Optimal Congestion Control and Request Routing in Information-Centric Networking

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motivation

- CCN transport model
  - multi-point to point
  - unique end-point at the receiver
  - network nodes perform smart packet processing
- traffic management by request flow control and forwarding
- design lightweight protocols and run large scale experimentation
  - almost no tuning
  - repeatable experimentation (daily base)

outline

- Short introduction of CCN forwarding
- Network model description
- Network protocols
- Experimentation

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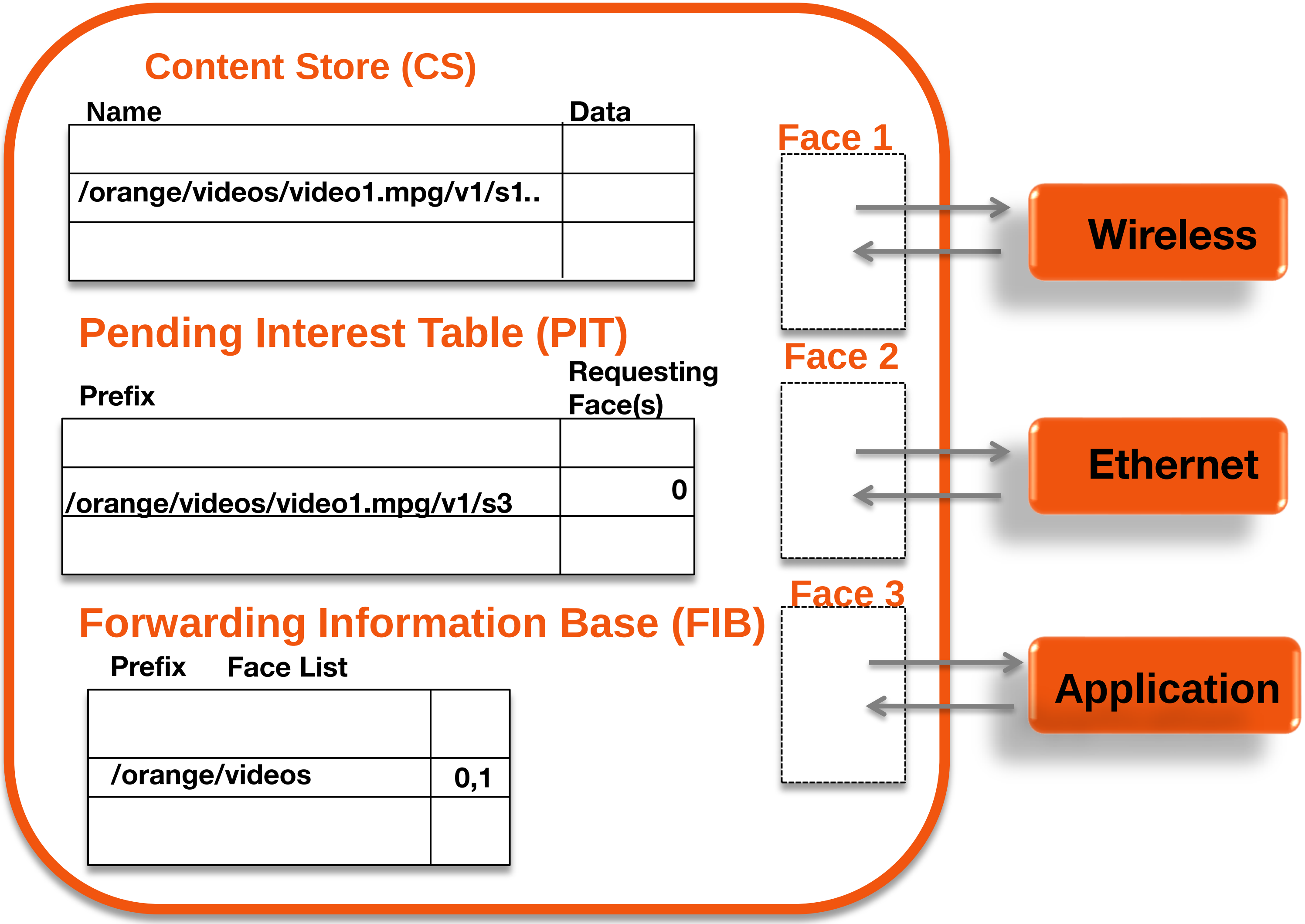
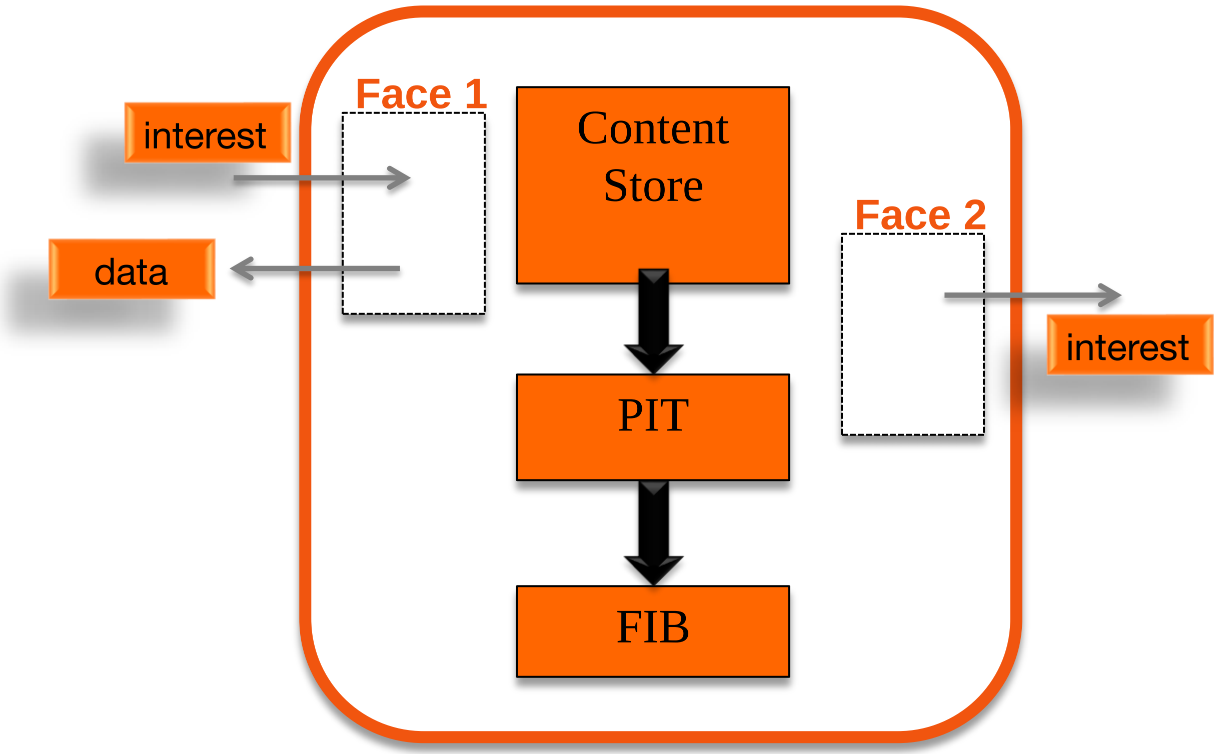
CCN node forwarding (1/3)

- an application:
  - requests content by expressions of INTEREST
  - only INTERESTs packets are routed
- a node receiving an INTEREST from an input face
  - sends DATA back to the input face if in the local content store
  - else checks a local matching pending interest
  - else checks a match in the local FIB
    - forward the INTEREST through the matching output interface

CCN node forwarding (2/3)



CCN forwarding (3/3)



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network model notation

- The network is modeled as a graph with bi-directional arcs $\mathcal{G} = (\mathcal{V}, \mathcal{A})$
- If INTEREST flows on link (i, j) DATA flows on the reverse link (j, i)
- Links have finite capacity $C_{ij} > 0, \forall (i, j) \in \mathcal{A}$
- A content retrieval $n \in \mathcal{N}$ is uniquely associated to a user node in $\mathcal{U} \subset \mathcal{V}$
- The variables x_{ij}^{n} denotes the DATA rate of flow $n \in \mathcal{N}$ over link (i, j)
- The variables $\tilde{x}_{ji}^{n}$ denotes the INTEREST rate of flow $n \in \mathcal{N}$ over link (j, i)
- The set of ingress nodes $\Gamma^{+}(i)$ for node $i \in \mathcal{V}$
- The set of egress nodes $\Gamma^{-}(i)$ for node $i \in \mathcal{V}$

- We define the function $h^{n}(i) \in \{0, 1\}$ to identify the location of content in the network

$$\mathcal{S}(n) = \{i : h^{n}(i) = 1\}$$

global objectives

$$\begin{cases} \boxed{\max_{\boldsymbol{y}} \sum_n \boldsymbol{U}_n(y_i^n) - \sum_{i,j \in \mathcal{A}} \boldsymbol{C}_{ij}(\rho_{ij})} \\ \sum_{n \in \mathcal{N}} x_{ij}^n = \rho_{ij} \qquad \forall (i,j) \in \mathcal{A} \\ \sum_{\ell \in \Gamma^-(i)} x_{\ell i}^n = y_i^n, \quad \forall i, n \\ \sum_{j \in \Gamma^+(i)} x_{ij}^n (1 - h^n(i)) = y_i^n \qquad \forall i \notin \mathcal{U}, n \\ \rho_{ij} \leq C_{ij} \qquad \forall (i,j) \in \mathcal{A} \\ x_{ij}^n \geq 0 \qquad \forall i, j, n \end{cases}$$

User utility maximization and network cost minimization

link load

node ingress traffic

flow conservation constraint

link capacity constraint

primal decomposition

$$\begin{cases} \min\limits_{\boldsymbol{x}} \sum\limits_{i,j \in \mathcal{A}} \boldsymbol{C}_{ij} \left(\sum\limits_{n \in \mathcal{N}} x_{ij}^n \right) \\ \sum\limits_{\ell \in \Gamma^-(i)} x_{\ell i}^n = y_i^n, \quad \forall i, n \\ \sum\limits_{j \in \Gamma^+(i)} x_{ij}^n (1 - h^n(i)) = y_i^n \qquad \forall i \notin \mathcal{U}, n \\ x_{ij}^n \geq 0 \qquad \forall (i,j) \in \mathcal{A} \qquad \forall n \in \mathcal{N} \end{cases}$$

master problem
network cost minimization

$$\begin{cases} \max\limits_{\boldsymbol{y}} \sum\limits_{n} \boldsymbol{U}_n(y^n) \\ \sum\limits_{n:(i,j) \in \mathcal{L}(n)} y^n \leq C_{ij} \qquad \forall (i,j) \in \mathcal{A} \\ y^n \geq 0 \qquad \forall n \in \mathcal{N} \end{cases}$$

sub-problems
at the receivers

network cost minimization P1

$$
\begin{cases}
\min\limits_{\boldsymbol{x}} \sum\limits_{i,j \in \mathcal{A}} \boldsymbol{C}_{ij} \left(\sum\limits_{n \in \mathcal{N}} x_{ij}^n \right) \\
\sum\limits_{\ell \in \Gamma^-(i)} x_{\ell i}^n = y_i^n, \quad \forall i, n \\
\sum\limits_{j \in \Gamma^+(i)} x_{ij}^n (1 - h^n(i)) = y_i^n \qquad \forall i \notin \mathcal{U}, n \\
x_{ij}^n \geq 0 \qquad \forall (i,j) \in \mathcal{A} \qquad \forall n \in \mathcal{N}
\end{cases}
$$

Lagrangians for P1

$$L_C(\boldsymbol{x}, \boldsymbol{\mu}) =$$

$$\sum_{i,j} \boldsymbol{C}_{ij} \left(\sum_{n \in \mathcal{N}} x_{ij}^n \right) - \sum_n \sum_i \mu_i^n (\sum_{l \in \Gamma^-(i)} x_{li}^n - \sum_{j \in \Gamma^+(i)} x_{ij}^n)$$

$$= \sum_{i,j} \boldsymbol{C}_{ij}(\rho_{ij}) - \sum_n \sum_{i,l} \mu_i^n x_{li}^n + \sum_n \sum_{i,j} \mu_i^n x_{ij}^n$$

$$= \sum_i \boxed{\sum_{l \in \Gamma^-(i)} [\boldsymbol{C}_{li}(\rho_{li}) - \sum_n (\mu_i^n - \mu_l^n) x_{li}^n]}$$

user utility maximization P2

$$
\begin{cases}
\max\limits_{\boldsymbol{y}} \sum\limits_{n} \boldsymbol{U}_n(y^n) \\
\sum\limits_{n:(i,j)\in\mathcal{L}(n)} y^n \leq C_{ij} \qquad \forall (i,j) \in \mathcal{A} \\
y^n \geq 0 \qquad \forall n \in \mathcal{N}
\end{cases}
$$

Lagrangian for P2

$$L_{\boldsymbol{U}}(\boldsymbol{y}, \boldsymbol{\lambda}) = \sum_n \boldsymbol{U}_n(y^n) - \sum_{ij} \lambda_{ij}\Big(\sum_{n:(i,j)\in\mathcal{L}(n)} y^n - C_{ij}\Big)$$

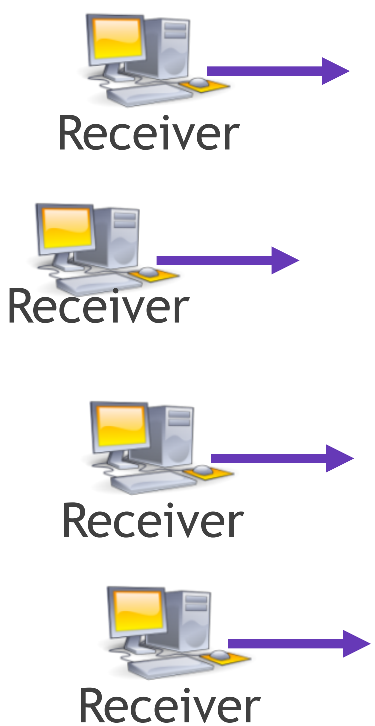
$$= \sum_n \boldsymbol{U}_n(y^n) - \sum_n \sum_{(i,j)\in\mathcal{L}(n)} \lambda_{ij} y^n + \sum_{ij} \lambda_{ij} C_{ij}$$

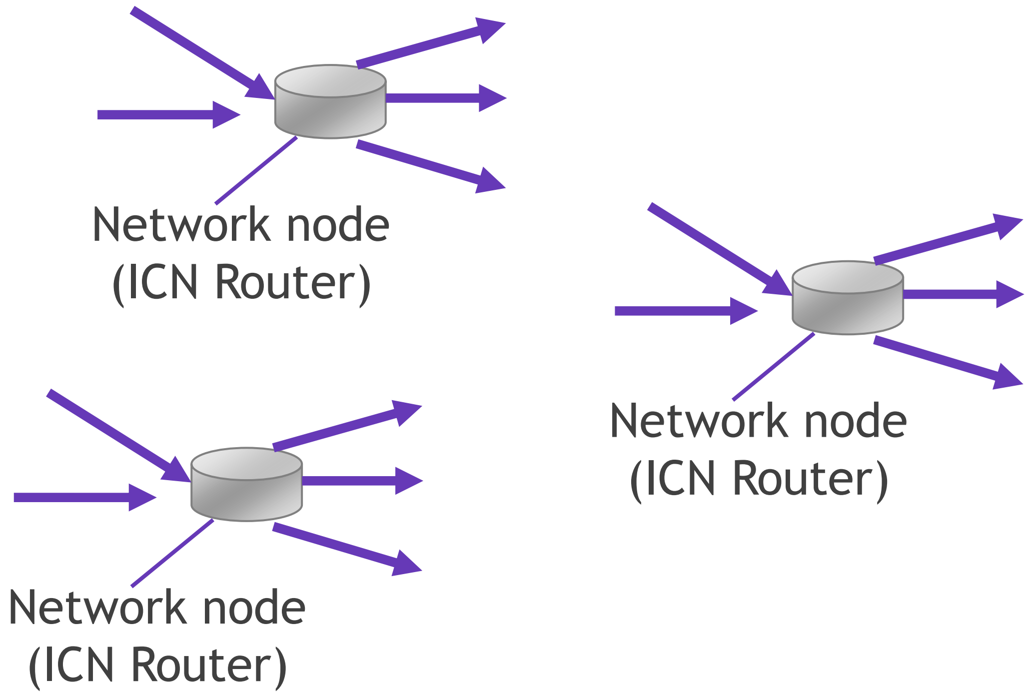
$$= \sum_n \boxed{(\boldsymbol{U}_n(y^n) - \lambda^n y^n)} + \sum_{(i,j)} \lambda_{ij} C_{ij}$$

$$\lambda^n \equiv \sum\nolimits_{(i,j)\in\mathcal{L}(n)} \lambda_{ij}$$

optimal distributed solution

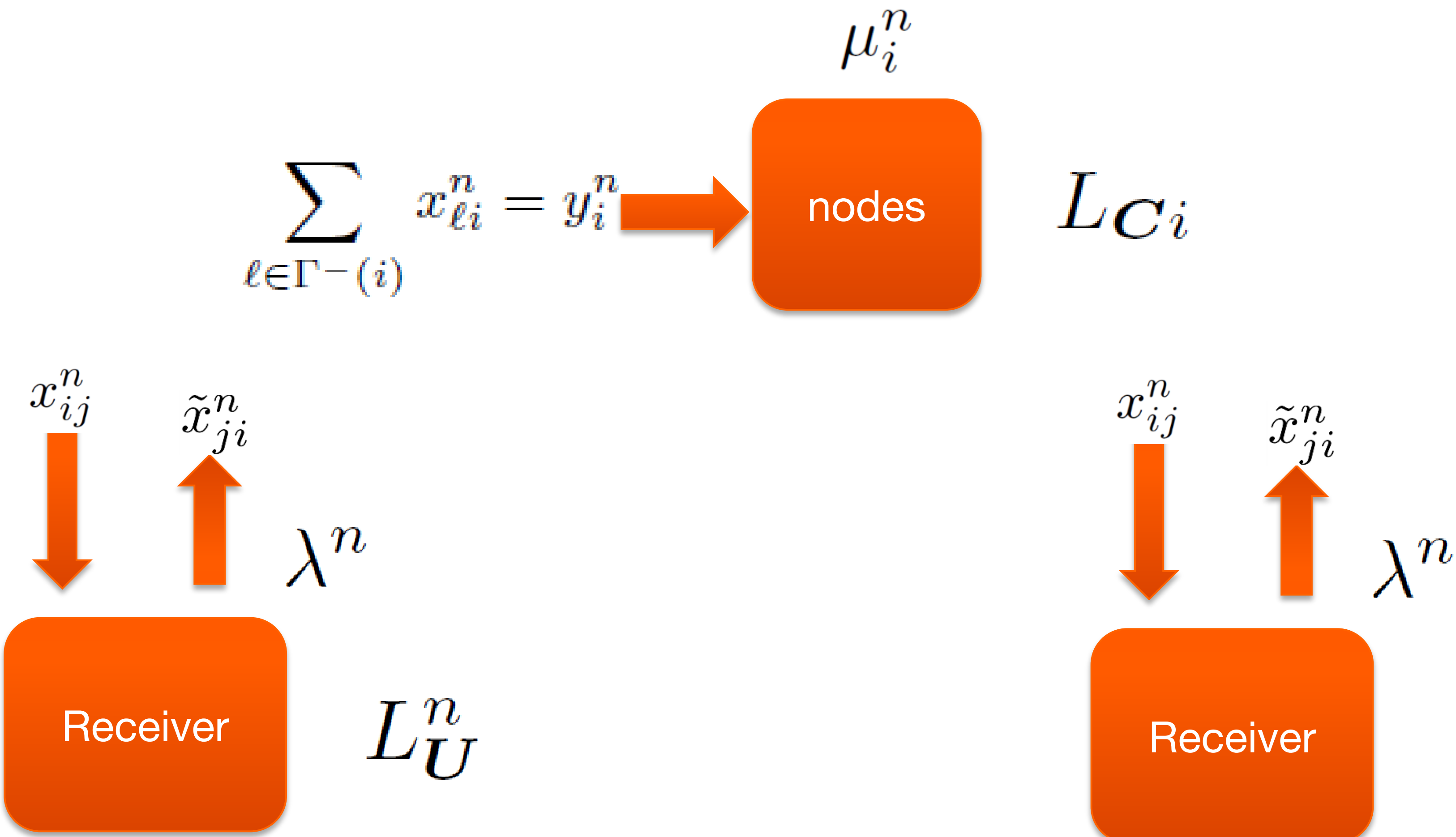
$$L_{\boldsymbol{U}}^n = \boldsymbol{U}_n(y^n) - \lambda^n y^n$$





$$L_{\boldsymbol{C}i} = \sum_{l \in \Gamma^-(i)} \left[\boldsymbol{C}_{li}(\rho_{li}) - \sum_n (\mu_i^n - \mu_l^n) x_{li}^n\right]$$

algorithm main functioning



local Lagrangians optimization

- standard techniques based on gradients
  - minimization of $L_{\boldsymbol{C}i}$
  - maximization of $L_{\boldsymbol{U}}^{n}$
- Gradient based solutions

$$\nabla f(x_1, \ldots, x_N, \ldots, \mu_l, \ldots) \cdot e_i = \frac{\partial x_i}{\partial t}$$

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receiver driven congestion control (1/2)

- computation of link Lagrange multipliers
- compute path aggregate $\lambda^n \equiv \sum_{(i,j)\in\mathcal{L}(n)} \lambda_{ij}$
- maximize local Lagrangian

$$\frac{d}{dt}\lambda_{ij}(t) = \kappa_{ij}(t)\Big(\sum_{n:(i,j)\in\mathcal{L}(n)} y^n(t) - C_{ij}\Big)$$

$$\frac{d}{dt}y^n(t) = \gamma^n(t)(\boldsymbol{U}'_n(y^n(t)) - \lambda^n(t))$$

receiver driven congestion control (2/2)

- by taking $\kappa_{ij}(t) = \frac{1}{C_{ij}}$

$$\frac{d}{dt}\lambda_{ij}(t) = \kappa_{ij}(t)\Big(\sum_{n:(i,j)\in\mathcal{L}(n)} y^n(t) - C_{ij}\Big)$$

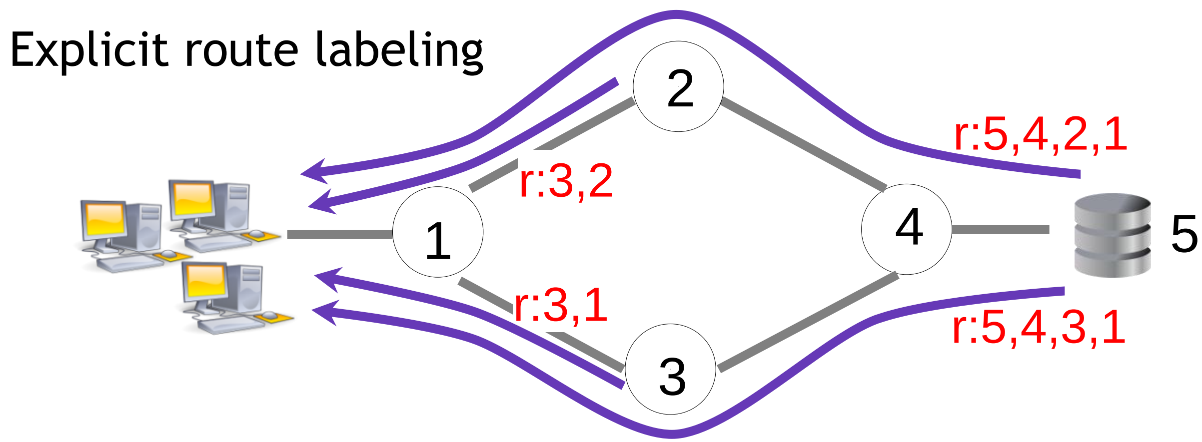
- Fluid queue delay evolution at a link
- So that $\lambda^n(t)$ is the total path delay associated to a given flow
- The INTEREST/DATA protocol can be used to measure such delay at the receiver

per-path delay measurements

- give a label to a path so that the receiver can keep per path statistics

$$\lambda^n(r,t) = \sum_{(i,j)\in r : r\in\mathcal{R}^n} \lambda_{ij}(t)$$

$$\frac{d}{dt} y^n(t) = \gamma^n(t)(\boldsymbol{U}'_n(\tilde{y}^n(t)) - \sum_{r\in\mathcal{R}^n(s)} \lambda^n(r,t)\phi(r,t))$$



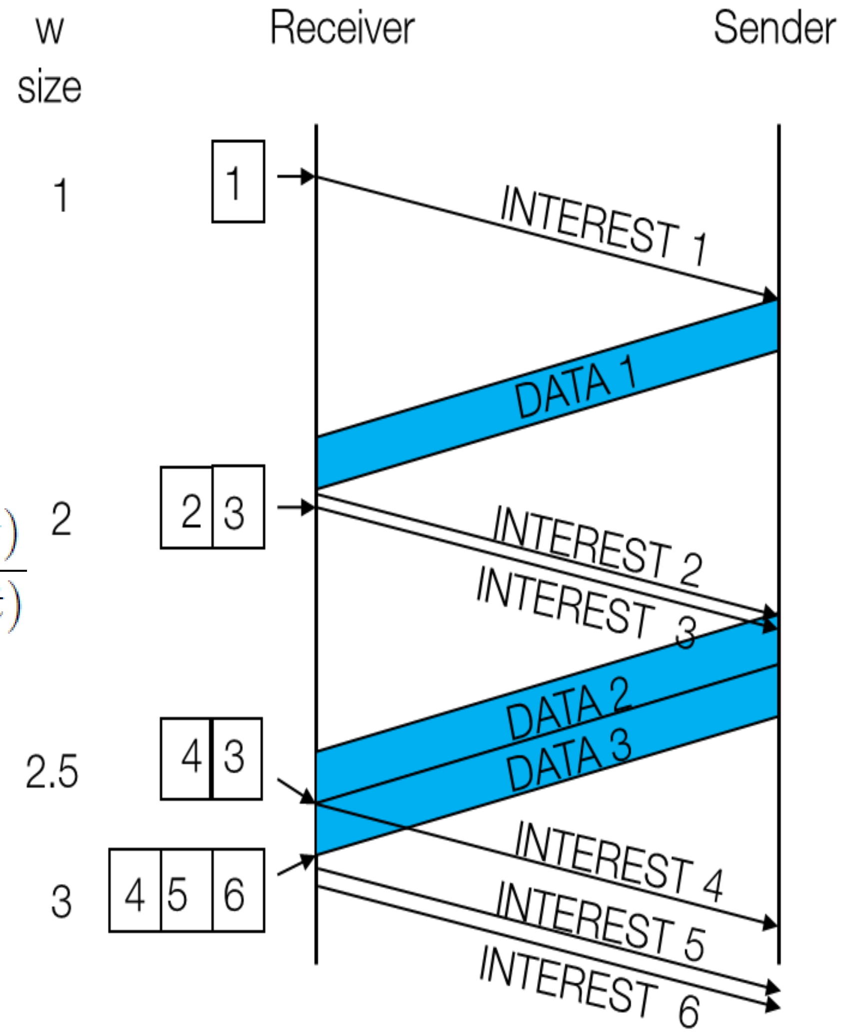
the network protocol:
window based flow control @RX

$$y^n \longrightarrow \widetilde{y^n}$$

$$p_r(t) = p_{\min} + \Delta p_{\max} \frac{R_r(t) - R_{\min,r}(t)}{R_{\max,r}(t) - R_{\min,r}(t)}$$

$$\frac{d}{dt} W(t) = \frac{\eta}{R(t)} - \beta W(t) \sum_{r \in \mathcal{R}} p_r(t) \phi_r(t) \frac{W(t)}{R_r(t)}$$

- one single window
- splitting is managed by the forwarding engine
- congestion signals decomposed in paths



request forwarding (1/2)

- The local Lagrangian minimization at every network node is equivalent to minimizing the Lagrangian multiplier μ_i^n
- proof by imposing Karush-Kuhn-Tucker condition on the local Lagrangians

$$\frac{\partial \boldsymbol{C}_{ji}}{\partial x_{ji}^n} = \frac{\partial \boldsymbol{C}_{ji}}{\partial \rho_{ji}} \frac{\partial \rho_{ji}}{\partial x_{ji}^n} = \frac{\partial \boldsymbol{C}_{ji}}{\partial \rho_{ji}} = \mu_i^n - \mu_j^n$$

$$\frac{\partial \boldsymbol{C}_{ji}}{\partial x_{ji}^n} \leq \frac{\partial \boldsymbol{C}_{li}}{\partial x_{li}^n}, \qquad \forall l \in \Gamma^-(i)$$

- by iterating up to a hitting cache

$$\mathcal{S}(n) = \{i : h^n(i) = 1\}$$

request forwarding (2/2)

- using a gradient algorithm we can obtain the Lagrangian multipliers μ_i^n
- which have a protocol interpretation: they are the total number of pending interest for a given flow (content item)

$$x_{ij}^n \longrightarrow \widetilde{x_{ji}^n}$$

$$\frac{d\mu_i^n}{dt} = \eta_i^n \left(\sum_{j \in \Gamma^+(i)} x_{ij}^n - \sum_{l \in \Gamma^-(i)} x_{li}^n \right)$$

Pending Interest Table (PIT)

chunk name	interface
ccnx:/data/**4**	1,2
ccnx:/data/**3**	1
ccnx:/data/**6**	1

local optimization of PIT size

- minimize the sum of pending interests on all interfaces

$$\mu = \sum_{j \in \Gamma^-(i)} \mu_j$$

$$\sum_{j \in \Gamma^-(i)} x_j = y$$

- drawbacks
  - the optimal solution of this problem has zero rate on some interfaces
  - additional probing techniques
  - requires to know an analytical expression of the delay

changing the objective

- minimize the most loaded interface

$$\min \max_j \mu_j(x_j)$$
$$\sum_{j\in\Gamma^-(i)} x_j \;=\; y$$

- advantages
  - the solution is very simple $\mu_j = \mu$

$$\mu = \lim_{T\to\infty} \frac{1}{T}\int_0^T \mu_j(t)dt = \lim_{T\to\infty} \frac{\int_0^T x_j(t)\mathrm{VRTT}_j(x_j(t))dt}{\sum_l \Delta T_l}$$
$$= \frac{\Delta \bar{T}_j}{\sum_l \Delta \bar{T}_l} y \mathrm{VRTT}_j(y) = \phi_j \bar{\mu}_j$$

$$\phi_j \;=\; \mu/\bar{\mu}_j \qquad\qquad 1/\mu \;=\; \sum_j \mu_j$$

request forwarding network protocol

- the number of pending interests for a given name prefix is available in the PIT
- filter out high variable components with low pass filters
- load balance future requests using a randomized load balancer $\phi_j = \mu/\bar{\mu}_j$

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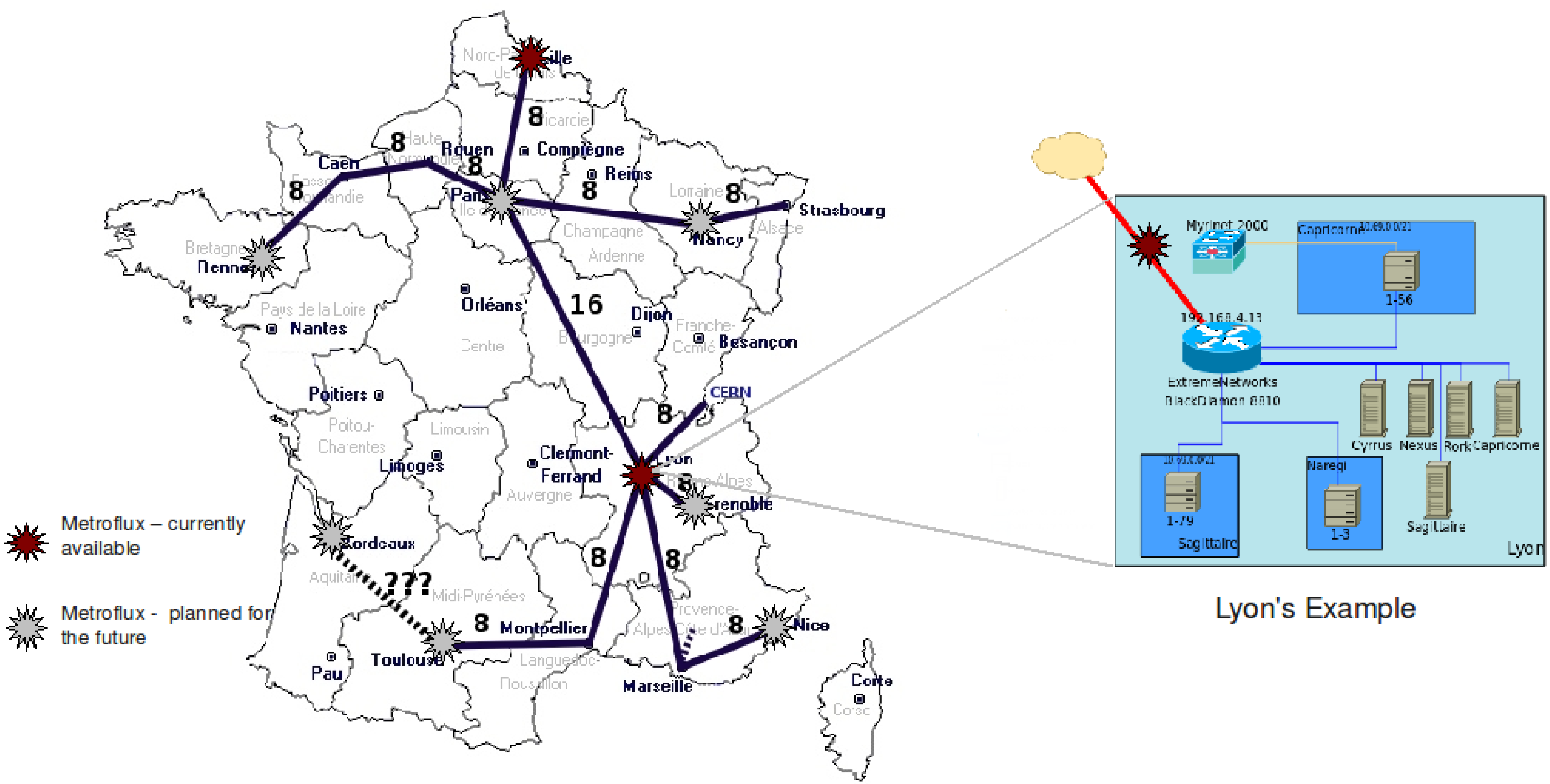
implementation

- we implemented the above described mechanisms in CCNx-0.6.1 (works on latest releases also)
- novel caching framework
  - flexible to implement your preferred caching system
  - LRU for this paper
- new strategy layer
  - exploit an “almost” clean available “API”
- a new data retrieval application (Interest generator)
  - implementation of flow control + path labeling in nodes
- new virtual repo based on WashU (thanks Patrick)
  - allows for large scale virtual content repositories
  - with ccnr you would spend 90% of your test filling repos.

Experimentation

- we performed several experiments in a data center
  - dynamic bootable 3.x linux kernels images
  - CCNx overlay over IP tunnels among servers
  - IP over IP as a layer 2 encapsulation only
  - Linux tc to shape IP overlay link rates
  - pre-configured CCNx routing to fill FIBs
- we analyzed 4 different scenarios:
  - scenario 1: efficiency in multipath flow control
  - scenario 2: impact of in-network caching
  - scenario 3: request forwarding scalability
  - scenario 4: link failure reaction

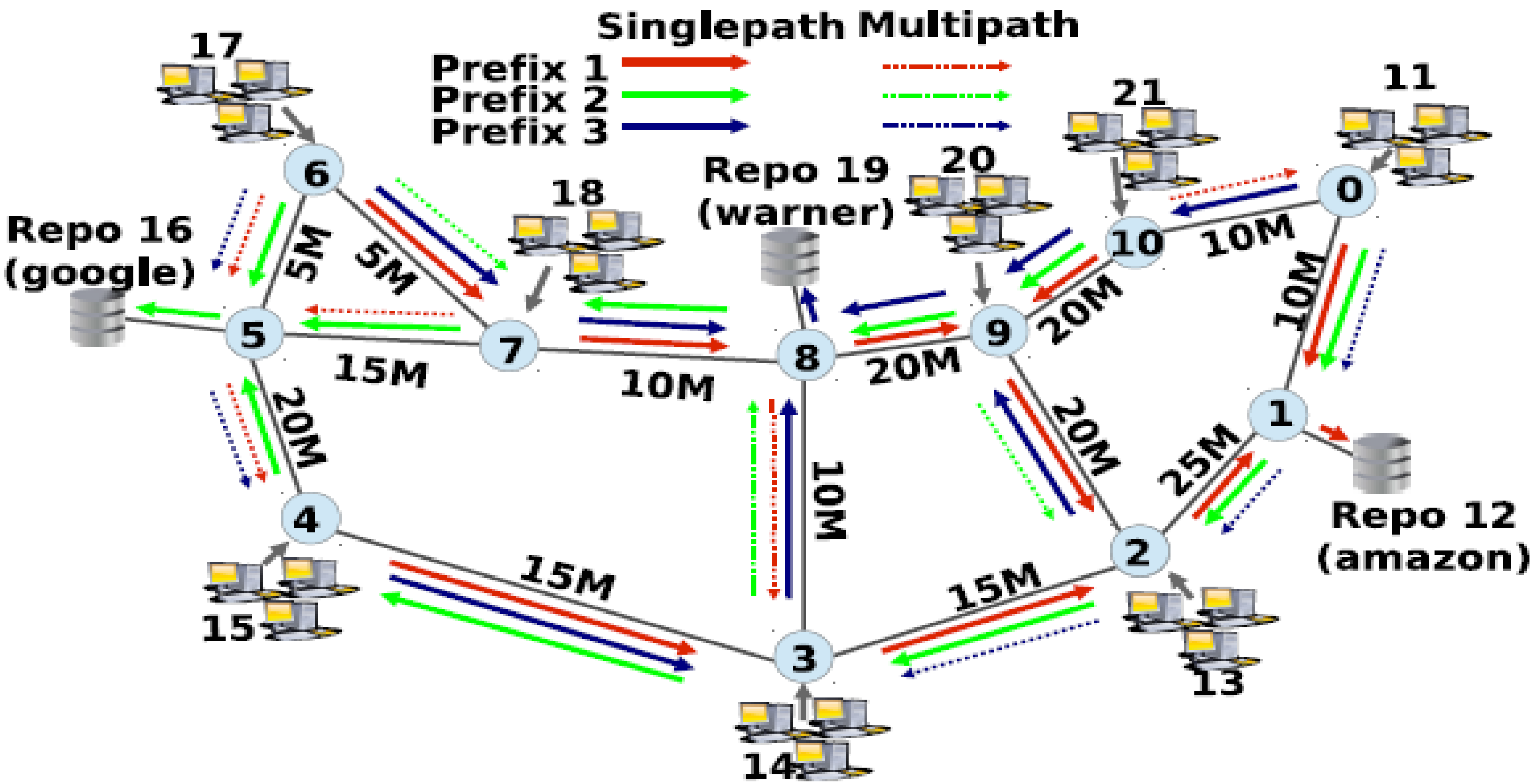
data center for large scale experimentation: the Grid5000



Lyon's Example

Example of cluster in Grid5000

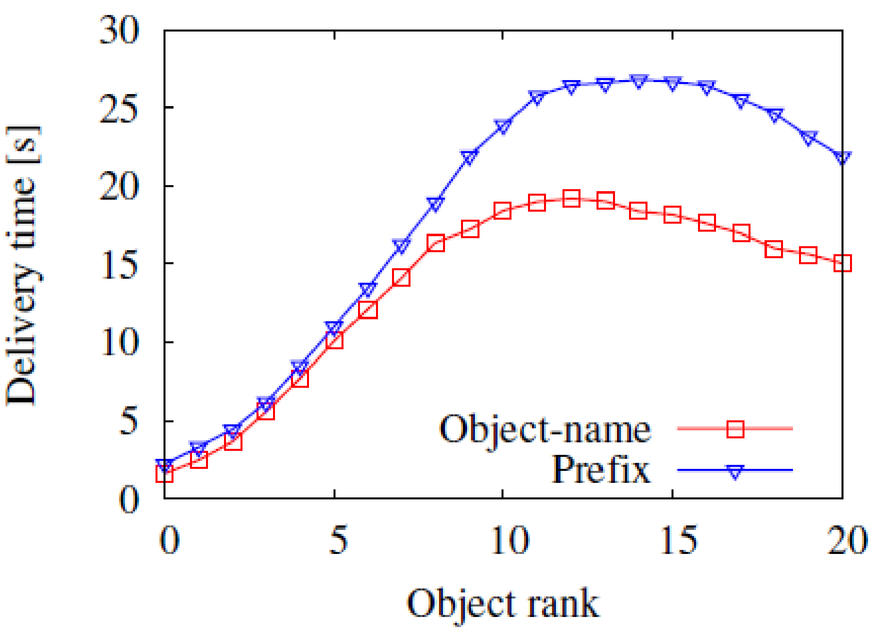
scenario 3

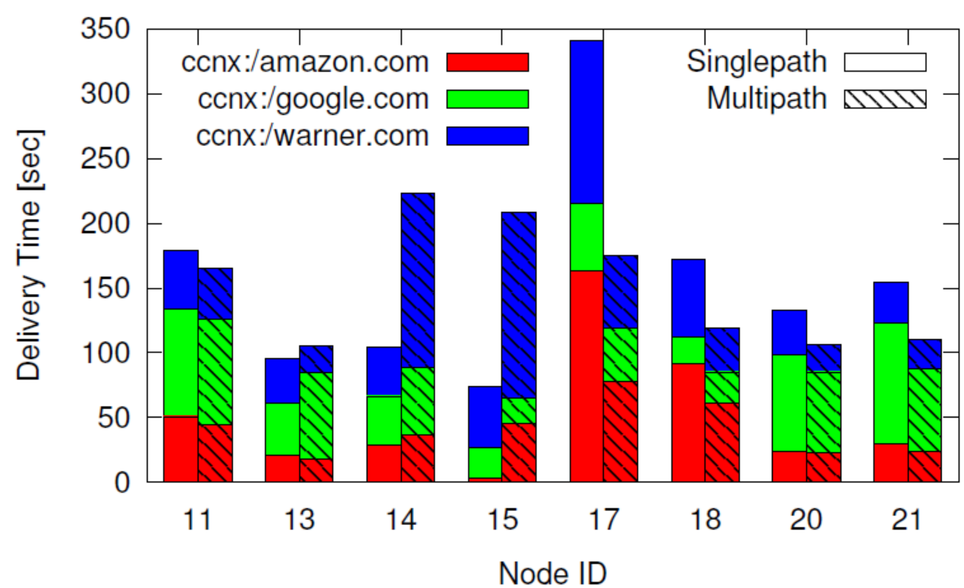


- Dynamic workload: Poisson + Zipf content popularity
- Flow level load: “data object retrieval rate” X “Size” / Capacity < 1
- Three content providers within a name prefix: Amazon, Google, Warner

experimental results – scenario 3

- observations
  - 100% utilization of bandwidth bottlenecks
  - caching benefits downstream bandwidth bottlenecks
  - per-prefix forwarding scalable but suboptimal
- caching benefits for popular content
- multipath benefits for less popular content
- for some content items trade-off between caching and multipath can be reached extracting some name-prefixes from the PIT for the FIB





conclusion and current work

- CCN forwarding plane can be optimized with lightweight protocols
  - the forwarding engine is reach enough to build simple protocols
  - multi-point communication is intrinsically supported by the underlying communication model
- protocol development and large scale experimentation helps improving current prototypes
  - software/hardware prototyping at 40Gbps
  - no high speed with the current software

Questions