Named Data Networking for 5G Wireless

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Overview

- NDN: a major information-centric networking architecture built for content distribution.

- Enables full utilization of bandwidth and storage.

- VIP framework for optimal caching, forwarding and congestion control.

- Unified content-aware architecture for optimization of 5G wireless edge.

- Jointly optimize physical-layer resources with mobility, routing, caching, congestion control for high throughput, low latency and energy expenditure.

Named Data Networking

- Future Internet Architecture grant from NSF.
- UCLA, UCSD, UIUC, UC Irvine, PARC, Northeastern, Washington U, U Arizona, Colorado State, U Memphis.
- Intellectual leadership by Van Jacobson.
- Leading Information-centric Networking (ICN) architecture.
- Website: http://named-data.net

Networking Today

- IP (1974): end-to-end store and forward: focuses on machines talking to machines.
- Internet usage today is dominated by content distribution
- Video is king: Netflix $+$ Youtube $\sim$ 50% of downstream traffic!
- Popular videos on Youtube viewed 100 million times.
- Middleware such as CDNs and P2P try to mediate between applications and TCP/IP.
- Need more fundamental solution.

Importance of Storage

- Move bits in space and in time.
- Communication network (TCP/IP) uses limited storage: no caching.
- Distribution network: storage plays central role.
- Storage costs declining faster than bandwidth costs.
- Adding storage easier than adding bandwidth.

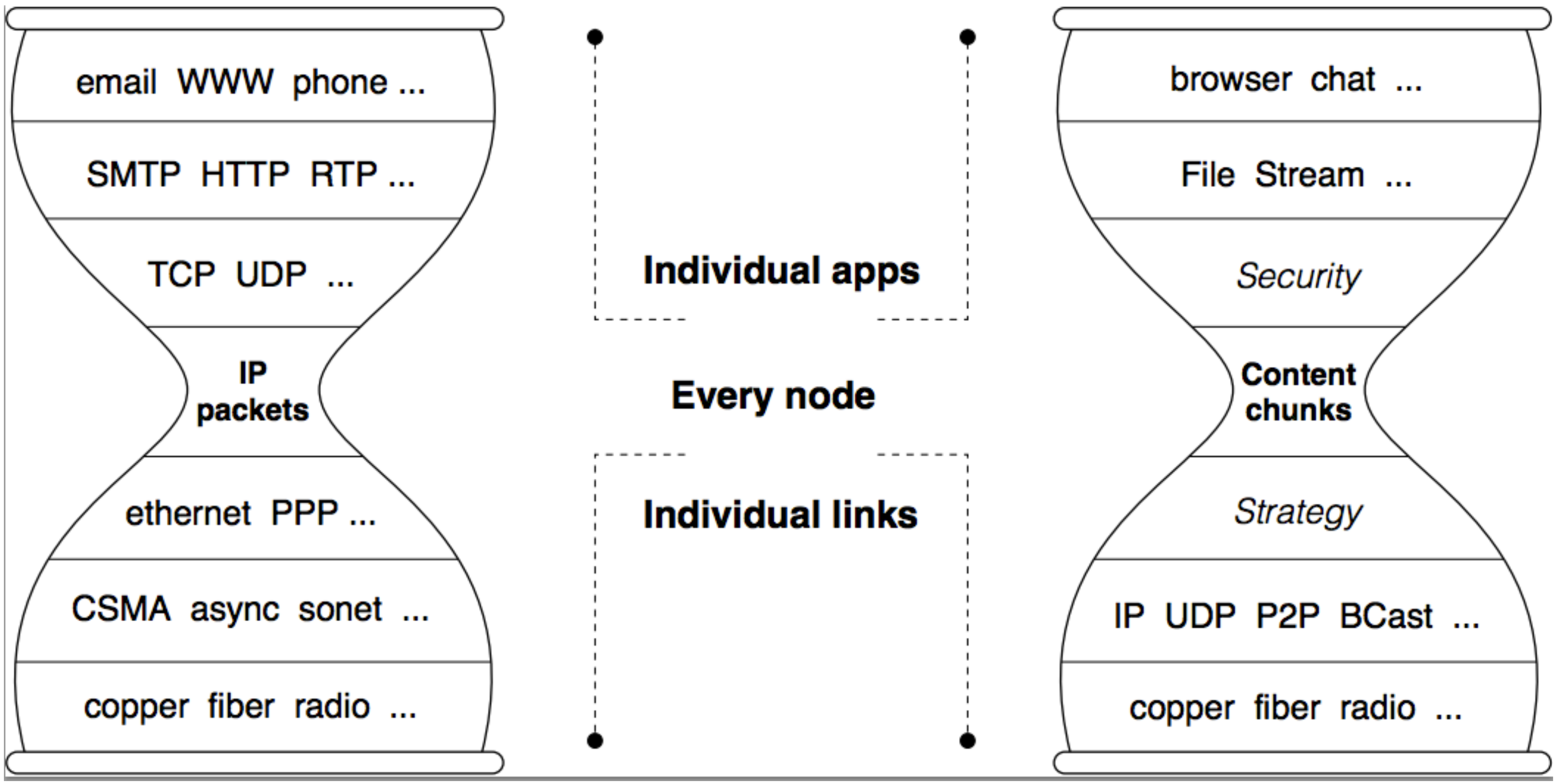
Basics of NDN

- Name data instead of endpoints: paradigm shift.
- No notion of end to end.
- To request data, send Interest Packet (IP) containing data name.
- IPs forwarded along routes determined by Forwarding Information Base (FIB) at each node.
- FIB tells node to which neighbor node(s) to transmit each IP.
- Incoming interface for received IPs recorded in Pending Interest Table (PIT) at each node. Multiple requests for same object collapsed/suppressed.

Basics of NDN

- When node receives IP it can fulfill, creates Data Packet (DP) containing requested data name, data object and digital signature.
- DP is transmitted back along path taken by corresponding IP, as recorded by PIT at each node. DP is multicast by node if corresponding IPs are collapsed/suppressed at node.
- Nodes on reverse path optionally cache data objects in received DPs.
- Request for data object fulfilled by content source or by any caching node.

Internet vs. NDN Hourglass



Caching and Forwarding for NDN

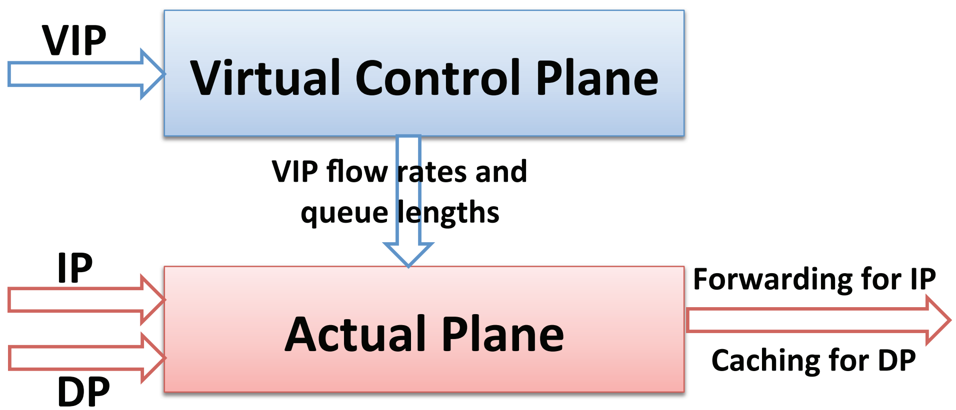
- Traditionally, caching designed separately from routing/forwarding.
- NDN: move bits both in space and in time.
- Optimally utilize both bandwidth and storage for content distribution: joint design of traffic engineering and caching strategies.
- Challenging theoretical problem.

VIP Framework

- VIP framework for dynamic caching and forwarding for NDN.
- Maximizes user demand rate satisfied by NDN network.
- Superior performance in user delay, cache hit rate.
- Distributed, dynamic algorithms for caching and forwarding under changing content, user demands, and network conditions.

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.

Throughput Optimal Caching and Forwarding

- VIP count used as common metric for determinin caching and forwarding in virtual and actual control planes.
- Forwarding strategy in virtual plane uses backpressure algorithm (Tassiulas and Ephremides 92) on VIP counts.
- First use of backpressure technique within ICN; applied within virtual plane.
- Caching strategy given by the solution of max-weight knapsack problem involving VIP counts.

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 = closure of 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 $\boldsymbol{\lambda}$.
- Algorithm exploits both bandwidth and storage resources to maximally balance out VIP load, preventing congestion buildup.
- Forwarding and caching in actual plane takes advantage of exploration in virtual plane to direct forwarding and caching of real IPs.

VIP Congestion Control

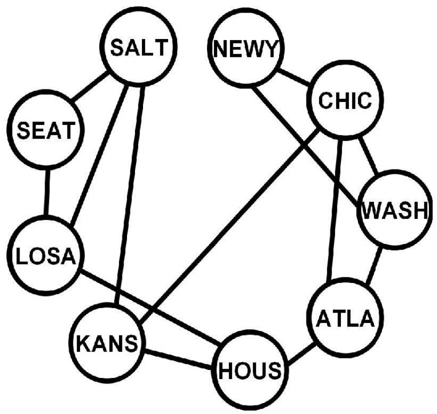
- Even with optimal caching and forwarding, excessively large request rates can overwhelm network.
- No source-destination pairs: TCP/IP congestion control algorithms inappropriate.
- Need content-based congestion control to cut back demand rates fairly.
- VIP framework: can optimally combine congestion control with caching and forwarding.

VIP Congestion Control

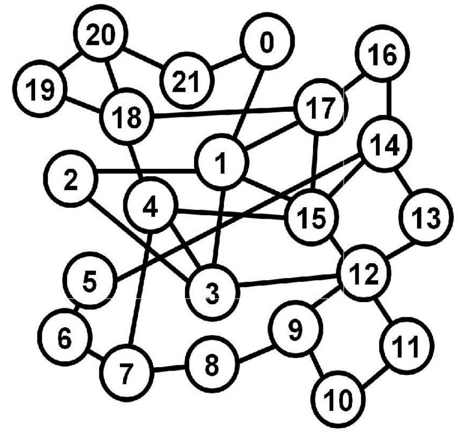
- Arriving IPs (VIPs) first enter transport layer queues before being admitted to network layer.
- VIP counts relay congestion signal to IP entry nodes via backpressure effect.
- Congestion control: support a portion of VIPs which maximizes sum of utilities subject to network layer VIP queue stability.
- Choice of utility functions lead to various fairness notions (e.g. max-min, proportional fairness).

Numerical Experiments

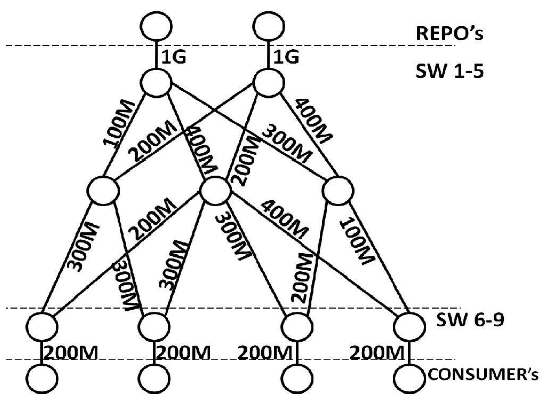
Abilene Topology



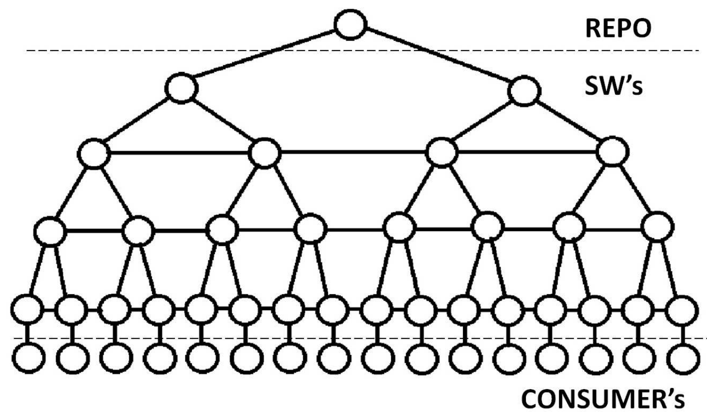
GEANT Topology



Fat Tree Topology



Wireless Backhaul Topology



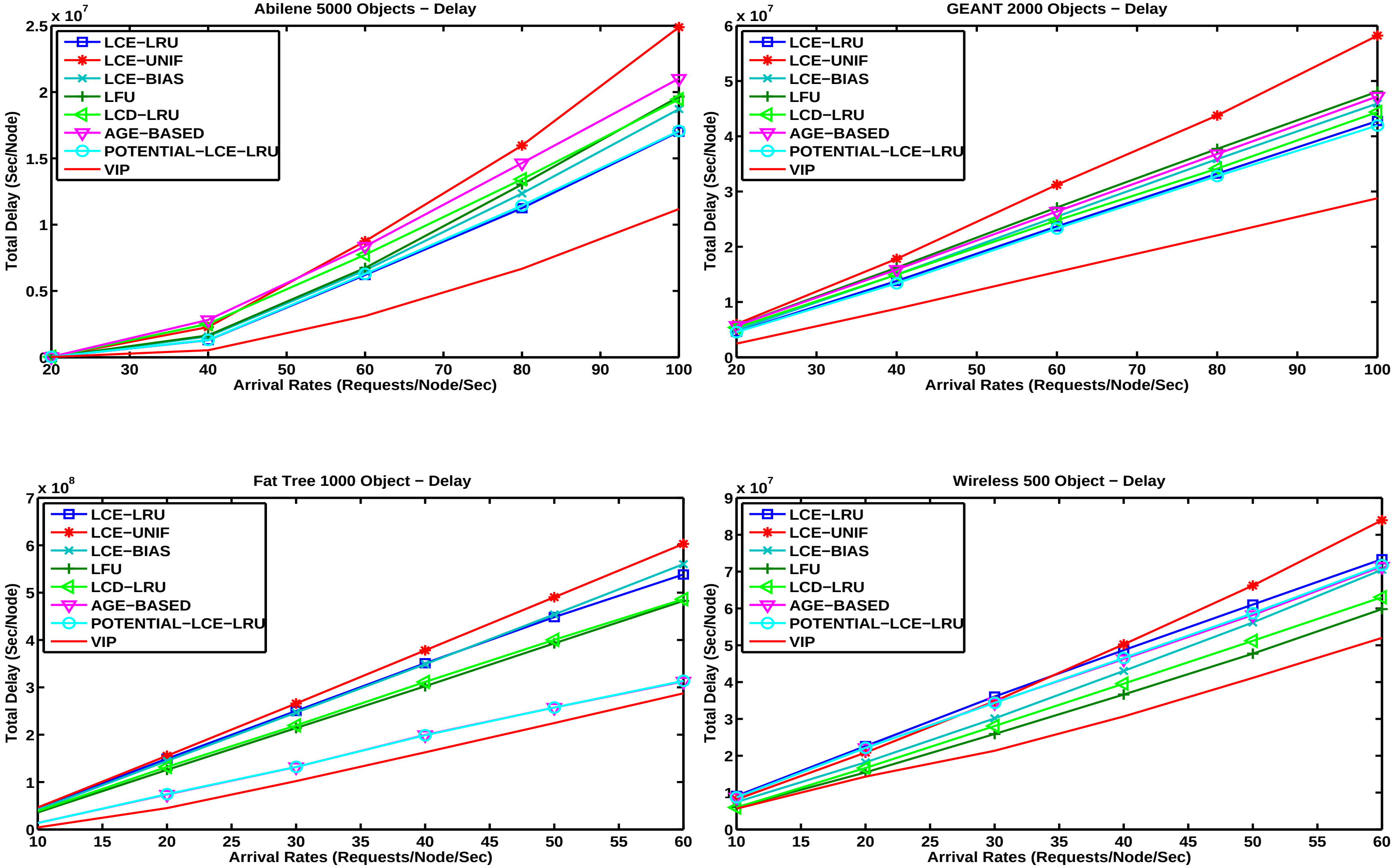
Network Parameters

- 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.

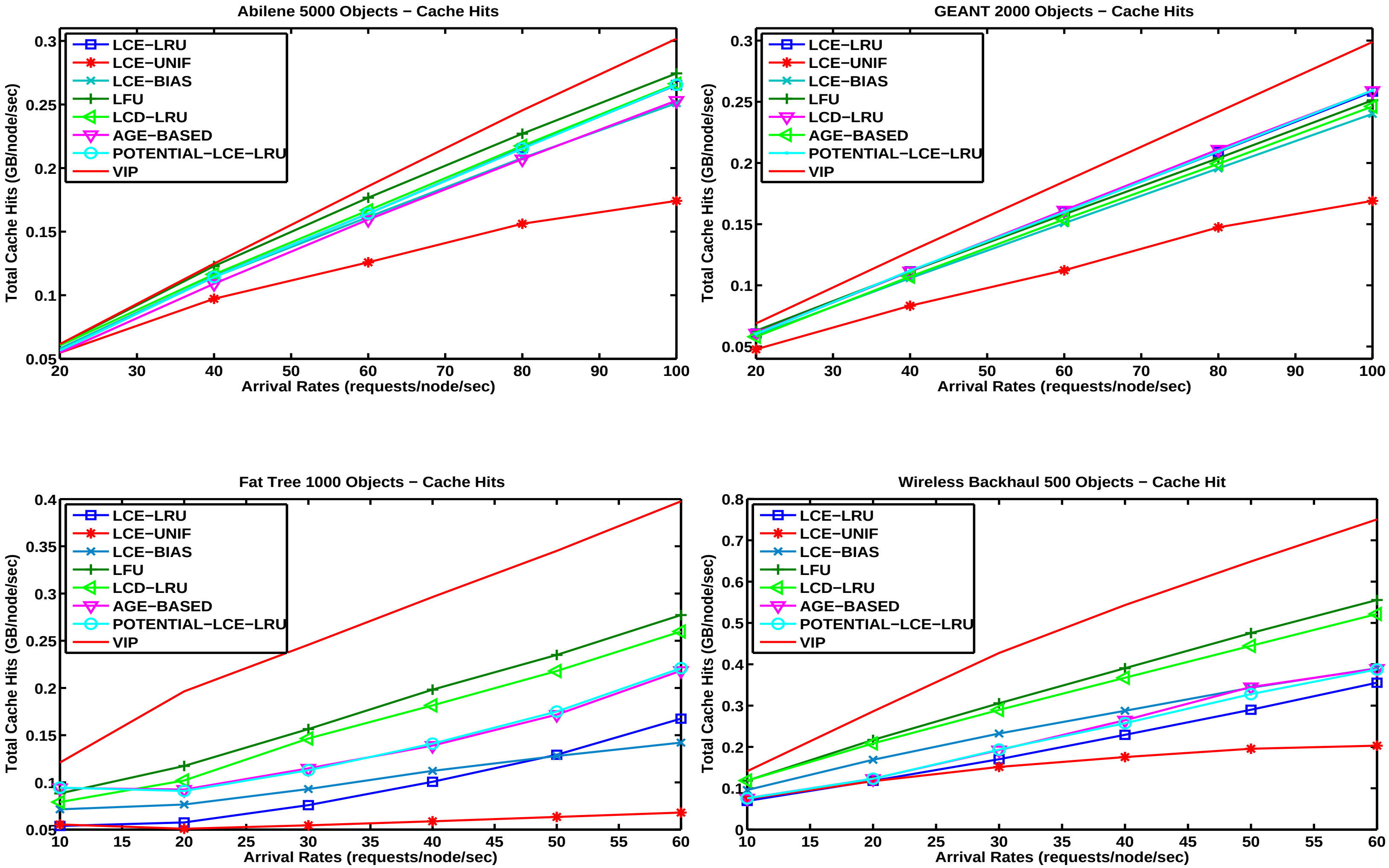
Numerical Experiments: Caching and Forwarding

- 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).

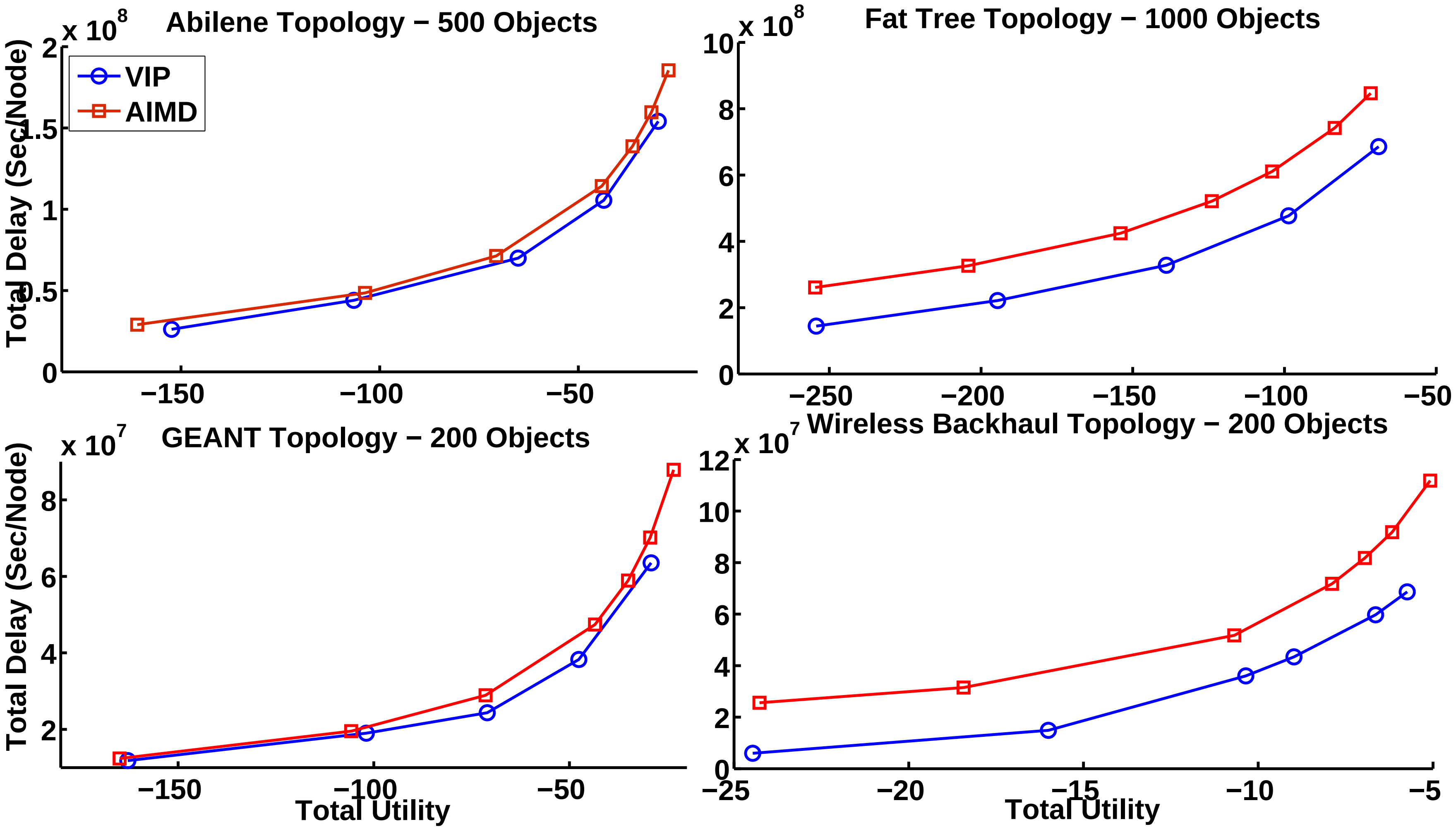
Network Parameters

- 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



NDN for 5G Wireless

- 5G: 1000$\times$ capacity, ultra-low response times, large-scale deployments.
- mmWave, cell densification, massive MIMO, CoMP, ICIC, C-RAN.
- TCP/IP: challenges in delivering multipath routing, multi-homing, multicasting, caching, mobility management, security, within wireless environment.
- NDN: built-in content caching, multipath forwarding, multicasting, multihoming, mobility management, intrinsic security.
- Build unified approach based on ICN to revolutionize design of 5G and B5G wireless edge networks.
- Content-aware optimization of entire wireless network stack from bottom hardware layer to top application layer
- Extend VIP approach for joint optimization for 5G wireless edge.

Conclusions

- NDN represents fundamental paradigm shift in networking.
- Joint traffic engineering and caching central to NDN,.
- General VIP framework for caching, forwarding and congestion control.
- Unified content-aware architecture for optimization of 5G wireless edge.
- Jointly optimize physical-layer resources with mobility, routing, caching, congestion control for high throughput, low latency and energy expenditure.