An Adaptive Multi-channel P2P Video-on-Demand System using Plug-and-Play Helpers

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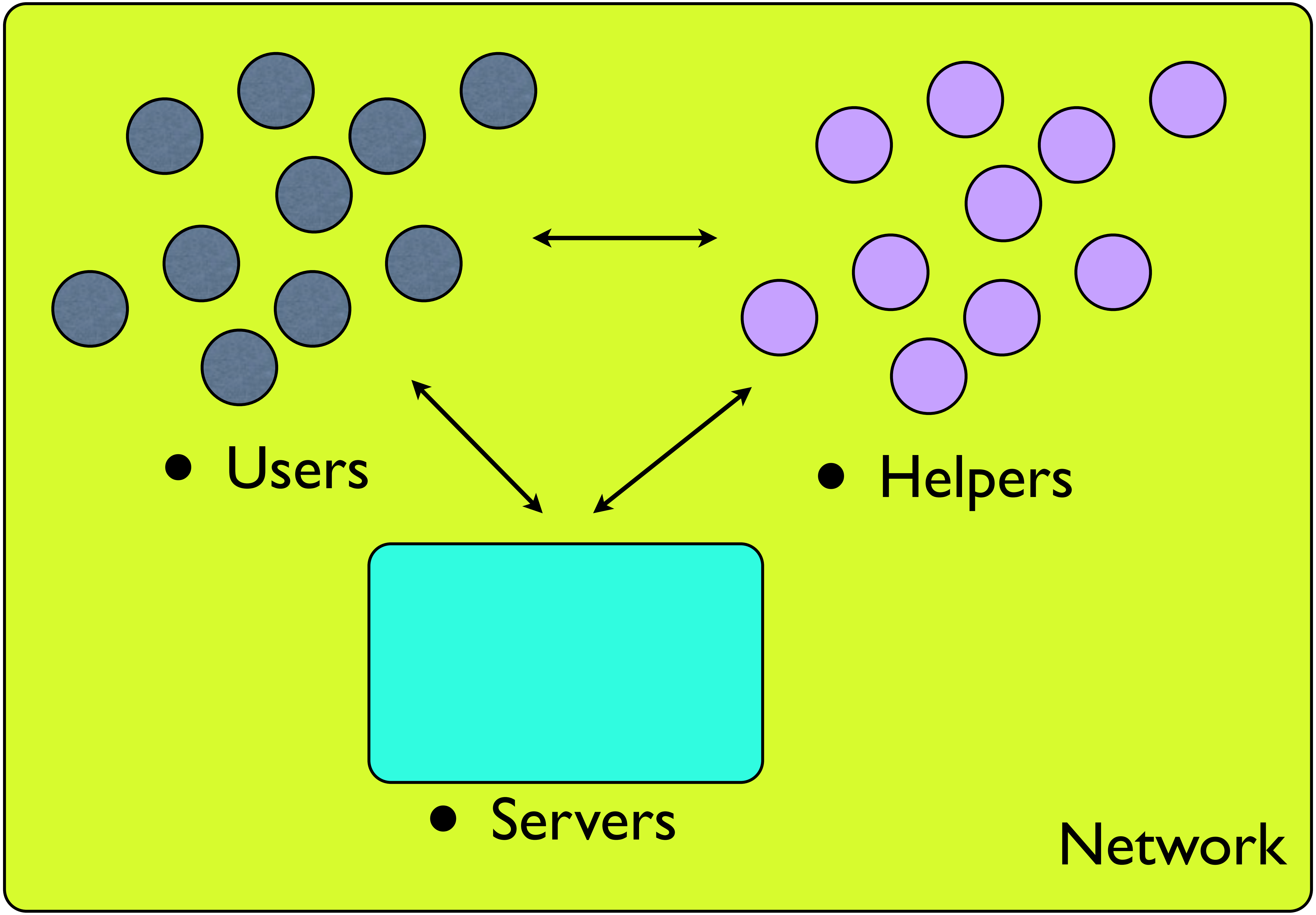
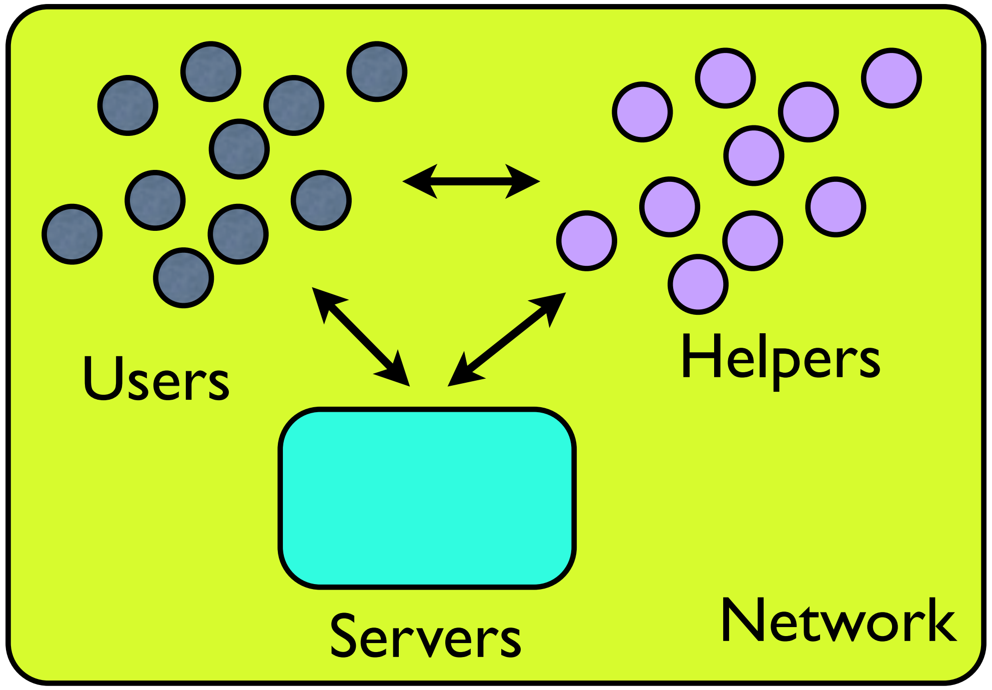
General Problem

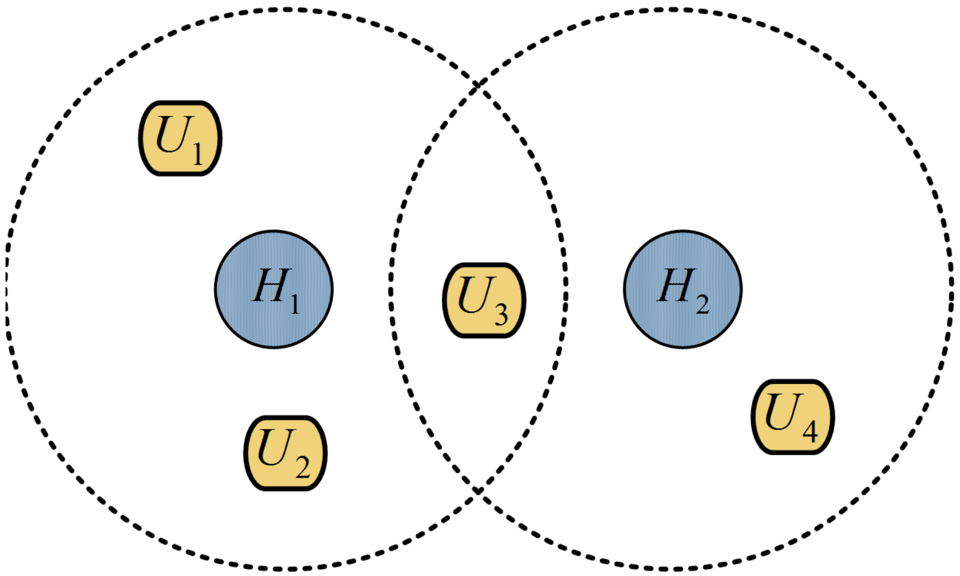


General Problem



Applications
-P2P File sharing
-P2P VoD
-Distributed storages
-Wireless cachcing
...

example



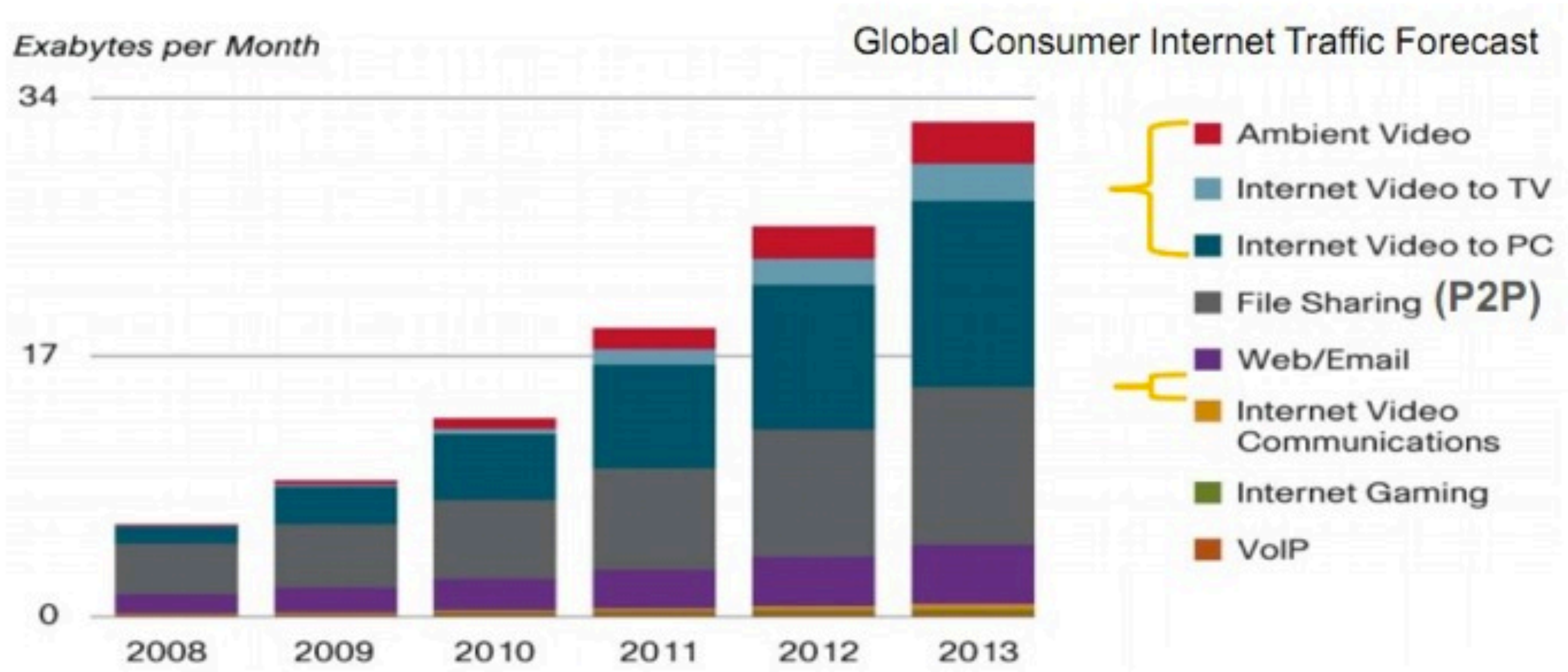
$$\begin{aligned} \text{maximize} \quad & \sum_{k=1}^{K} \omega_k \sum_{n \in A_k} P_n \\ \text{subject to} \quad & |C_h| \leq M, \quad \forall\, h \\ & A_k = \cup_{h \in \mathcal{N}(k)} C_h, \quad \forall\, k \end{aligned}$$

- "FemtoCaching: Wireless Video Content Delivery through Distributed Caching Helpers", Negin Golrezaei, Karthikeyan Shanmugam, Alexandros G. Dimakis

P2P VoD

Exponentially growing demands!

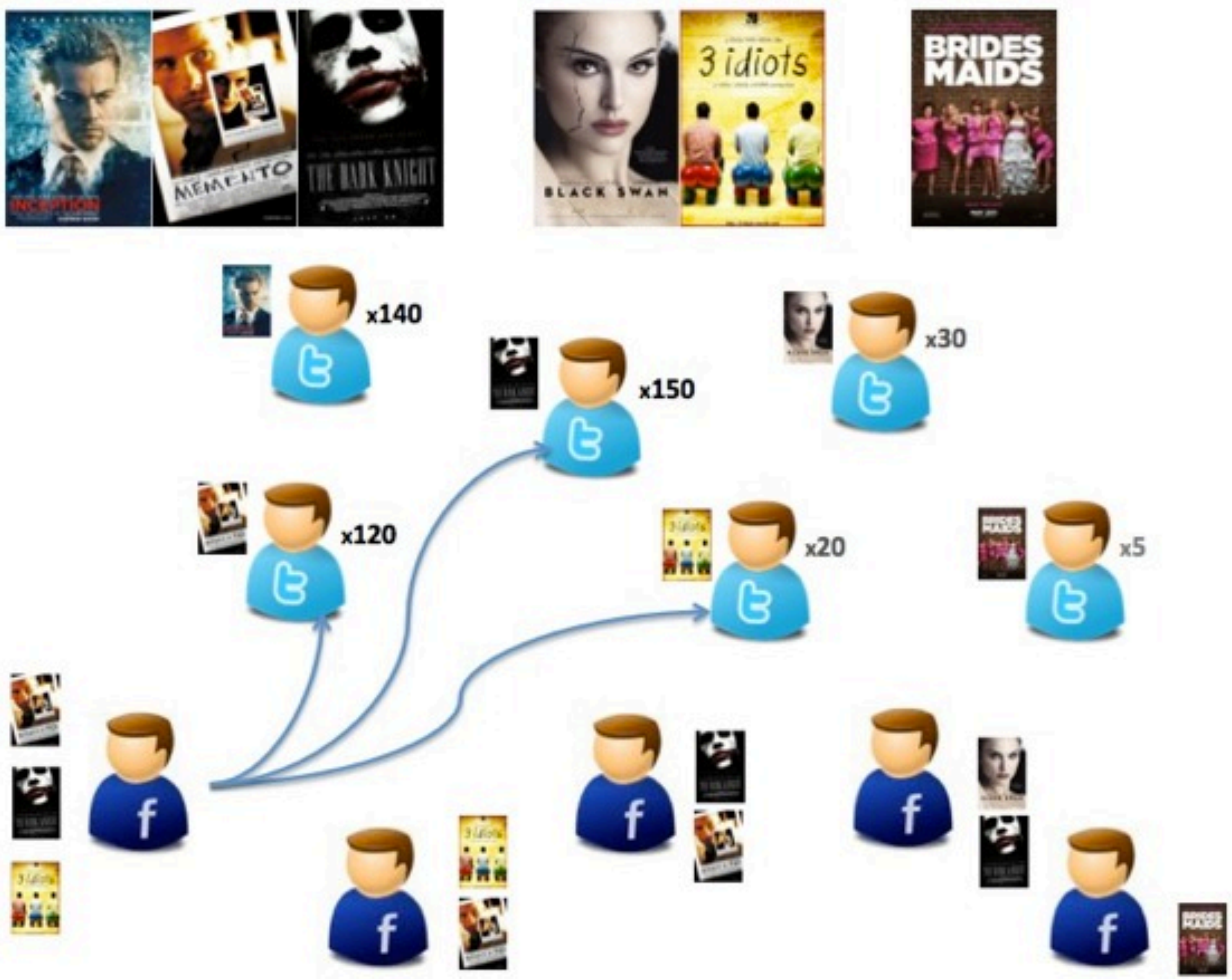
- Internet video > 60% of total traffic by 2013
- Total impact of Internet video > 91%
  - ✓ P2P video download: 70% - 80% of total P2P file sharing
  - ✓ Non – Internet IP traffic: IP transport of TV/VoD
  - ✓ VoD traffic will double every two years through 2013.



[Cisco Visual Networking Index – Forecast and Methodology, 2008–2013]

P2P VoD

Unique!



Uniqueness

-Streaming

  -Delay

  -Timeline

-Popularity

  -Time-varying

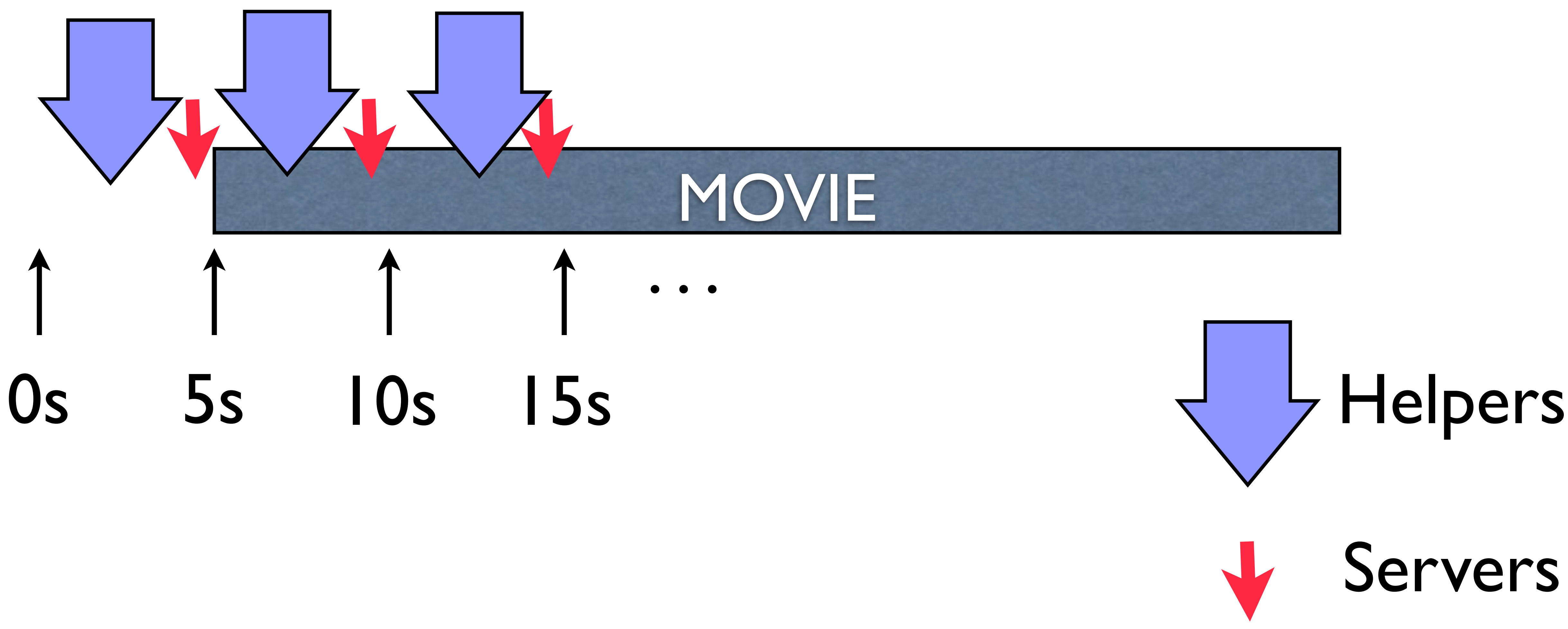
  -Heavy-tailed

Problem setup - Goal

Objective : Minimize server load

How to deal with the delay? *SET THE WORST DELAY!*

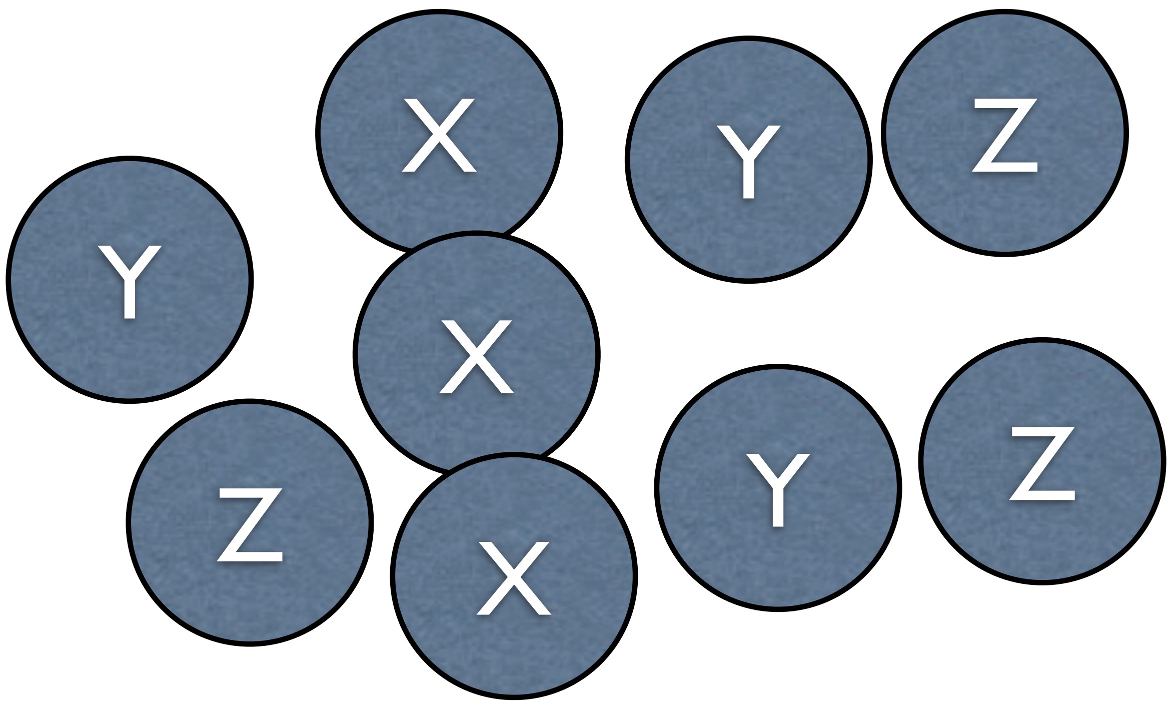
A user download packets from caches and download missing packets from the server if it needs when the playhead approaches the end of the buffer.



Problem setup - Idea1

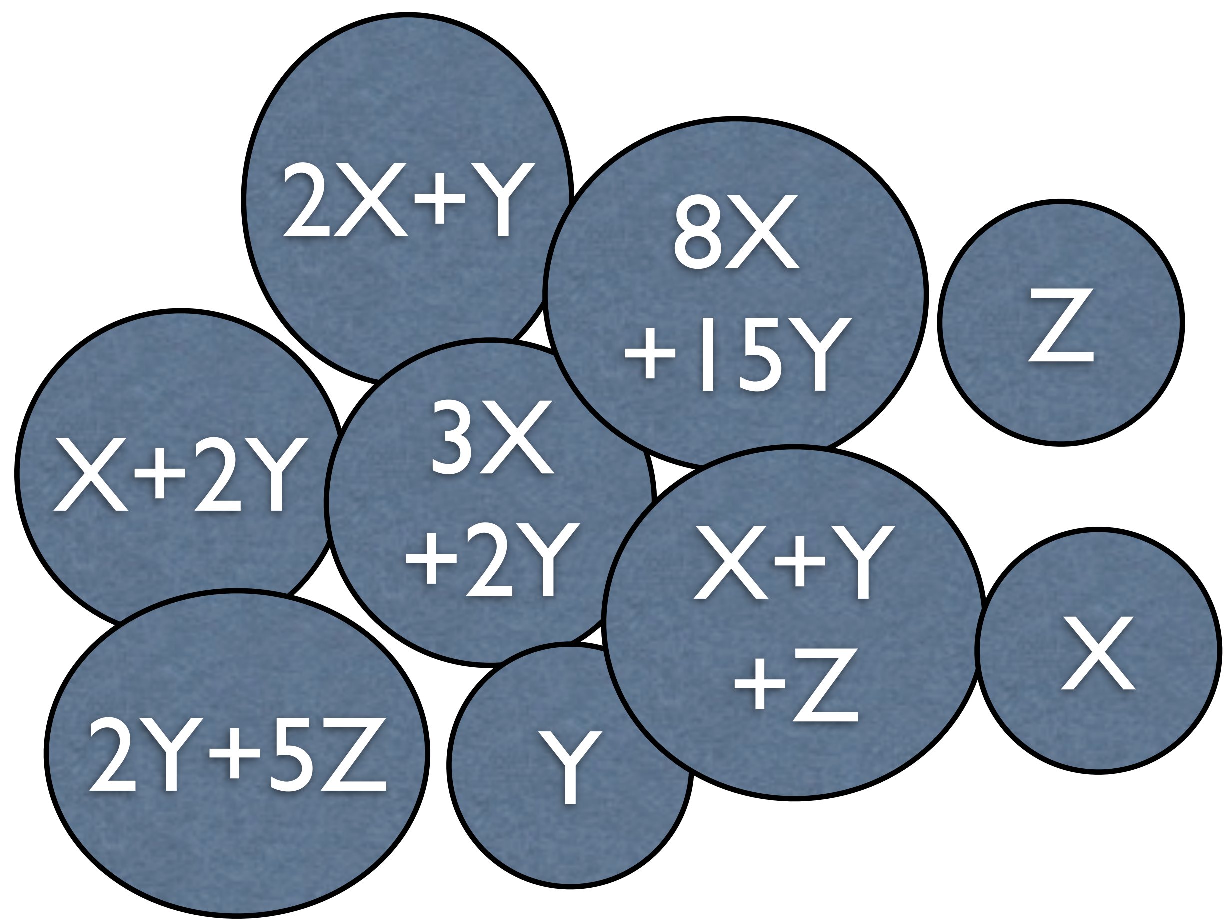
Store whole movies? Bad idea :(

Store coded slices!



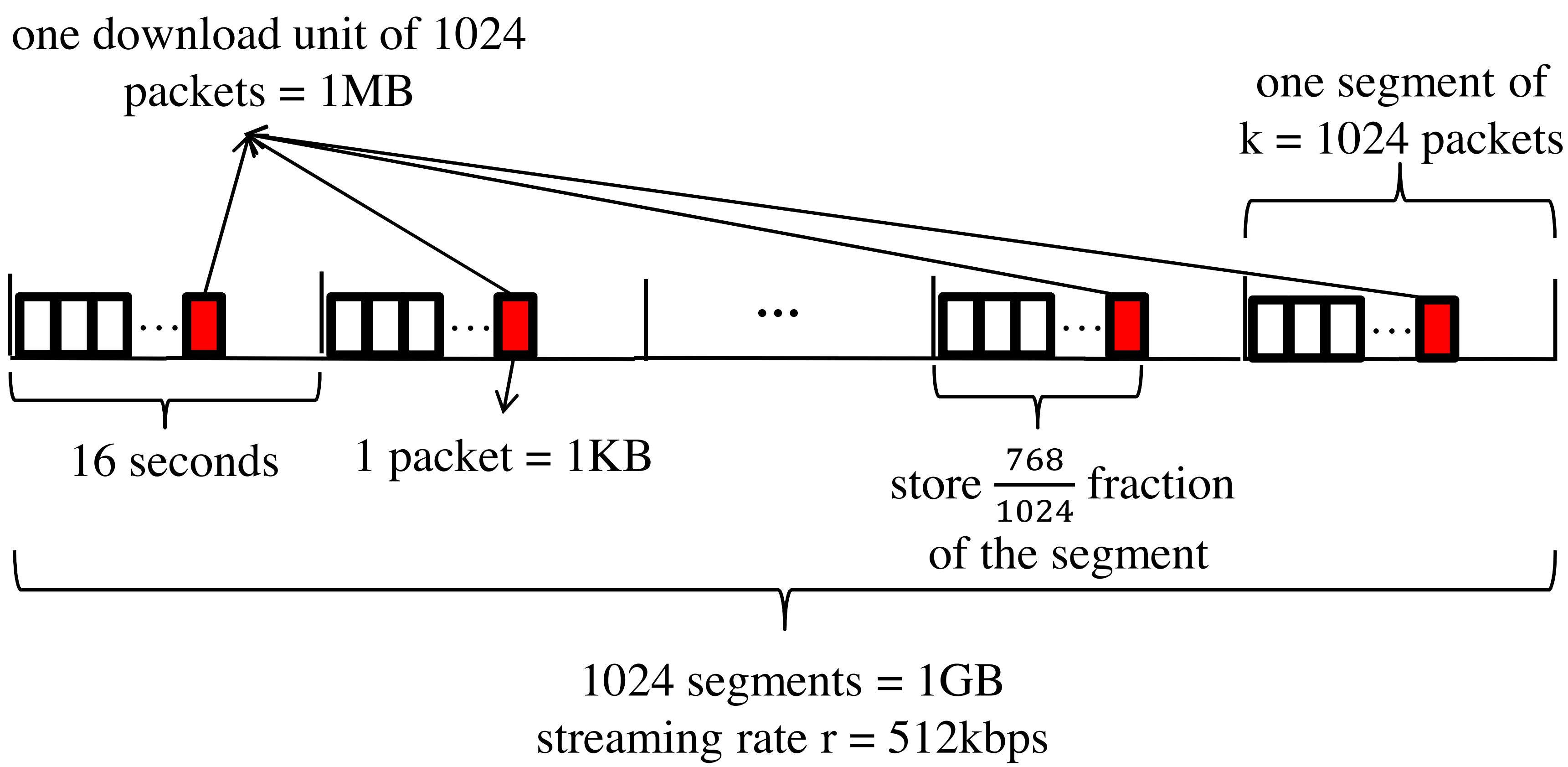
Collisions!
(coupon collecting)

(almost) No Collisions!



Problem setup - Idea2

Uniformly download across the movie



Combinatorial model reduces to Fluid model!

Problem

$$\max_{c,\mathbf{f},\mathbf{x}} \quad \sum_{m=1}^{M} \sum_{i_m=1}^{I_m} \min\Big(\sum_{j\in\mathbb{N}^c_{i_m}} x_{ji_m}, r_m\Big)$$

$$\text{s.t.} \quad x_{ji_m} \le f_{jm} r_m, \ \forall j, m, i_m \in \mathbb{N}^c_{j,m}$$

$$\sum_{m=1}^{M} \sum_{i_m\in\mathbb{N}^c_{j,m}} x_{ji_m} \le B_j, \ \forall j$$

$$\sum_{m=1}^{M} f_{jm} V_m \le S_j, \ \forall j$$

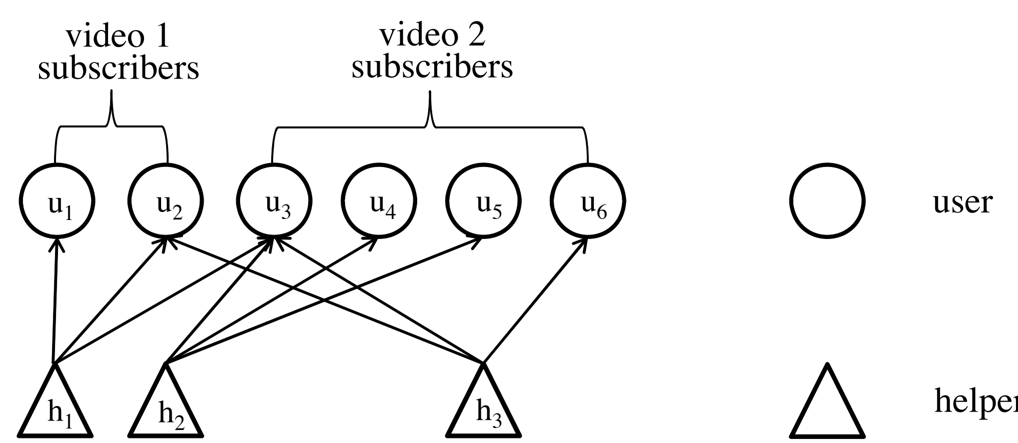
$$0 \le f_{jm} \le 1, \ \forall j, m$$

P1. solve under fixed c

P2. search for better c

$$c \in \mathbb{C}$$

Notation	Definition
M	total number of videos
I_m	total number of users watching video m
J	total number of helpers
r_m, l_m, V_m	video m's streaming rate, duration and size
$\mathbb{C}$	set of feasible overlay configurations
$\mathbb{N}_{i_m}$	user i_m's helper neighborhood
$\mathbb{N}_j$	helper j's user neighborhood
$\mathbb{N}^c_{i_m}$	set of helpers connected to user i_m under c
$\mathbb{N}^c_{j,m}$	set of users connected to helper j under c
B_j, S_j	upload, storage capacity of helper j
x_{ji_m}	upload rate from helper j to user i_m
f_{jm}	fraction of video m stored by helper j, in $[0, 1]$
k_{ji_m}	helper j's availability price to user i_m
λ_j, μ_j	bandwidth, storage prices of helper j



Two-stage optimization

Solution of P1

$$\begin{aligned}\max_{c,\mathbf{f},\mathbf{x}} \quad & \sum_{m=1}^{M}\sum_{i_m=1}^{I_m}\min(\sum_{j\in\mathbb{N}^c_{i_m}} x_{ji_m}, r_m)\\ \text{s.t.} \quad & x_{ji_m} \le f_{jm} r_m,\ \forall j, m, i_m \in \mathbb{N}^c_{j,m}\\ & \sum_{m=1}^{M}\sum_{i_m\in\mathbb{N}^c_{j,m}} x_{ji_m} \le B_j,\ \forall j\\ & \sum_{m=1}^{M} f_{jm} V_m \le S_j,\ \forall j\\ & 0 \le f_{jm} \le 1,\ \forall j, m\\ & c \in \mathbb{C}\end{aligned}$$

fix c

$$\max_{\mathbf{x}} \sum_{m,i_m}(\min(\sum_{j\in\mathbb{N}^c_{i_m}} x_{ji_m}, r_m) - \sum_{j\in\mathbb{N}^c_{i_m}}(\lambda_j + k_{ji_m})x_{ji_m}) + \max_{\mathbf{0}\le\mathbf{f}\le\mathbf{1}}\sum_{j,m}(r_m \sum_{i_m\in\mathbb{N}^c_{j,m}} k_{ji_m} - \mu_j V_m) f_{jm}$$

primal-dual interior-point
+ Krasovskii-LaSalle principle

$$\begin{aligned}\dot{x}_{ji_m} &= \alpha\left(g_{x_{ji_m}} - (\lambda_j + k_{ji_m})\right)^{[0,+\infty)}_{x_{ji_m}},\ \forall j, m, i_m \in \mathbb{N}^c_{j,m}\\ \dot{f}_{jm} &= \beta(\textstyle\sum_{i_m\in\mathbb{N}^c_{j,m}} k_{ji_m} - l_m\mu_j)^{[0,1]}_{f_{ji_m}},\ \forall j, m\\ \dot{\lambda}_j &= \gamma(\textstyle\sum_{m=1}^{M}\sum_{i_m\in\mathbb{N}^c_{j,m}} x_{ji_m} - B_j)^{[0,+\infty)}_{\lambda_j},\ \forall j\\ \dot{\mu}_j &= \delta(\textstyle\sum_{m=1}^{M} f_{ji_m} V_m - S_j)^{[0,+\infty)}_{\mu_j},\ \forall j\\ \dot{k}_{ji_m} &= \varepsilon(x_{ji_m} - f_{jm} r_m)^{[0,+\infty)}_{k_{ji_m}},\ \forall j, m, i_m \in \mathbb{N}^c_{j,m}.\end{aligned}$$

$$h_y^{[a,b]} = \begin{cases}\min(0,h), & y \ge b;\\ h, & a < y < b\\ \max(0,h), & y \le a,\end{cases}$$

$$g = \min(\textstyle\sum_{j\in\mathbb{N}^c_i} x_{ji_m}, r_m)$$

Proof of Convergence

$$\begin{aligned} V(\mathbf{y}) &= \frac{1}{2\alpha}\|\mathbf{x}-\mathbf{x}^*\|^2 + \frac{1}{2\beta}\|\mathbf{f}-\mathbf{f}^*\|^2 + \frac{1}{2\gamma}\|\lambda-\lambda^*\|^2 \\ &\quad + \frac{1}{2\varepsilon}\|\mathbf{k}-\mathbf{k}^*\|^2 + \frac{1}{2\delta}\|\mu-\mu^*\|^2 \end{aligned}$$

$$\begin{aligned} \dot{V}(\mathbf{y}) &= \sum(x_{ji_m}-x^*_{ji_m})(g_{x_{ji_m}}-(\lambda_j+k_{ji_m}))^{[0,+\infty)}_{x_{j_i m}} \\ &\quad + \sum(f_{jm}-f^*_{jm})(\sum k_{ji_m}-l_m\mu_j)^{[0,1]}_{f_{ji_m}} \\ &\quad + \sum(\lambda_j-\lambda^*_j)(\sum x_{ji_m}-B_j)^{[0,+\infty)}_{\lambda_j} \\ &\quad + \sum(k_{ji_m}-k^*_{ji_m})(x_{ji_m}-f_{jm}r_m)^{[0,+\infty)}_{k_{ji_m}} \\ &\quad + \sum(\mu_j-\mu^*_j)(\sum f_{ji_m}V_m-S_j)^{[0,+\infty)}_{\mu_j} \end{aligned}$$

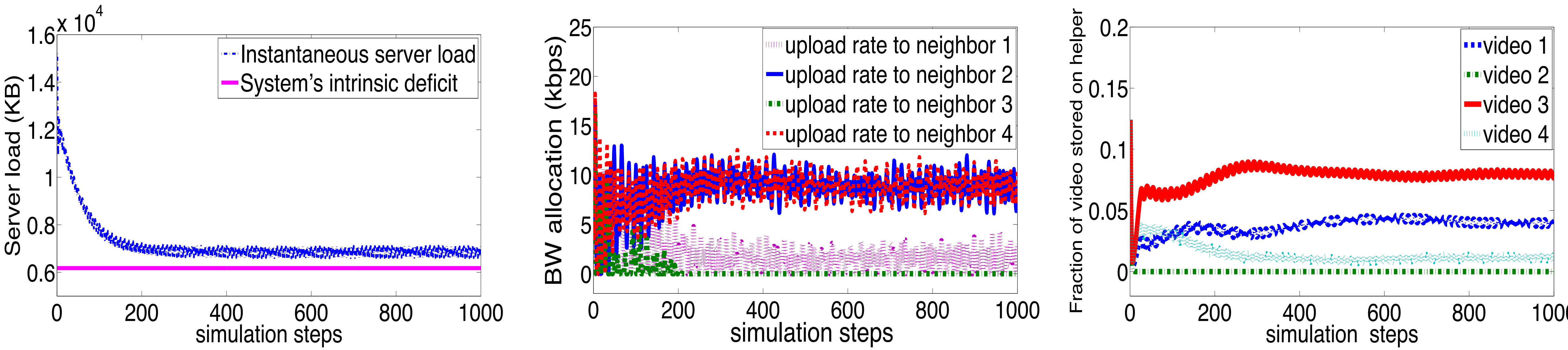
$$\boxed{\begin{aligned} &(g_{x^*_{ji_m}}-(\lambda^*_j+k^*_{ji_m}))^{[0,+\infty)}_{x^*_{j_i m}} = 0 \\ &(\textstyle\sum_{i_m\in\mathbb{N}^m_j} k^*_{ji_m}-l_m\mu^*_j)^{[0,1]}_{f^*_{ji_m}} = 0 \\ &\lambda^*_j(\textstyle\sum_{m=1}^M\sum_{i_m\in\mathbb{N}^m_j} x^*_{ji_m}-B_j) = 0 \\ &\mu^*_j(\textstyle\sum_{m=1}^M f^*_{ji_m}V_m-S_j) = 0 \\ &k^*_{ji_m}(x^*_{ji_m}-f^*_{jm}r_m) = 0 \end{aligned}}$$

KKT cond.

$$\begin{aligned} \dot{V}(\mathbf{y}) &\le \sum(x_{ji_m}-x^*_{ji_m})(g_{x_{ji_m}}-(\lambda_j+k_{ji_m})) \\ &\quad + \sum(f_{jm}-f^*_{jm})(\sum k_{ji_m}-l_m\mu_j) \\ &\quad + \sum(\lambda_j-\lambda^*_j)(\sum x_{ji_m}-B_j) \\ &\quad + \sum(k_{ji_m}-k^*_{ji_m})(x_{ji_m}-f_{jm}r_m) \\ &\quad + \sum(\mu_j-\mu^*_j)(\sum f_{ji_m}V_m-S_j) \\ &= \sum(x_{ji_m}-x^*_{ji_m})(g_{x_{ji_m}}-g_{x^*_{ji_m}}) \\ &\quad + \sum(x_{ji_m}-x^*_{ji_m})(g_{x^*_{ji_m}}-(\lambda^*_j+k^*_{ji_m})) \\ &\quad + \sum(f_{jm}-f^*_{jm})(\sum k^*_{ji_m}-l_m\mu^*_j) \\ &\quad + \sum(\lambda_j-\lambda^*_j)(\sum x^*_{ji_m}-B_j) \\ &\quad + \sum(k_{ji_m}-k^*_{ji_m})(x^*_{ji_m}-f^*_{jm}r_m) \\ &\quad + \sum(\mu_j-\mu^*_j)(\sum f^*_{ji_m}V_m-S_j) \\ &\le \sum(x_{ji_m}-x^*_{ji_m})(g_{x_{ji_m}}-g_{x^*_{ji_m}}) \\ &\quad +0+0+0+0+0 \le 0 \end{aligned}$$

Concavity of utility fcn g

Results of P1



(a) Server load, sync. (b) Bandwidth alloc., sync. (c) Storage alloc., sync.

Problem 2

$$\boxed{\max_c U(c) \qquad \text{s.t.} \quad c \in \mathbb{C}}$$

NP Hard

$$\boxed{\begin{aligned} \max_p \quad & \sum_{c\in\mathbb{C}} p_c U(c) \\ \text{s.t.} \quad & \sum_{c\in\mathbb{C}} p_c = 1 \quad \text{and} \quad 0 \leq p_c \leq 1,\ \forall c \in \mathbb{C} \end{aligned}}$$

$$\boxed{H(p) = -\sum_{c\in\mathbb{C}} p_c \log p_c}$$

$$\boxed{\begin{aligned} \max_{\mathbf{p}} \quad & \sum_{c\in\mathbb{C}} p_c U(c) - \frac{1}{\kappa} \sum_{c\in\mathbb{C}} p_c \log p_c \\ s.t. \quad & \sum_{c\in\mathbb{C}} p_c = 1 \quad \textit{and} \quad 0 \leq p_c \leq 1,\ \forall c \in \mathbb{C} \end{aligned}}$$

$$\boxed{p_c^* = \frac{\exp\left(\kappa U(c)\right)}{\sum_{c\in\mathbb{C}} \exp\left(\kappa U(c)\right)},\ \forall c \in \mathbb{C}}$$

Problem 2

$$\max_{\mathbf{p}} \quad \sum_{c\in\mathbb{C}} p_c U(c) - \frac{1}{\kappa}\sum_{c\in\mathbb{C}} p_c \log p_c$$

bounded relaxation $\frac{1}{\kappa}\log|\mathbb{C}|$

$$s.t. \quad \sum_{c\in\mathbb{C}} p_c = 1 \quad and \quad 0 \le p_c \le 1, \ \forall c \in \mathbb{C}$$

$$\boxed{p_c^* = \frac{\exp\left(\kappa U(c)\right)}{\sum_{c\in\mathbb{C}} \exp\left(\kappa U(c)\right)}, \quad \forall c \in \mathbb{C}}$$

Instead of sticking with the best one, hoping around good topologies!

Suggestion 1 : Uniform-neighbor-choking

$$q_{c,c'} = \begin{cases} \frac{\tau}{\exp\left(\kappa(U(c))\right)} & c, c' \text{ satisfy } S; \\ 0 & \text{otherwise.} \end{cases} \longrightarrow q_{c,c'}p_c^* = q_{c',c}p_{c'}^*$$

- $\exists \tilde{c}$ s.t. $\tilde{c} \subseteq c, \tilde{c} \subseteq c', |c \setminus \tilde{c}| = |c' \setminus \tilde{c}| = 1;$
- Link $c \setminus \tilde{c}$ and link $c' \setminus \tilde{c}$ originates from the *same* peer.

Problem 2

$$\boxed{\begin{array}{ll} \max_{\mathbf{p}} & \sum_{c\in\mathbb{C}} p_c U(c) - \frac{1}{\kappa}\sum_{c\in\mathbb{C}} p_c \log p_c \\ s.t. & \sum_{c\in\mathbb{C}} p_c = 1 \quad and \quad 0 \le p_c \le 1,\ \forall c \in \mathbb{C} \end{array}}$$

bounded relaxation $\frac{1}{\kappa}\log|\mathbb{C}|$

$$\boxed{p_c^* = \frac{\exp\left(\kappa U(c)\right)}{\sum_{c\in\mathbb{C}} \exp\left(\kappa U(c)\right)},\ \forall c \in \mathbb{C}}$$

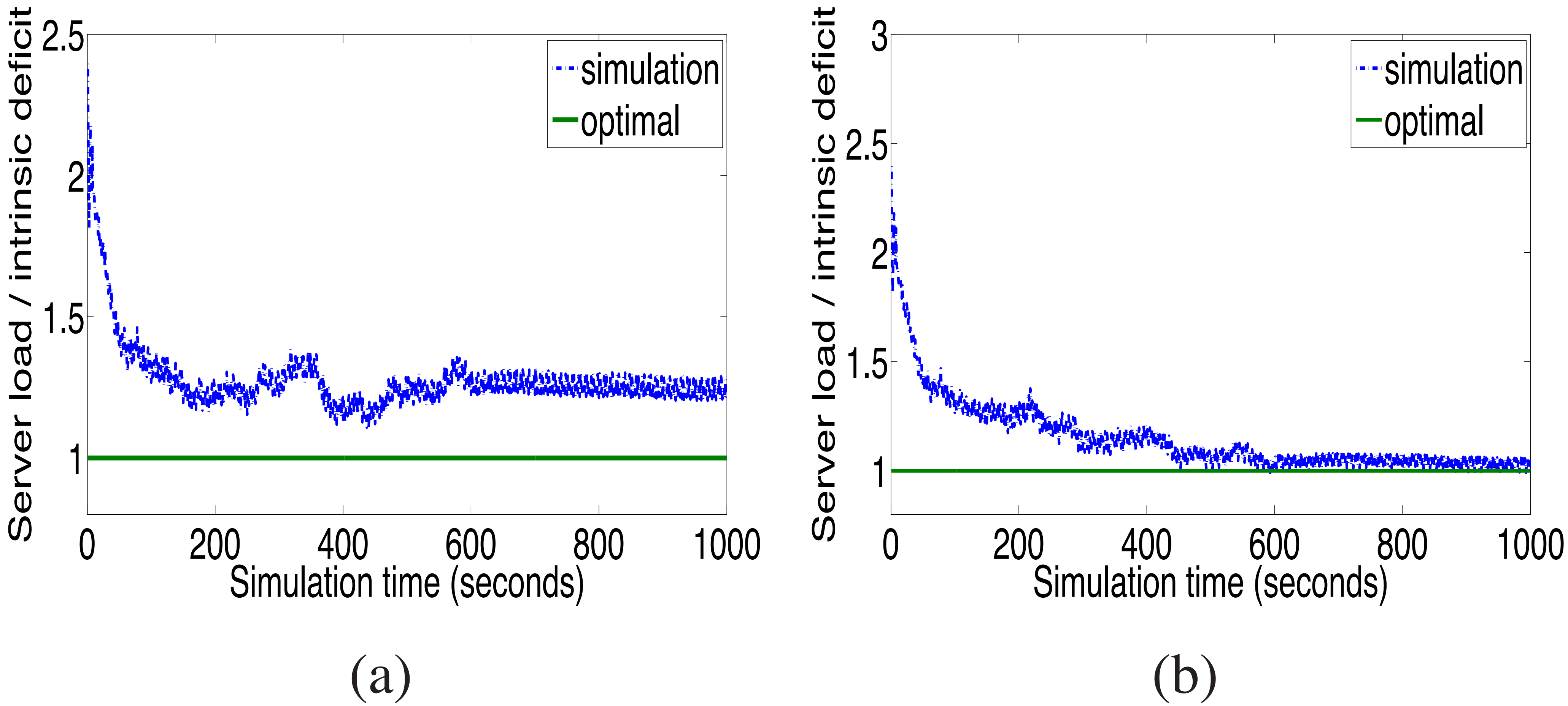
Suggestion 2 : Soft-worst-neighbor-choking

$$\bar{q}_{c,c'} = \frac{\tau}{\exp\left(\kappa x^{c\setminus\tilde{c}}\right)}$$

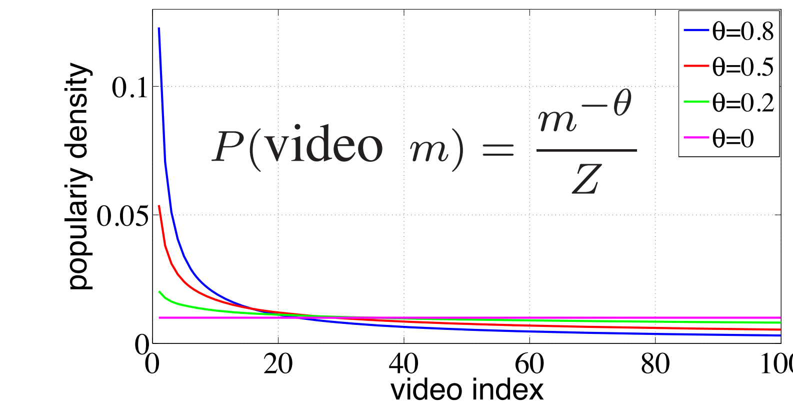
$U(c) - U(\tilde{c}) \le x^{c,\tilde{c}}$ if it's tight

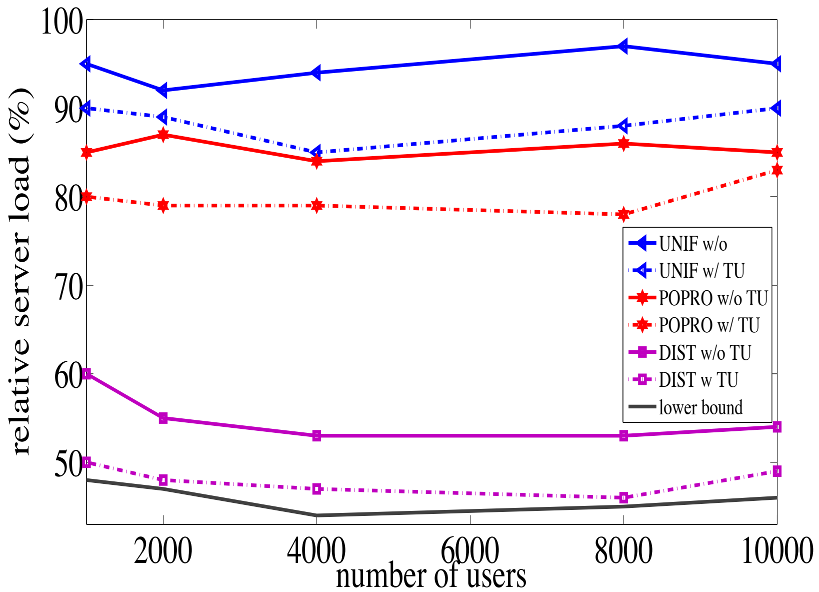
$$\bar{q}_{c,c'} = \frac{\tau}{\exp\left(\kappa\left(U(c) - U(\tilde{c})\right)\right)} \longrightarrow \bar{q}_{c,c'}p_c^* = \bar{q}_{c',c}p_{c'}^*$$

Results of P2

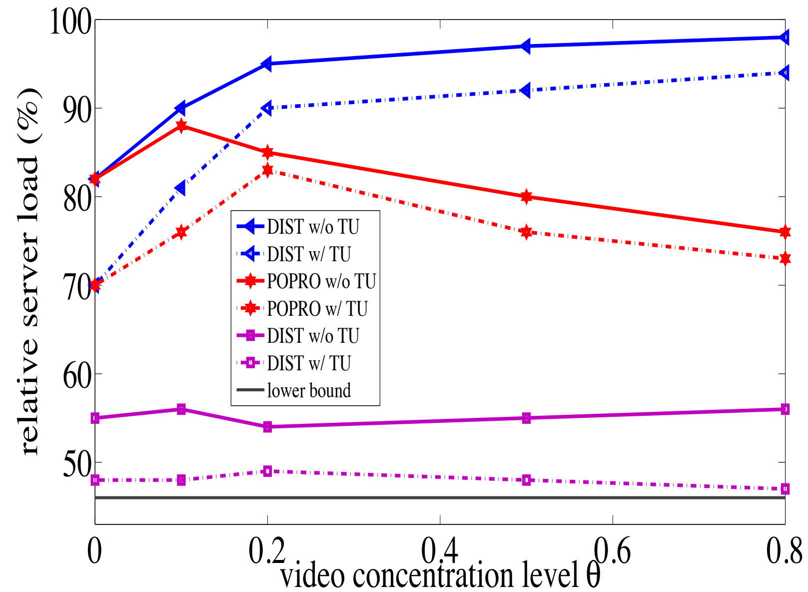


Overall Results

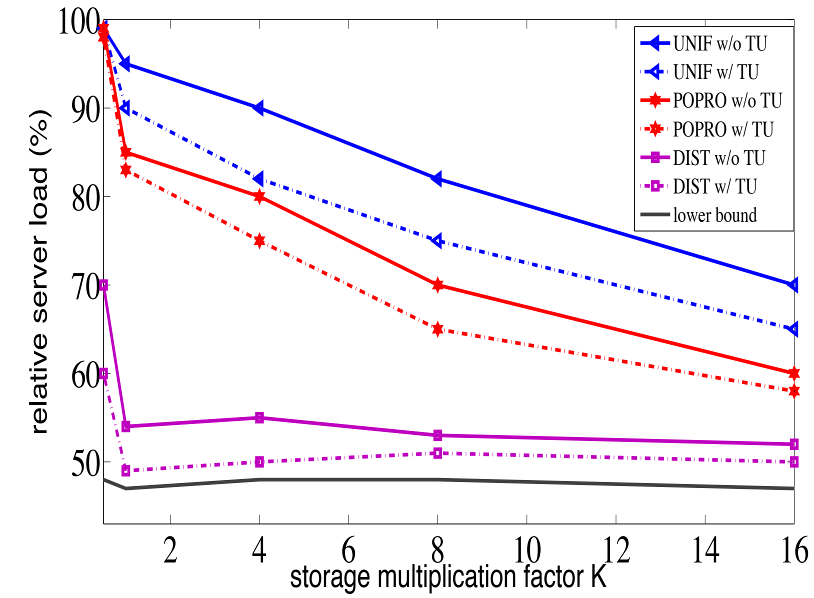




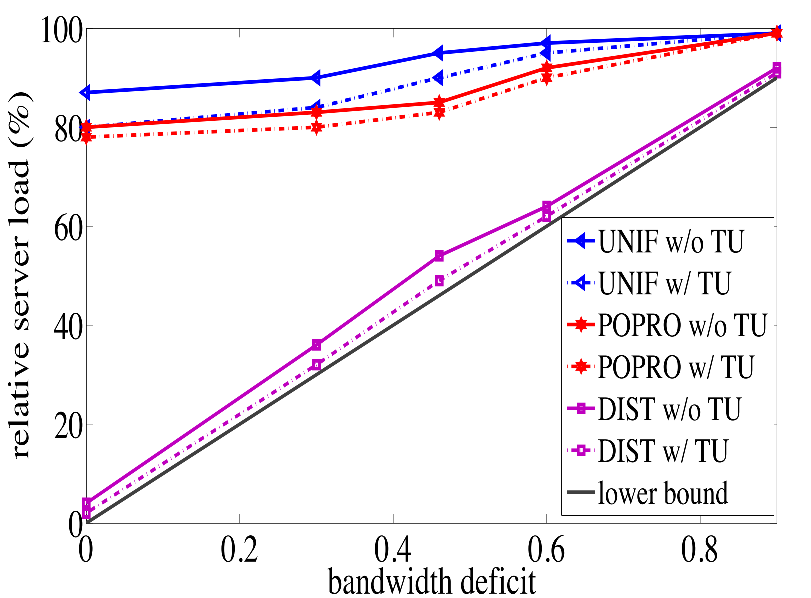
(a)



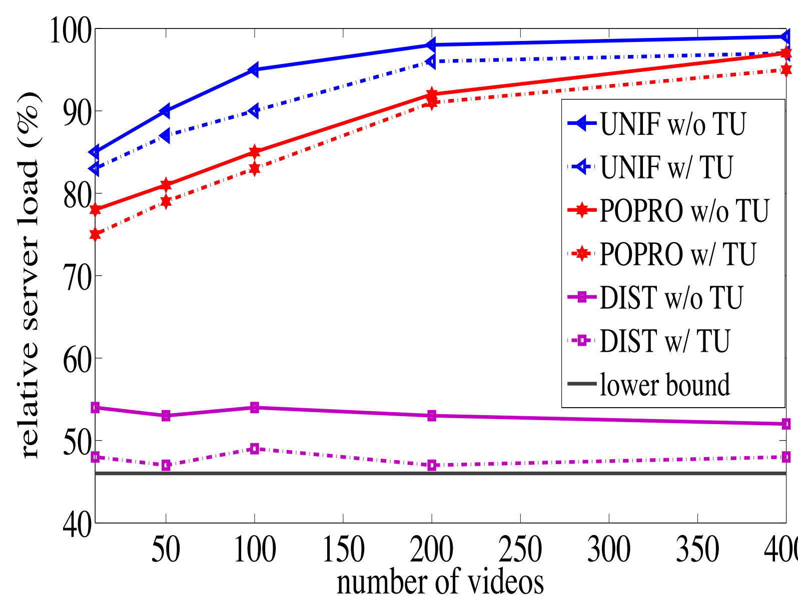
(b)



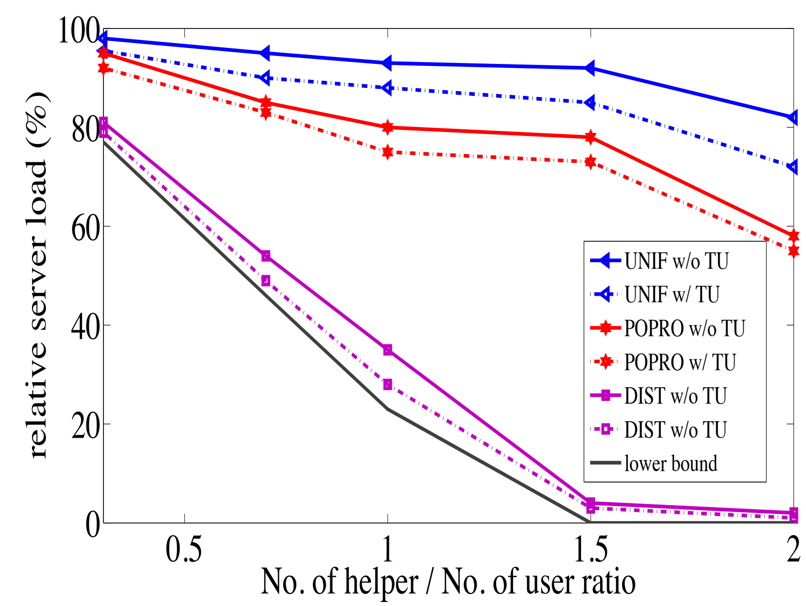
(c)



(d)



(e)



(f)

Real System

-Simulation might not be enough to prove the performance
-Real system is also implemented using Python and Flex
-'GAP' between theory and practice
  -No more fluid
  -Real network
  -Computational cost (video CODEC, MDS code)
  -and so on...

Conclusion

-Problem formulation

-Fluid model

-Solved P1(Resource allocation problem)

-Primal-dual & convergence proof

-Solved P2(Topology update problem)

-Relax it and design a MC

-Distributed manner and performs well under heterogeneous and dynamic settings.

-Future works

-Economic models?

-Network coding?