Congestion Control and Fairness in Named Data Networks

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Overview

- NDN enables full utilization of bandwidth and storage.
- Focus on user demand rate for content satisfied by network, rather than session rates.
- General VIP framework for caching, forwarding and congestion control.
- Distributed caching, forwarding, congestion control algorithms which maximize aggregate utility subject to network layer stability.
- VIP congestion control enables fairness among content types.
- Experimental results: superior performance in user delay, rate of cache hits, utility-delay tradeoff.

Network Model

- General connected network with bidirectional links and set of caches.
- Each node n aggregates many network users.
- Content in network identified as set $\mathcal{K}$ of data objects.
- For each data object k, there is set of content source nodes.
- IPs for given data object can enter at any node, exit when satisfied by matching DP at content source, or at caching points.
- Content sources fixed, while caching points may vary in time.
- Assume routing (topology discovery and data reachability) already done: FIBs populated for various data objects.

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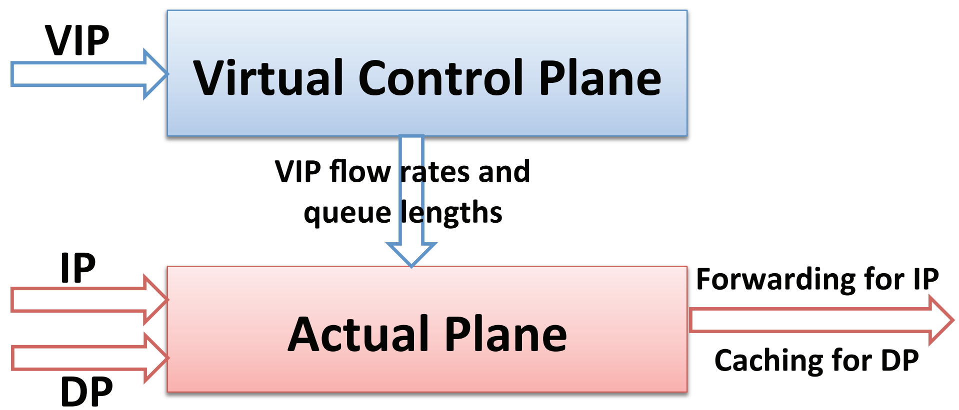
Virtual Interest Packets and VIP Framework

- For each interest packet (IP) for data object k entering network, generate 1 (or c) corresponding VIP(s) for object k.
- IPs may be suppressed/collapsed at NDN nodes, VIPs are not suppressed/collapsed.
- VIPs represent locally measured demand/popularity for data objects.



- General VIP framework: control and optimization on VIPs in virtual plane; mapping to actual plane.

VIP Potentials and Gradients

- Each node n maintains a separate VIP queue for each data object k.
- VIP queue size for node n and data object k at beginning of time slot t is counter $V_n^k(t)$.
- Initially, all VIP counters are 0. As VIPs are created along with IP requests, VIP counters incremented at entry nodes.
- VIPs for object k removed at content sources and caching nodes for object k: sinks or attractors.
- Physically, VIP count represent potential. For any data object, there is downward gradient from entry points of IP requests to sinks.

Throughput Optimal Caching and Forwarding

- VIP count used as common metric for determining caching and forwarding in virtual and actual control planes.

- Forwarding strategy in virtual plane uses backpressure algorithm.

- Multipath forwarding algorithm; incorporates link capacities on reverse path taken by DPs.

- Caching strategy given by the solution of max-weight knapsack problem involving VIP counts.

- VIP forwarding and caching algorithm exploits both bandwidth and storage resources to maximally balance out VIP load, preventing congestion buildup.

- Both forwarding and caching algorithms are distributed.

VIP Stability Region and Throughput Optimality

- λ_n^k = long-term exogenous VIP arrival rate at node n for object k:

- VIP network stability region Λ = set of all $\boldsymbol{\lambda} = (\lambda_n^k)_{k\in\mathcal{K},n\in\mathcal{N}}$ for which there exist some feasible joint forwarding/caching policy which can guarantee that all VIP queues are stable.

- VIP Algorithm is throughput optimal in virtual plane: adaptively stabilizes all VIP queues for any $\boldsymbol{\lambda} \in \mathrm{int}(\Lambda)$ without knowing $\boldsymbol{\lambda}$.

- Forwarding of Interest Packets in actual plane: forward each IP on link with maximum average VIP flow over sliding window.

- Caching of Data Packets in actual plane: designed stable caching algorithm based on VIP flow in virtual plane.

VIP Congestion Control

- Even with optimal caching and forwarding, excessively large request rates can overwhelm network.

- No source-destination pairs: traditional congestion control algorithms inappropriate.

- Need content-based congestion control to cut back demand rates fairly.

- VIP framework: can optimally combine congestion control with caching and forwarding.

- Hop-by-hop content-based backpressure approach; no concept of flow.

VIP Congestion Control

- Arriving IPs (VIPs) first enter transport layer queues before being admitted to network layer.

- VIP counts relay congestion signal to IP entry nodes via backpressure effect.

- Congestion control: support a portion of VIPs which maximizes sum of utilities subject to network layer VIP queue stability.

- Choice of utility functions lead to various fairness notions (e.g. max-min, proportional fairness).

Utility Maximization Subject to Network Stability

- $\boldsymbol{\theta}$-optimal admitted VIP rate:

$$\begin{aligned} \bar{\boldsymbol{\alpha}}^*(\boldsymbol{\theta}) = \arg\max_{\bar{\boldsymbol{\alpha}}} \quad & \sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{K}} g_n^k\left(\bar{\alpha}_n^k\right) \\ \text{s.t.} \quad & \bar{\boldsymbol{\alpha}} + \boldsymbol{\theta} \in \Lambda \\ & \mathbf{0} \preceq \bar{\boldsymbol{\alpha}} \preceq \boldsymbol{\lambda} \end{aligned}$$

- $g_n^k(\cdot)$: increasing, concave content-based utility functions.
- $\bar{\boldsymbol{\alpha}}$ = IP (VIP) input rates admitted to network layer.
- $\boldsymbol{\theta}$ = margin to boundary of VIP stability region Λ.
- Maximum sum utility achieved at $\overline{\boldsymbol{\alpha}}^*(\mathbf{0})$ when $\boldsymbol{\theta} = \mathbf{0}$.
- Tradeoff between sum utility attained and user delay.

Transport and Network Layer VIP Dynamics

- Transport-layer queue evolution:

$$Q_n^k(t+1) = \min\left\{\left(Q_n^k(t) - \alpha_n^k(t)\right)^+ + A_n^k(t), Q_{n,\max}^k\right\} \tag{1}$$

- Network-layer VIP count evolution:

$$V_n^k(t+1) \leq \left(\left(V_n^k(t) - \sum_{b\in\mathcal{N}} \mu_{nb}^k(t)\right)^+ + \alpha_n^k(t) + \sum_{a\in\mathcal{N}} \mu_{an}^k(t) - r_n s_n^k(t)\right)^+ \tag{2}$$

Joint Congestion Control, Caching and Forwarding

- Virtual queues $Y_n^k(t)$ and auxiliary variables $\gamma_n^k(t)$.
- Initialize: $Y_n^k(0) = 0$ for all k, n.
- Congestion Control: for each k and n, choose:

$$\alpha_n^k(t) = \begin{cases} \min\left\{Q_n^k(t), \alpha_{n,\max}^k\right\}, & Y_n^k(t) > V_n^k(t) \\ 0, & \text{otherwise} \end{cases}$$

$$\begin{aligned} \gamma_n^k(t) = \arg\max_{\gamma} \quad & W g_n^k(\gamma) - Y_n^k(t) \\ s.t. \quad & 0 \leq \gamma \leq \alpha_{n,\max}^k \end{aligned}$$

  where $W > 0$ is control parameter affecting utility-delay tradeoff.

  Based on chosen $\alpha_n^k(t)$ and $\gamma_n^k(t)$, transport layer queue updated as in (1) and virtual queue updated as:

$$Y_n^k(t+1) = \left(Y_n^k(t) - \alpha_n^k(t)\right)^+ + \gamma_n^k(t)$$

- Caching and Forwarding: Same as VIP Algorithm above. Network layer VIP count updated as in (2).

Joint Congestion Control, Caching and Forwarding

- Joint algorithm adaptively stabilizes all VIP queues for any $\boldsymbol{\lambda}$ inside or outside Λ, without knowing $\boldsymbol{\lambda}$.
- Users need not know utility functions and demand rates of other users.

Theorem 3 *For an arbitrary IP arrival rate* $\boldsymbol{\lambda}$ *and for any* $W > 0$,

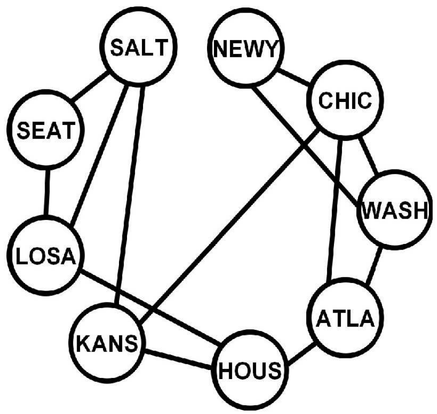
$$\limsup_{t\to\infty} \frac{1}{t} \sum_{\tau=1}^{t} \sum_{n\in\mathcal{N},k\in\mathcal{K}} \mathbb{E}[V_n^k(\tau)] \leq \frac{2N\hat{B} + WG_{\max}}{2\hat{\epsilon}}$$

$$\liminf_{t\to\infty} \sum_{n\in\mathcal{N},k\in\mathcal{K}} g_n^k\left(\overline{\alpha}_n^k(t)\right) \geq \sum_{n\in\mathcal{N},k\in\mathcal{K}} g_n^{(c)}\left(\overline{\alpha}_n^{k*}(\mathbf{0})\right) - \frac{2N\hat{B}}{W}$$

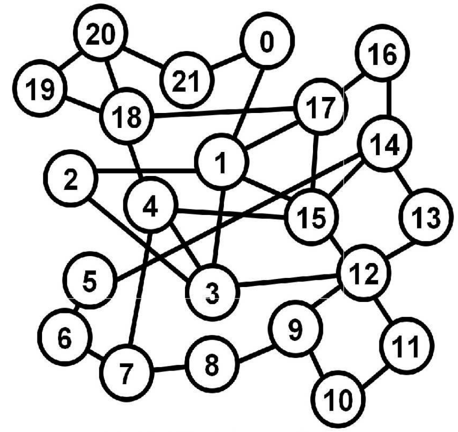
where $\hat{B} \triangleq \frac{1}{2N}\sum_{n\in\mathcal{N}}\Big((\mu_{n,\max}^{out})^2+(\alpha_{n,\max}+\mu_{n,\max}^{in}+r_{n,\max})^2+2\mu_{n,\max}^{out}r_{n,\max}\Big)$,
$\hat{\epsilon} \triangleq \sup_{\{\boldsymbol{\epsilon}:\boldsymbol{\epsilon}\in\Lambda\}} \min_{n\in\mathcal{N},k\in\mathcal{K}}\left\{\epsilon_n^k\right\}$, $\alpha_{n,\max} \triangleq \sum_{k\in\mathcal{K}} \alpha_{n,\max}^k$,
$G_{\max} \triangleq \sum_{n\in\mathcal{N},k\in\mathcal{K}} g_n^k\left(\alpha_{n,\max}^k\right)$, $\overline{\alpha}_n^k(t) \triangleq \frac{1}{t}\sum_{\tau=1}^{t}\mathbb{E}[\alpha_n^k(\tau)]$.

Numerical Experiments

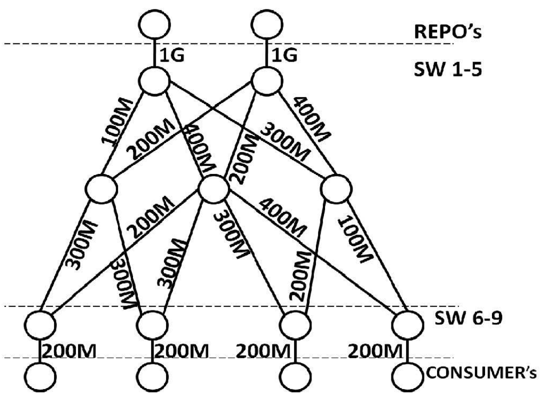
Abilene Topology



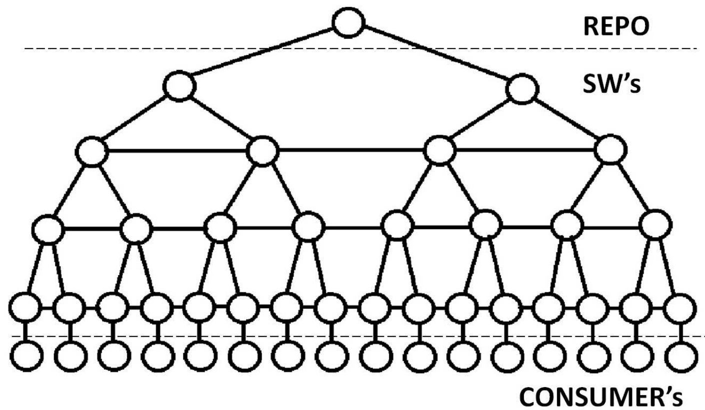
GEANT Topology



Fat Tree Topology



Wireless Backhaul Topology



Network Parameters

- Abilene: 5000 objects, cache size $5GB$ (1000 objects), link capacity 500 Mb/s; all nodes generate requests and can be data sources.

- GEANT: 2000 objects, cache size $2GB$ (400 objects), link capacity 200 Mb/s; all nodes generate requests and can be sources.

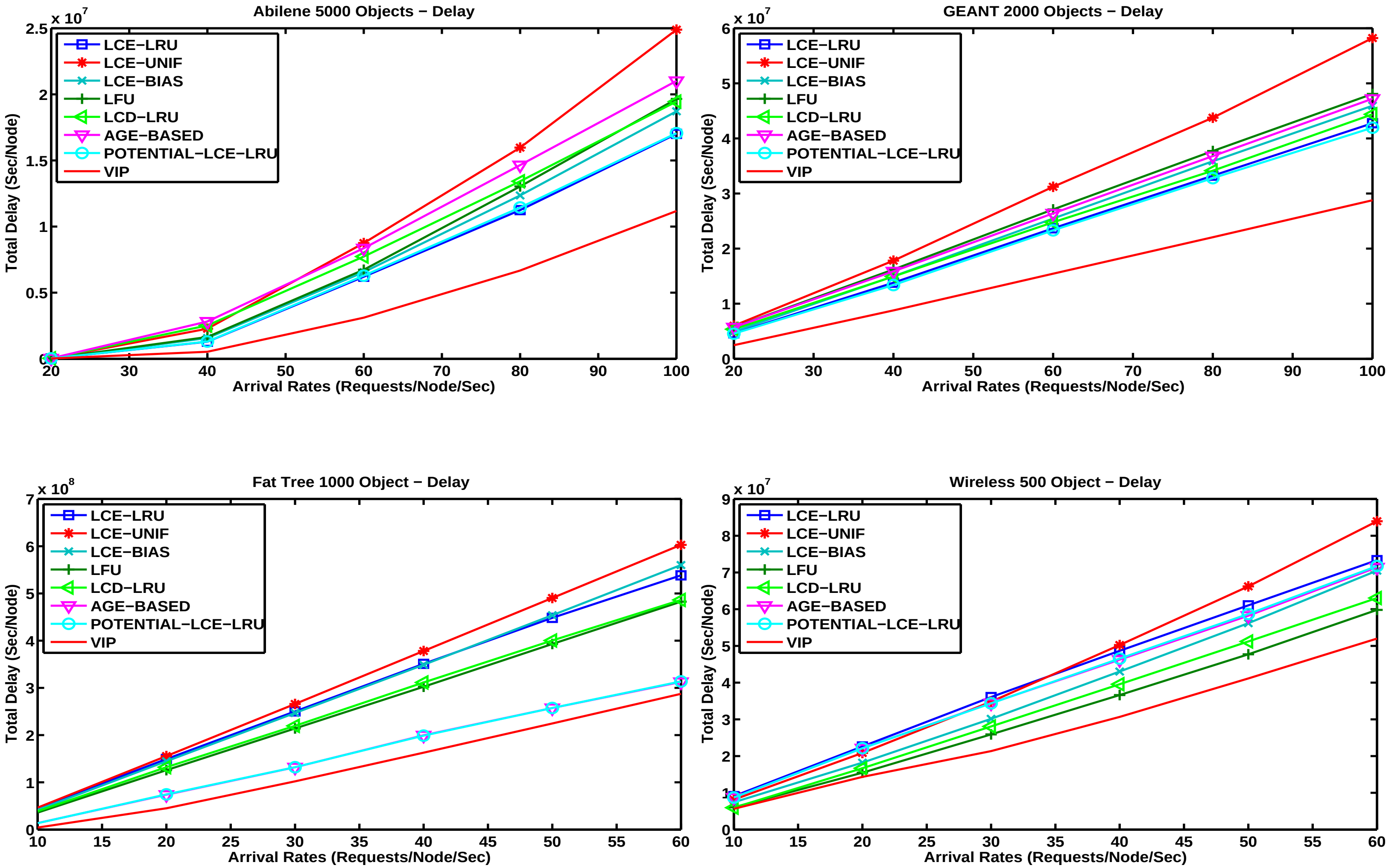
- Fat Tree: 1000 objects, cache size $1GB$ (200 objects); CONSUMER nodes generate requests; REPOs are source nodes.

- Wireless Backhaul: 500 objects, cache size $100MB$ (20 objects), link capacity $500Mb/s$; CONSUMER nodes generate requests; REPO is source node.

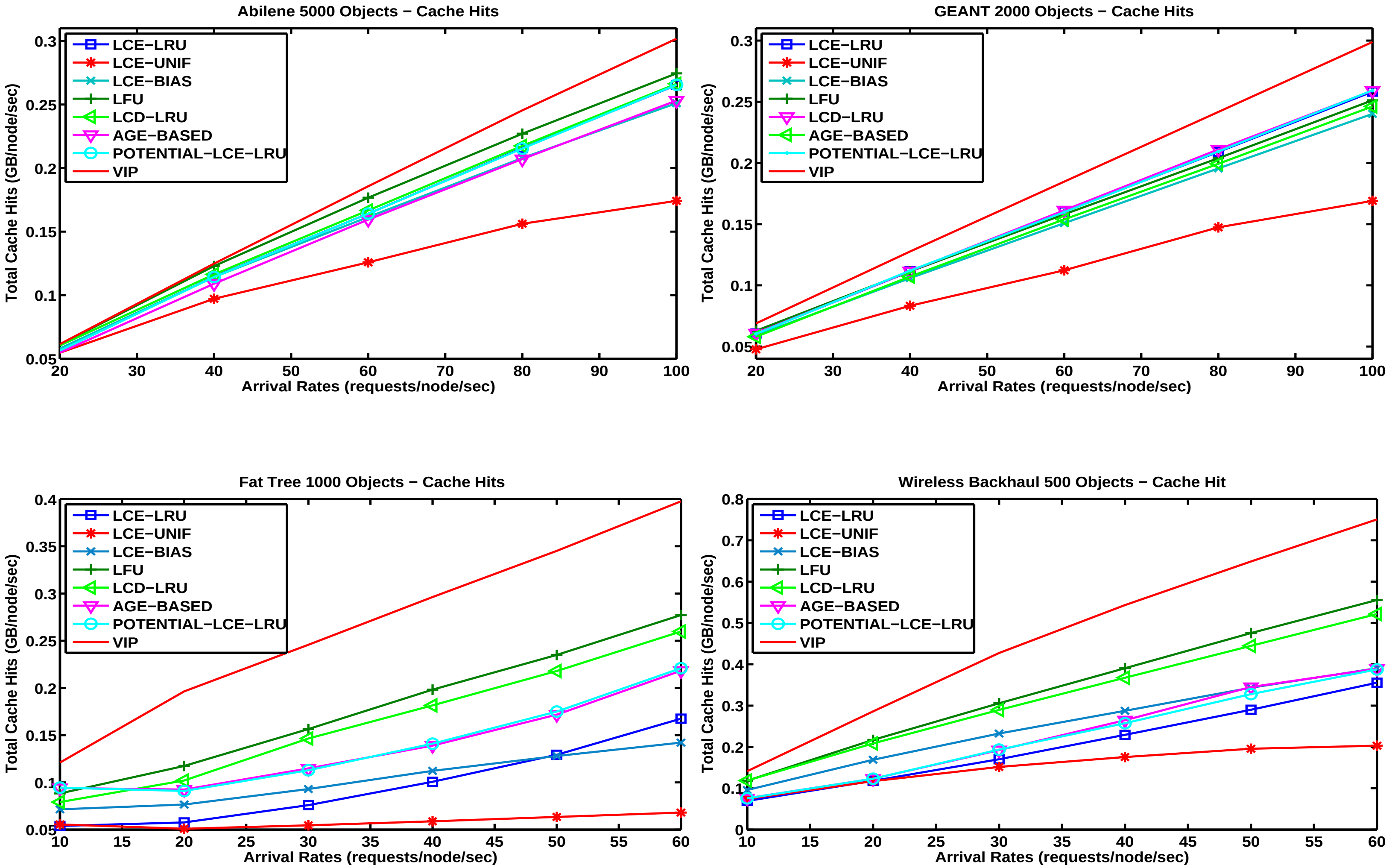
Numerical Experiments: Caching and Forwarding

- Arrival Process: IPs arrive according to Poisson process with same rate.
- Content popularity follows Zipf (0.75).
- Interest Packet size = 125B; Chunk size = 50KB; Object size = 5MB.
- Baselines:
  Caching Decision: LCE/LCD/LFU/AGE-BASED
  Caching Replacement: LRU/BIAS/UNIF/LFU/AGE-BASED
  Forwarding: Shortest path and Potential-Based Forwarding

Numerical Experiments: Delay Performance



Numerical Experiments: Cache Hit Performance



Numerical Experiments: Congestion Control

- α-fair utility functions with $\alpha = 1$ (proportionally fair), $\alpha = 2$, $\alpha \to \infty$ (max-min fair).

- Utility-delay comparison of Stable Caching VIP Algorithm with Congestion Control with AIMD Window-base congestion control with PIT-based forwarding and LRU caching (Carofiglio et al. 2013).

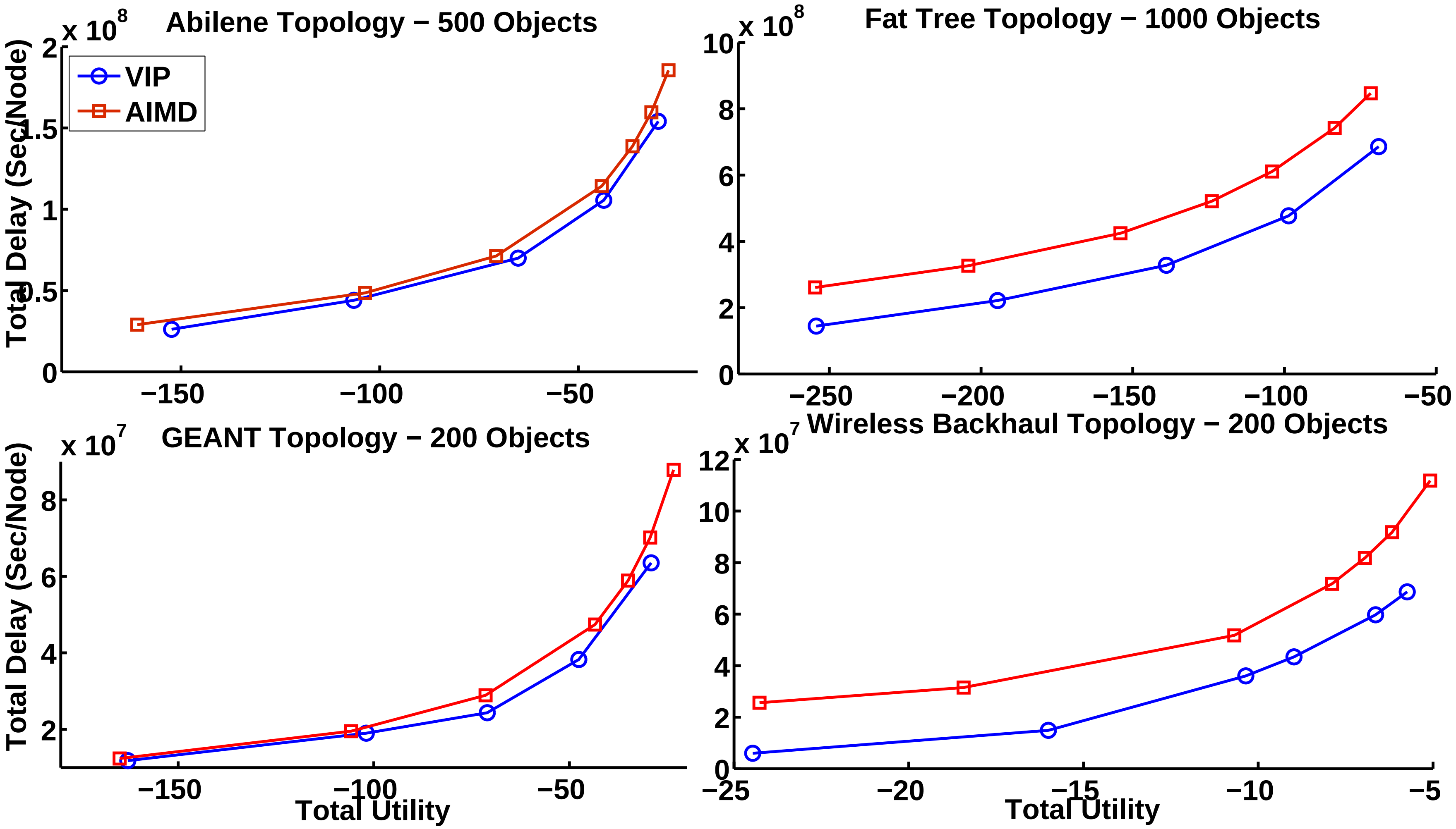
Network Parameters

- Abilene: 500 objects, cache size 500 MB (100 objects), link capacity 500 Mb/s; all nodes generate requests and can be data sources.

- Fat Tree: 1000 objects, cache size $1GB$ (200 objects); CONSUMER nodes generate requests, REPOs are source nodes.

- Wireless Backhaul: 200 objects, cache size $100MB$ (20 objects), link capacity 500 Mb/s; CONSUMER nodes generate requests, REPO is source node.

Numerical Experiments: Comparison with AIMD



Conclusions

- General VIP framework for caching, forwarding and congestion control.
- Distributed caching, forwarding, congestion control algorithms which maximize aggregate utility subject to network layer stability.
- Content-centric congestion control enables fairness among content types.
- Experimental results: superior performance in user delay, rate of cache hits, utility-delay tradeoff.
- VIP algorithms have flexible implementation wrt to caching, forwarding, congestion control.