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.
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

- \( \lambda_{kn}^k \) = long-term exogenous VIP arrival rate at node \( n \) for object \( k \):

- **VIP network stability region** \( \Lambda \) = set of all \( \lambda = (\lambda_{kn}^k)_{k \in \mathcal{K}, n \in \mathcal{N}} \) 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 \( \lambda \in \text{int}(\Lambda) \) without knowing \( \lambda \).

- 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

- $\theta$-optimal admitted VIP rate:

$$\bar{\alpha}^*(\theta) = \arg \max_{\bar{\alpha}} \sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{K}} g_n^k(\bar{\alpha}_n^k)$$

s.t. $\bar{\alpha} + \theta \in \Lambda$

$$0 \leq \bar{\alpha} \leq \lambda$$

- $g_n^k(\cdot)$: increasing, concave content-based utility functions.

- $\bar{\alpha} =$ IP (VIP) input rates admitted to network layer.

- $\theta =$ margin to boundary of VIP stability region $\Lambda$.

- Maximum sum utility achieved at $\bar{\alpha}^*(0)$ when $\theta = 0$.

- Tradeoff between sum utility attained and user delay.
Transport and Network Layer VIP Dynamics

• Transport-layer queue evolution:

\[ Q_n^k(t+1) = \min \left\{ (Q_n^k(t) - \alpha_n^k(t))^+ + A_n^k(t), Q_n^k_{\text{max}} \right\} \]  \hspace{1cm} (1)

• Network-layer VIP count evolution:

\[ V_n^k(t+1) \leq \left( \left( V_n^k(t) - \sum_{b \in \mathcal{N}} \mu_{nb}^k(t) \right)^+ + \alpha_n^k(t) + \sum_{a \in \mathcal{N}} \mu_{an}^k(t) - r_n s_n^k(t) \right)^+ \]  \hspace{1cm} (2)
Joint Congestion Control, Caching and Forwarding

- Virtual queues $Y^k_n(t)$ and auxiliary variables $\gamma^k_n(t)$.
- Initialize: $Y^k_n(0) = 0$ for all $k, n$.
- Congestion Control: for each $k$ and $n$, choose:
  \[
  \alpha^k_n(t) = \begin{cases} 
  \min \{Q^k_n(t), \alpha^k_{n,\text{max}}\}, & Y^k_n(t) > V^k_n(t) \\
  0, & \text{otherwise}
  \end{cases}
  \]
  \[
  \gamma^k_n(t) = \arg \max_{\gamma} W g^k_n(\gamma) - Y^k_n(t) \\
  s.t. \quad 0 \leq \gamma \leq \alpha^k_{n,\text{max}}
  \]
  where $W > 0$ is control parameter affecting utility-delay tradeoff.
  Based on chosen $\alpha^k_n(t)$ and $\gamma^k_n(t)$, transport layer queue updated as in (1) and virtual queue updated as:
  \[
  Y^k_n(t + 1) = \left(Y^k_n(t) - \alpha^k_n(t)\right)^+ + \gamma^k_n(t)
  \]
- 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 $\lambda$ inside or outside $\Lambda$, without knowing $\lambda$.

• Users need not know utility functions and demand rates of other users.

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

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

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

where $\hat{B} \triangleq \frac{1}{2N} \sum_{n \in \mathcal{N}} \left( (\mu_{n,\text{max}}^{\text{out}})^2 + (\alpha_{n,\text{max}} + \mu_{n,\text{max}}^{\text{in}} + r_{n,\text{max}})^2 + 2\mu_{n,\text{max}}^{\text{out}}r_{n,\text{max}} \right)$,

$\hat{\epsilon} \triangleq \sup\{\epsilon : \epsilon \in \Lambda\} \min_{n \in \mathcal{N}, k \in \mathcal{K}} \left\{ \epsilon_n^k \right\}$, \( \alpha_{n,\text{max}} \triangleq \sum_{k \in \mathcal{K}} \alpha_{n,max}^k \),

$$
G_{\max} \triangleq \sum_{n \in \mathcal{N}, k \in \mathcal{K}} g_n^k(\alpha_{n,\text{max}}^k), \quad \overline{\alpha}_n^k(t) \triangleq \frac{1}{t} \sum_{\tau=1}^{t} \mathbb{E}[\alpha_n^k(\tau)].
$$
Numerical Experiments
Network Parameters

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

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

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

- Wireless Backhaul: 500 objects, cache size $100\, MB$ (20 objects), link capacity $500\, Mb/s$; 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

- Abilene 5000 Objects – Delay
- GEANT 2000 Objects – Delay
- Fat Tree 1000 Object – Delay
- Wireless 500 Object – Delay

Arrival Rates (Requests/Node/Sec) vs Total Delay (Sec/Node) for different cache replacement algorithms.
Numerical Experiments: Cache Hit Performance
Numerical Experiments: Congestion Control

- $\alpha$-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 1 GB (200 objects); CONSUMER nodes generate requests, REPOs are source nodes.

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

Abilene Topology – 500 Objects

Fat Tree Topology – 1000 Objects

GEANT Topology – 200 Objects

Wireless Backhaul Topology – 200 Objects

VIP
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.