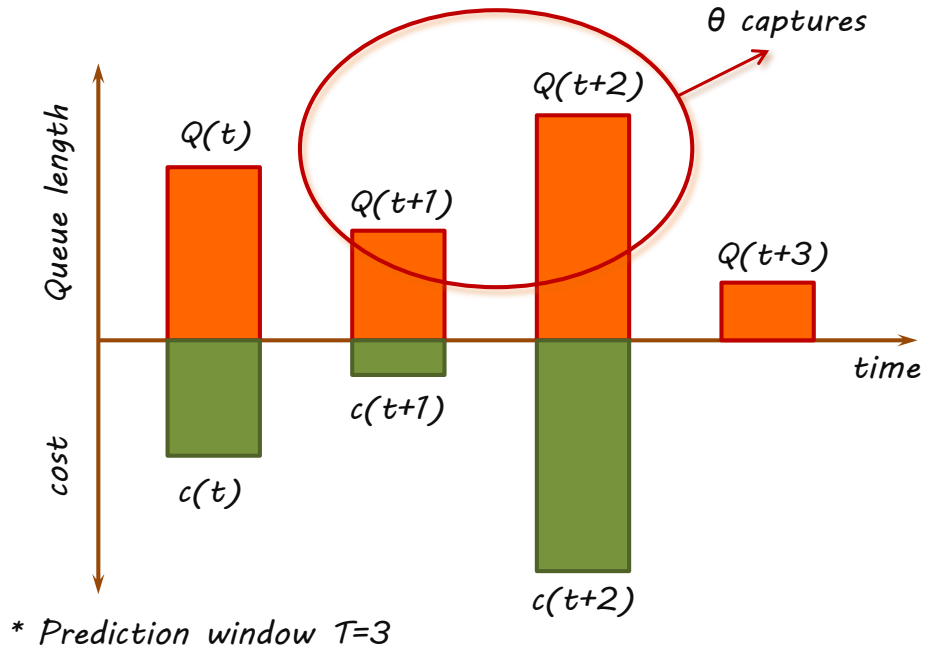
Predictive Delay-Aware Network Selection (P-DNS)

- V balances:
  - Total variance of queue length of the frame, *i.e.*,
    $$\sum_{\tau=t}^{t+2} \left(Q\left(\tau+1\right)-Q\left(\tau\right)\right)=Q\left(t+3\right)-Q\left(t\right)$$
  - Total operation cost of the frame, *i.e.*, $\sum_{\tau=t}^{t+2} c\left(\tau\right)$



Predictive Delay-Aware Network Selection (P-DNS)

- θ balances the queue variance within the frame
  - $\theta > 0$ assigns larger weights to the earlier slots of the frame $\rightarrow$ Serve users earlier rather than later $\rightarrow$ Reduce queue length of middle slots



Performance of P-DNS

- Consider perfect prediction

Performance of P-DNS

Under mild assumption on capacity region, for i.i.d. randomness:

$$c_{av}^{\text{P-DNS}} \triangleq \limsup_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}\{c(\alpha(\tau))\} \leq C(\theta) + \frac{B}{V},$$

$$Q_{av}^{\text{P-DNS}} \triangleq \limsup_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \sum_{l=1}^{L} \mathbb{E}\{Q_l(\tau)\} \leq \frac{B+VC(\theta)}{\theta}.$$

- Question Reduce the complexity of **P-DNS**?

Greedy Predictive Delay-Aware Network Selection (GP-DNS)

- Key idea: Solve the optimization in **P-DNS** approximately and iteratively (details omitted)
- Use ξ to describe the degree of approximation
  - $\xi = 1$: solve the optimization problem optimally
  - $\xi > 1$: a larger ξ implies a worse approximation

Performance of GP-DNS

Under i.i.d. randomness, **GP-DNS** with efficiency ξ achieves:

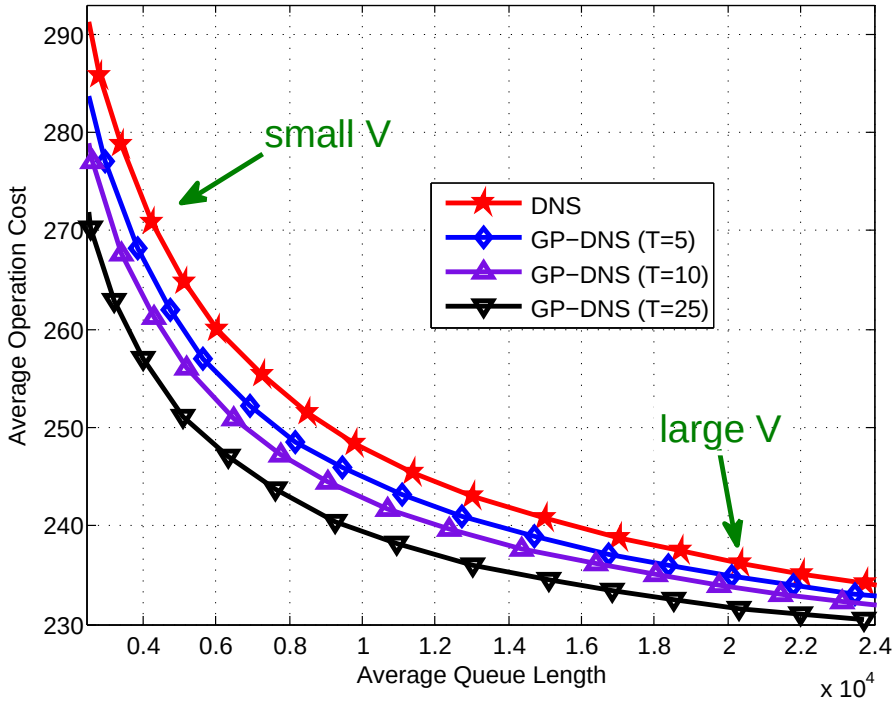
$$c_{av}^{\text{GP-DNS}} \triangleq \limsup_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}\{c(\boldsymbol{\alpha}(\tau))\} \leq \xi C(\theta) + \frac{B}{V},$$

$$Q_{av}^{\text{GP-DNS}} \triangleq \limsup_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \sum_{l=1}^{L} \mathbb{E}\{Q_l(\tau)\} \leq \frac{B+V\xi C(\theta)}{\theta}.$$

Numerical Results

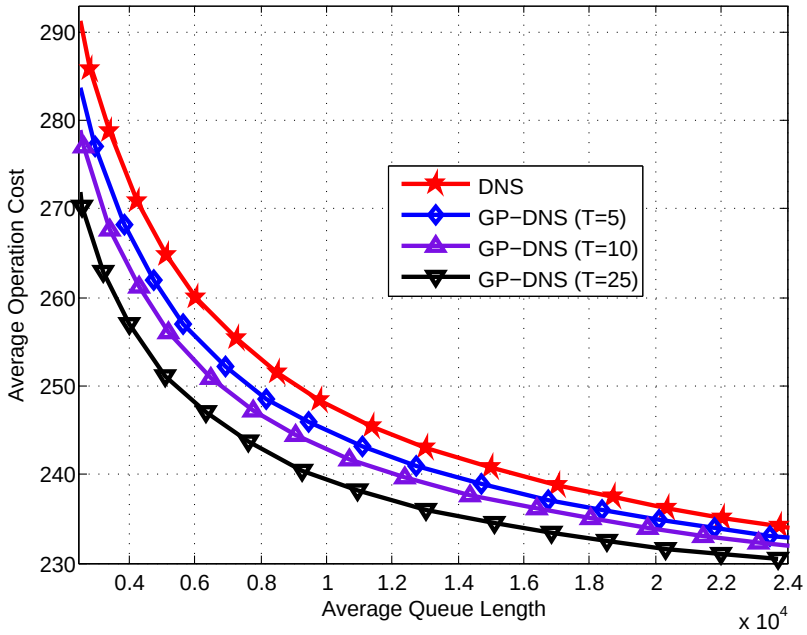
- Simulate **DNS** and **GP-DNS**
- Basic settings
  - 4 users, 8 networks, 64 locations
  - 1 cellular with full coverage, 672 Mbps (4G HSPA+)
  - 7 Wi-Fi networks, 150 Mbps (IEEE 802.11n)
- $c(\boldsymbol{\alpha}(t))$ and $r_l(\boldsymbol{\alpha}(t))$
  - Linear operation cost
  - Even data rate sharing
- Markovian randomness
- 100,000 slots

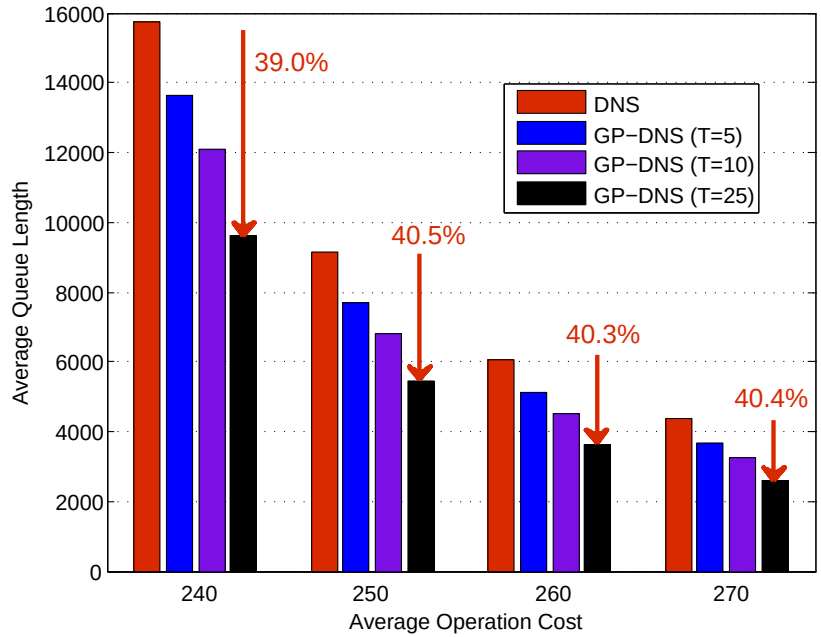
Observation 1: Cost-Delay Tradeoff



- As control parameter V increases,
  - Operation costs (of **DNS** or **GP-DNS**) approach the minimum value
  - Queue lengths *or* traffic delay (of **DNS** or **GP-DNS**) become larger

Observation 2: Prediction Improves Performance





- Cost-delay tradeoff increases with the prediction capability
  - If the operator pursues an operation cost of 250, **GP-DNS** with $T = 25$ (prediction window size) saves 40.5% traffic delay over **DNS**

Conclusion and Future Work

- Conclusion
  - Online network selection with cost-delay tradeoff
  - Current info.: **DNS**; current & future info.: **P-DNS**, **GP-DNS**
  - A novel frame-based Lyapunov analysis
- Future work
  - Heterogenous QoS requirement; inelastic traffic demand

THANK YOU

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