The Streaming Capacity of Sparsely-Connected P2P Systems with Distributed Control

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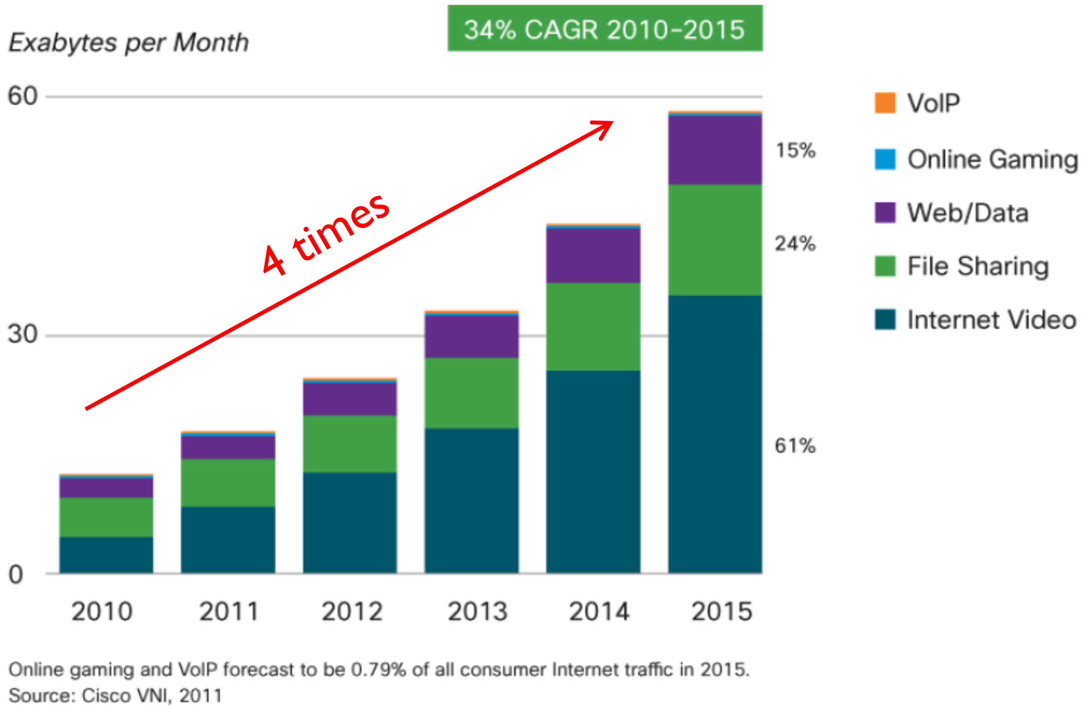
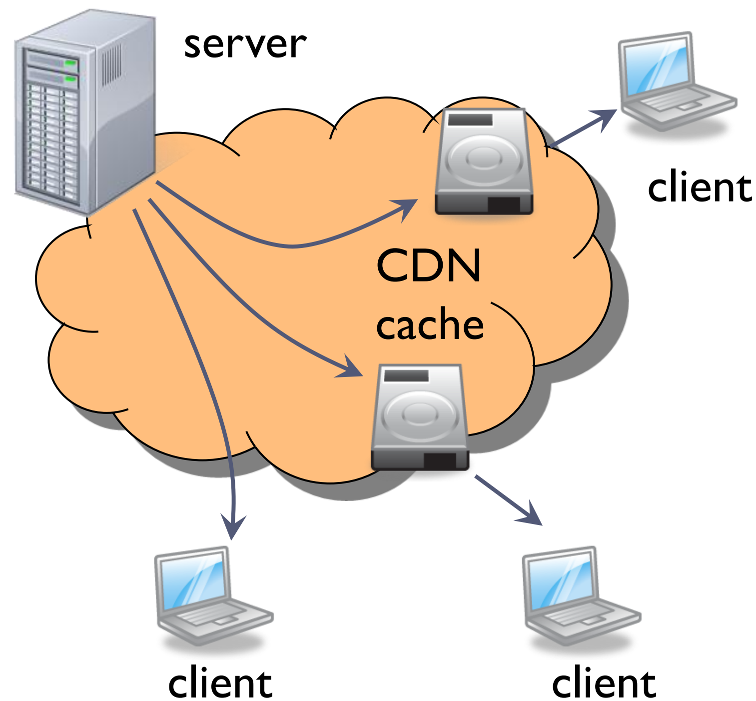
Significant Growth of Internet Video Traffic



- Internet video service providers: Youtube, Netflix, and many other.
- Consumer IP traffic will grow at a compound annual growth rate (CAGR) of 34%.
- By 2012, Internet video will account for over 50% of consumer Internet traffic.
- The sum of all video traffic (including TV, file sharing etc) will reach 90% of total IP traffic in 2015.

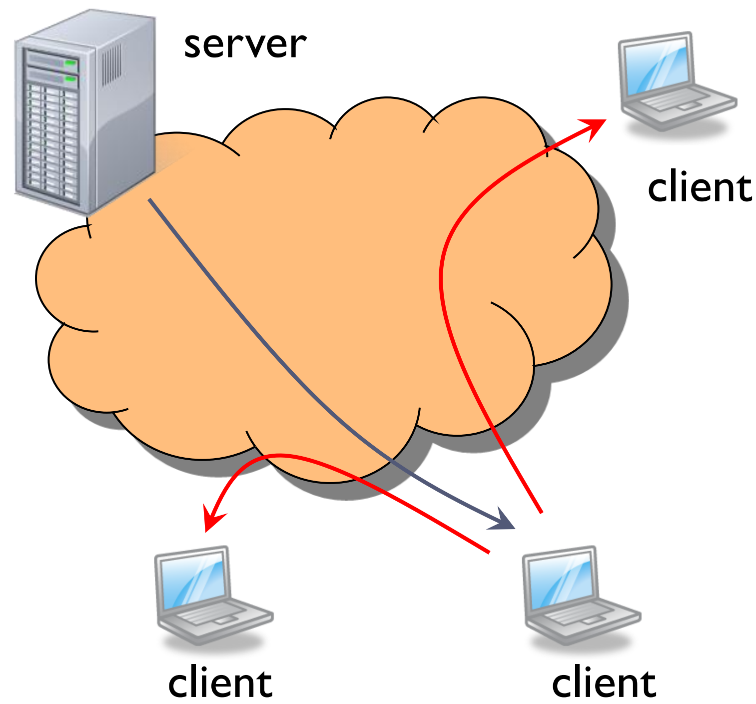
Video Streaming in the Internet: Current Status

- Video streaming directly from servers or CDNs (Content Distribution Networks) is costly
- In the US, this has been the dominant mode for video streaming
  - Credit Suisse estimated Youtube bandwidth cost in 2009 : $360M per year
  - Google likely paid significantly less due to peering with other ISP
- Licensing of video content could cost comparably or even more.
  - Netflix's lost deal with Starz: $300M for possibly a 5-year license



P2P Video Streaming: Current Status

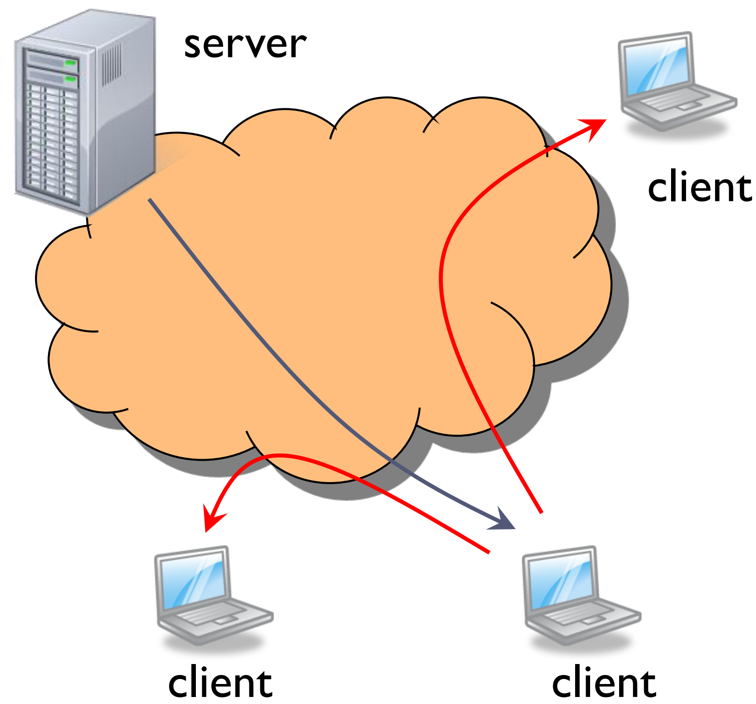
- Peer-to-peer (P2P) video streaming can potentially be much more scalable
  - Each client also contributes its upload capacity.
- In Asia, P2P streaming has become commercially successful
  - PPLive, UUSee, PPStream, etc.
- However, content has primarily been free or pirated
- High-value content appears to also move towards the server mode



Why hasn't P2P caught on yet for *high-value* content?

P2P Video Streaming: Issues

- Copyright issues?
- Lack of quality-of-service guarantees?
- Difficulty to maintain QoS in P2P systems:
  - Client upload capacity is time-varying
  - Peer "churns"
  - Large scale
  - Decentralized view and operation



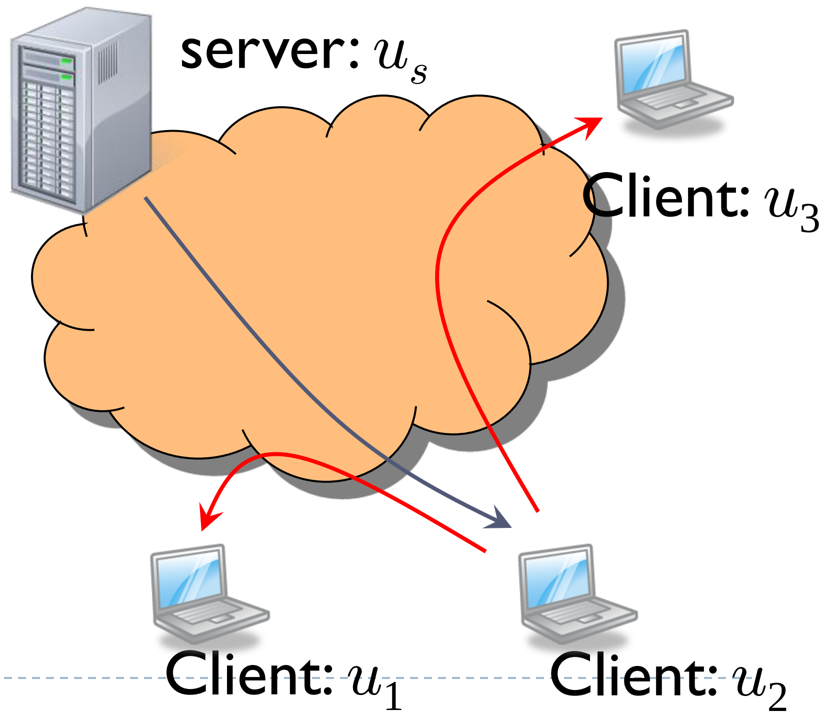
Why hasn't P2P caught on yet for *high-value* content?

Gap Between Practice and Theory

- Theoretical understanding of P2P streaming performance has significantly lag behind practice, which may have impeded further advance of P2P streaming.
- ***Our Focus:*** What is the best streaming rate C_f that a live-streaming P2P system can reliably support?
- Assuming upload capacity is the only constraint [Kumar et al '07]:

$$C_f \leq \min\{u_s, \boxed{\frac{u_s + \sum_{i=1}^{N} u_i}{N}}\}$$

- Question: Can this upper bound be attained?

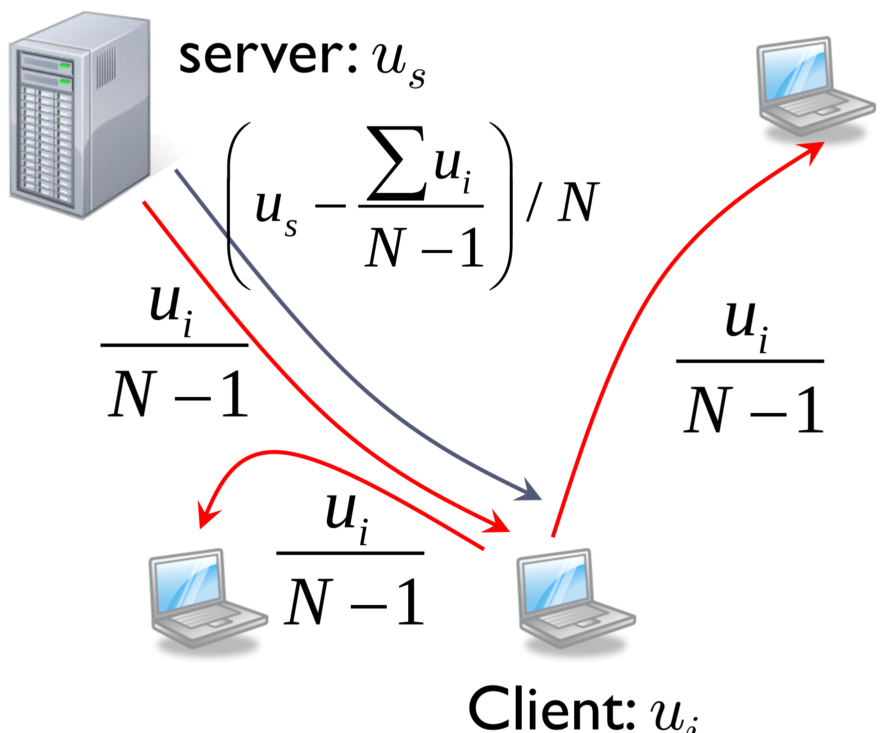


P2P Streaming Capacity

- Assume a complete graph: every peer can serve all other peers simultaneously [Mundinger et al '05, Chiu et al '06, Kumar et al '07]
- Each client gets

$$\left(u_s - \frac{\sum u_i}{N-1}\right)/N + \frac{u_i}{N-1} + \frac{\sum_{j\neq i} u_j}{N-1}$$

$$= C_f \triangleq \frac{u_s + \sum u_i}{N}$$



- How practical is this analysis?

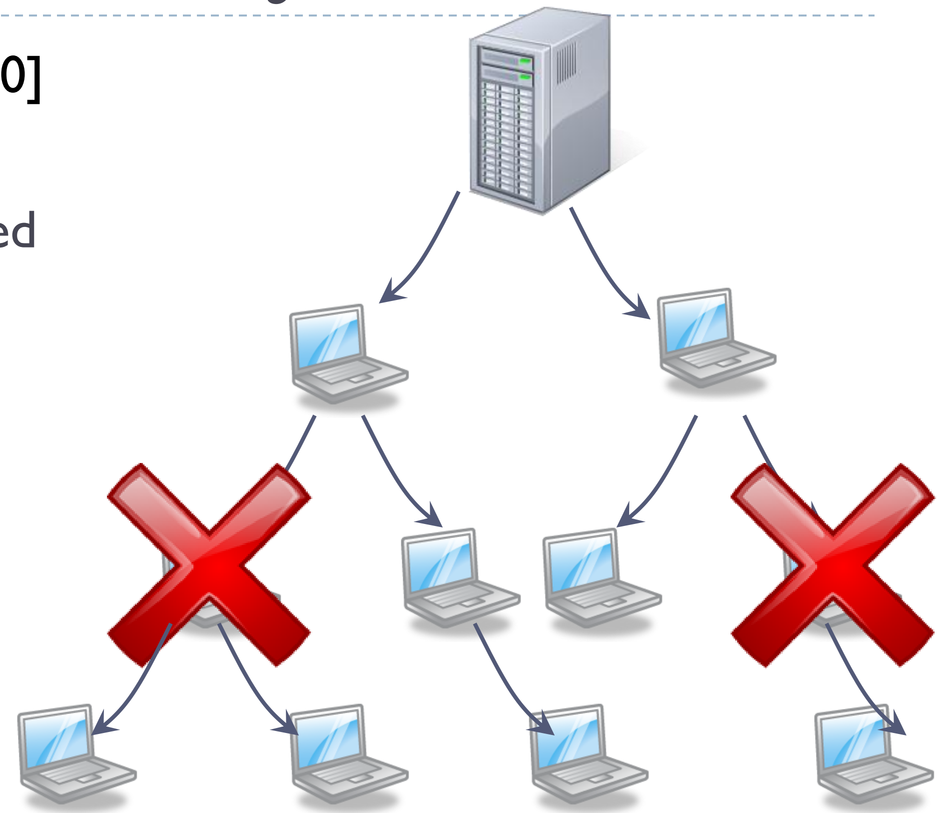
P2P Streaming Capacity

Such theoretical analysis is far from the reality in practical P2P systems!

- Real P2P streaming systems are sparsely connected:
  - Each peer only knows a small subset of other peers (neighbors).
  - Infeasible for each peer to know all other peers!
- Real P2P systems are distributed:
  - No central entity can have the global/up-to-date knowledge to perform such a perfect rate allocation.

Sparsely-Connected P2P Systems

- A multi-tree topology [Liu et al. 2010]
  - Still a centralized construction.
  - More recent work uses distributed Markov approximation [Zhang and Chen, 2012]
- If a peer close to the root leaves or its upload capacity decreases, significant performance disruption will occur.



Open Question:

- Can we achieve close-to-optimal streaming capacity with sparse connectivity and decentralized control that are robust against peer churns and variations of upload capacity ?

Our Contribution

- We show that a simple distributed scheme is sufficient to achieve close-to-optimal streaming capacity with high probability for large P2P systems.
  - Each peer has a small number of downstream neighbors $M = O(\log N)$
  - Each peer can choose neighbors uniformly randomly
  - Each peer evenly divides its upload capacity among the M neighbors
- Our results reveal important insights into the dynamics of large P2P systems.
- We design improved control schemes based on these insights that further improve the system performance.
- Our work provides an important step towards understanding and controlling QoS in large and unreliable P2P streaming systems.

Overview

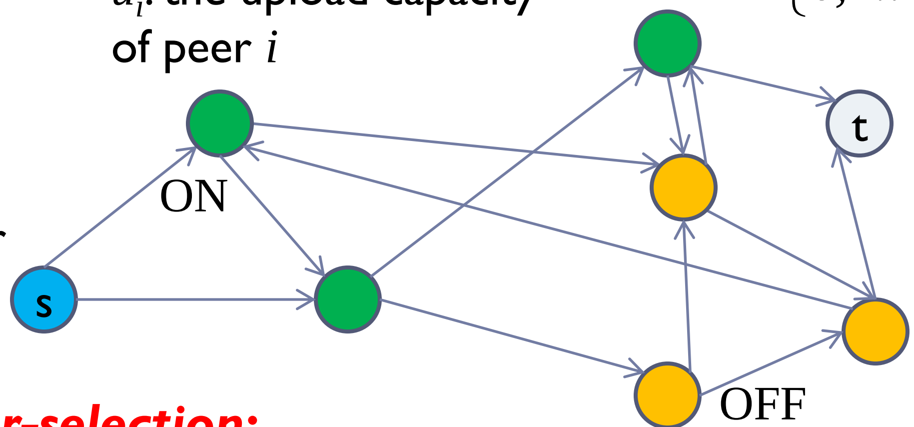
- ***System Model***
- Single-Channel: Uniform Rate Allocation
- Single-Channel: Adaptive Rate Allocation
- Multi-Channel Live Streaming
- Conclusion and Discussion

System Model: Single-Channel P2P Live Streaming with Random Peer Selection

N: number of peers
u_i: the upload capacity of peer i

$$u_i = \begin{cases} u, & \text{with prob. } p \\ 0, & \text{with prob. } 1-p \end{cases}$$

u_s: the upload capacity of server

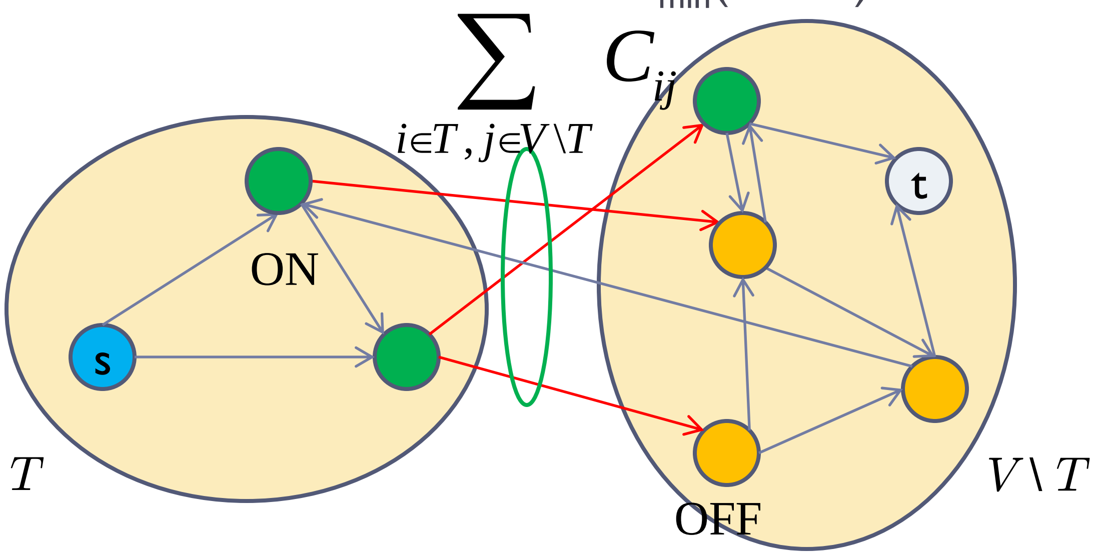


- ***Random peer-selection:***
  - Each peer randomly selects M downstream neighbors
  - Server randomly selects M ON peers as downstream neighbors
  - *Easy to implement and robust to peer churns.*
- C_{ij}: the capacity that peer i contributes to peer j.
- C_{ij}=0 if peer i is OFF or peer j is not a downstream neighbor of peer i

$$\sum_{j:\, i \to j} C_{ij} \le u_i \text{ and } \sum_{j:\, s \to j} C_{sj} \le u_s$$

System Model

- Streaming rate to destination peer t:
  - The minimum cut between s and t: $C_{\min}(s \to t)$



A directed capacitated graph

- The streaming rate of the entire system:
  - The minimum cut across all destination peers t:

$$\mathrm{C}_{\min-\min}\left(s \to V\right) = \min_{t \in V} \mathrm{C}_{\min}\left(s \to t\right)$$

  - Can be achieved in a distributed manner by network coding [Ahlswede et al 2000] or a latest-useful-chunk transmission policy [Massoulie and Twigg 2008]

Problem Statement

- C_f: The optimal streaming capacity assuming complete connectivity and centralized control

$$E[C_f] = \min\left\{u_s, \boxed{\frac{u_s + upN}{N}}\right\}$$

- ***Research Problems:***
  - How much performance penalty (compare to the optimal C_f) is incurred due to random peer-selection?
  - Are there simple and robust rate-allocation schemes that can achieve close-to-optimal capacity with minimal overhead?

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Single-Channel: Uniform Rate-Allocation

N: number of peers
u_i: the upload capacity of peer i

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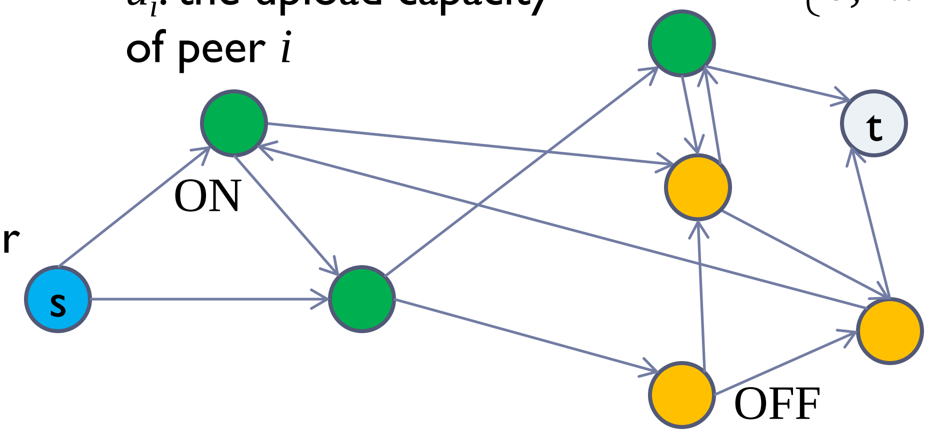


- ***Uniform rate-allocation***:
  - Each peer evenly divides its upload capacity to its M downstream neighbors
  - Same for server
- C_{ij}: the link capacity from peer i to peer j.

$$C_{ij} = \begin{cases} u/M, & \text{if peer } i \text{ is ON and } i \rightarrow j \\ 0, & \text{otherwise} \end{cases}$$

Main Result

- For any $\varepsilon \in (0,1)$ and $d > 1$, there exists $\alpha > 0$ such that if $M = \alpha \log N$, then

$$P(C_{\min-\min}(s \to V) \leq (1-\varepsilon)E[C_f]) \leq O\left(\frac{1}{N^{2d-1}}\right)$$

- Even with simple random peer-selection and uniform rate-allocation, the system can achieve close-to-optimal streaming capacity with very high probability!

Implications

- Sparse connectivity is sufficient!
  - $M = \alpha \log N$
- Simple and decentralized control
  - Random peer selection and uniform rate-allocation
- Larger is better!
  - The larger the network size, the easier to achieve close-to-optimal capacity
- Robustness
  - Even if a peer leaves, only its upstream peer needs to re-select a downstream neighbor.
  - When a peer switches from ON to OFF, its neighbors do not need to change anything (unless it is connected to the server directly).
  - No need to reconstruct the global topology!

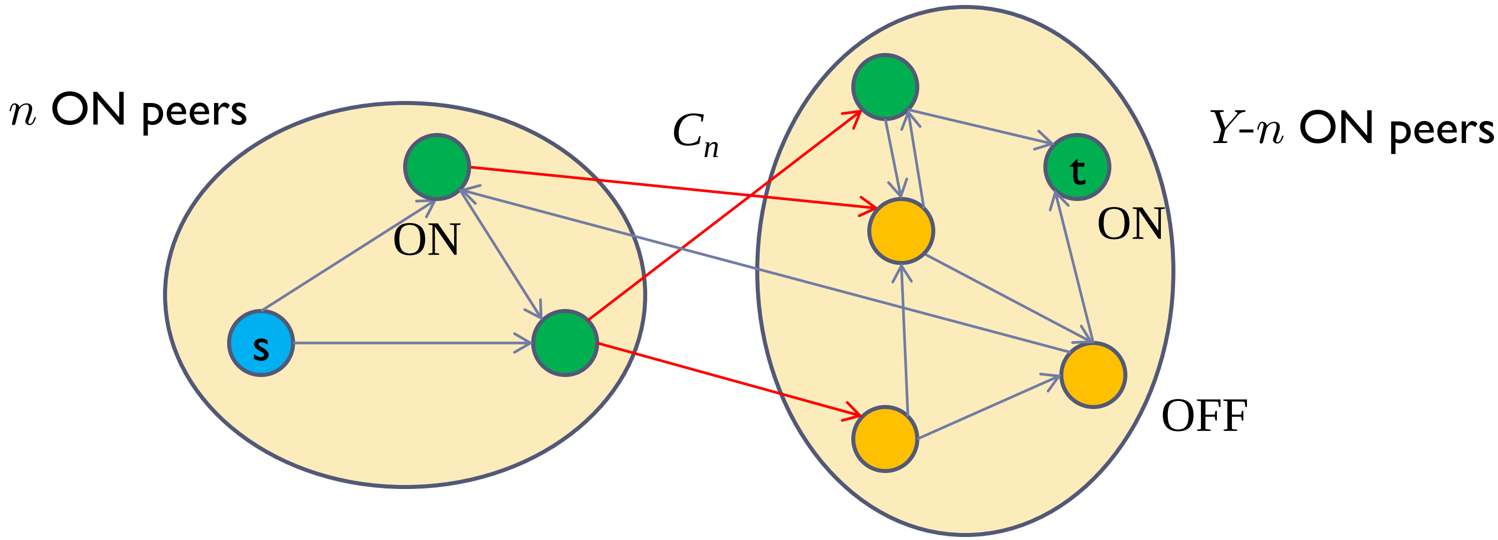
Large P2P streaming systems are in fact extremely

scalable

and

robust!

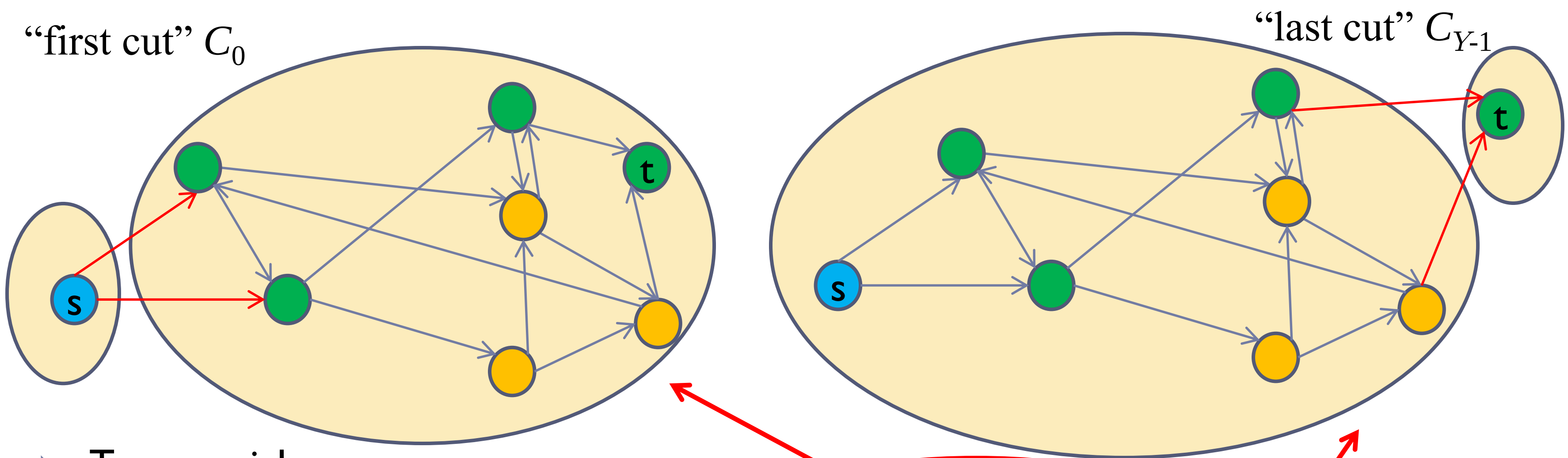
Intuition Behind the Main Result



- Fix a destination peer t. Suppose that peer t is ON.
- Let Y be the total number of ON peers: $Y \approx Np$
- C_n : the random capacity of a cut that has n ON peers on the server side

$$\mathbf{E}[C_n \mid Y] \geq \frac{u_s(Y-n)}{Y} + \frac{un(Y-n)}{N} = \begin{cases} u_s, & \text{if } n = 0 \\ \dfrac{u_s + upN}{N}, & \text{if } n = Y-1 \end{cases}$$

Intuition Behind the Main Result



- Two special cases:

$$E[C_n \mid Y = Np] \geq \begin{cases} u_s, & \text{if } n = 0 \\ \dfrac{u_s + upN}{N}, & \text{if } n = Y - 1 \end{cases}$$

- For all other n, we have

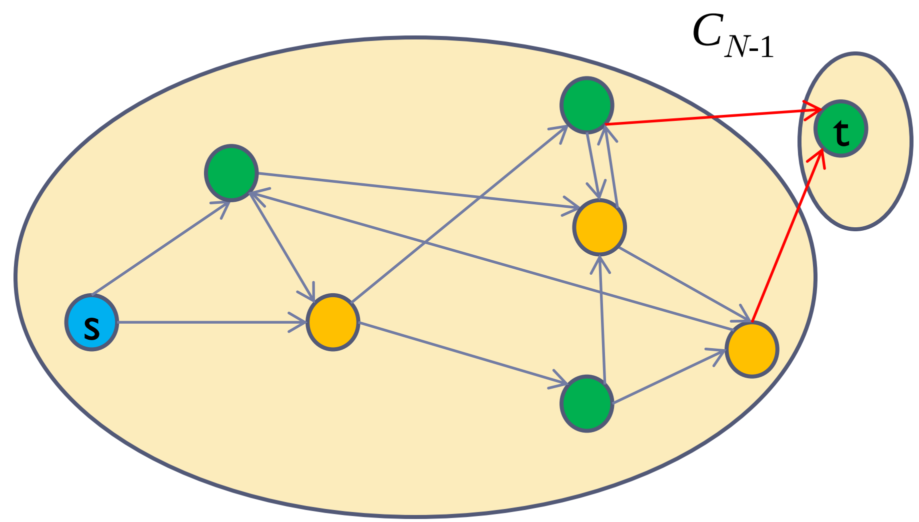
$$E[C_n] > E[C_f] \triangleq \min\{u_s, \boxed{\frac{u_s + upN}{N}}\}$$

- Since the number of edges in a cut, **$nM(Y\text{-}n)/N$,** is large when M and N increase, the capacity of any cut C_n should be no less than $(1-\varepsilon)$ C_f with high probability

Insights for P2P Protocol Design

The most critical cut is the last cut $C_{N\text{-}1}$

- The probability that $C_{N\text{-}1}$ fails (less than (1-ε) of optimal streaming rate C_f) is much larger than the probability that any other cut fails



Two main reasons:

- The expected capacity $\mathbf{E}[C_{N\text{-}1}]$ is the smallest
- The expected number of edges is the smallest: $nM(N\text{-}n)/N = M$ when $n=N\text{-}1$

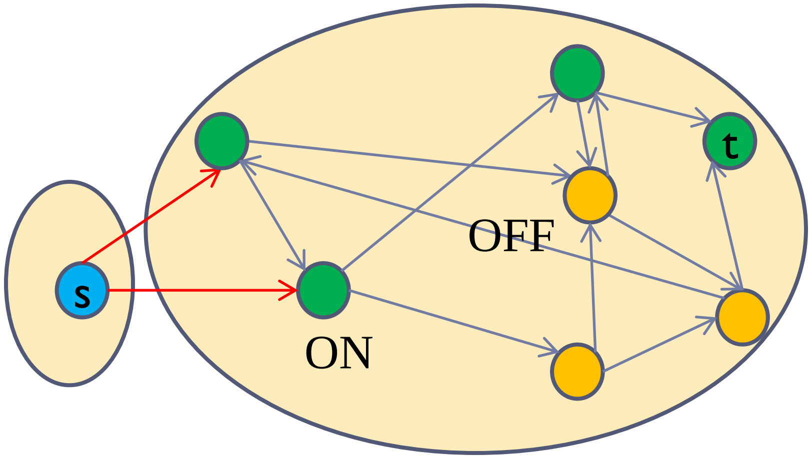
$$E[C_{N-1} \mid Y = Np] = \frac{u_s + upN}{N} = E[C_f]$$

Improved P2P control scheme should focus on improving the capacity of the last cut

Insights for P2P Protocol Design

ON/OFF status of each peer's upload capacity:

- A common wisdom is that peers close to the server should choose ON peers as downstream neighbors
- Our analysis indicates that only the server needs to be careful choosing ON peers.



Low-overhead P2P control scheme could focus on peer-selection and recovery at the server only.

Insights for P2P Protocol Design

Number of neighbors that each peer needs: $M = \alpha \log N$

- In order that

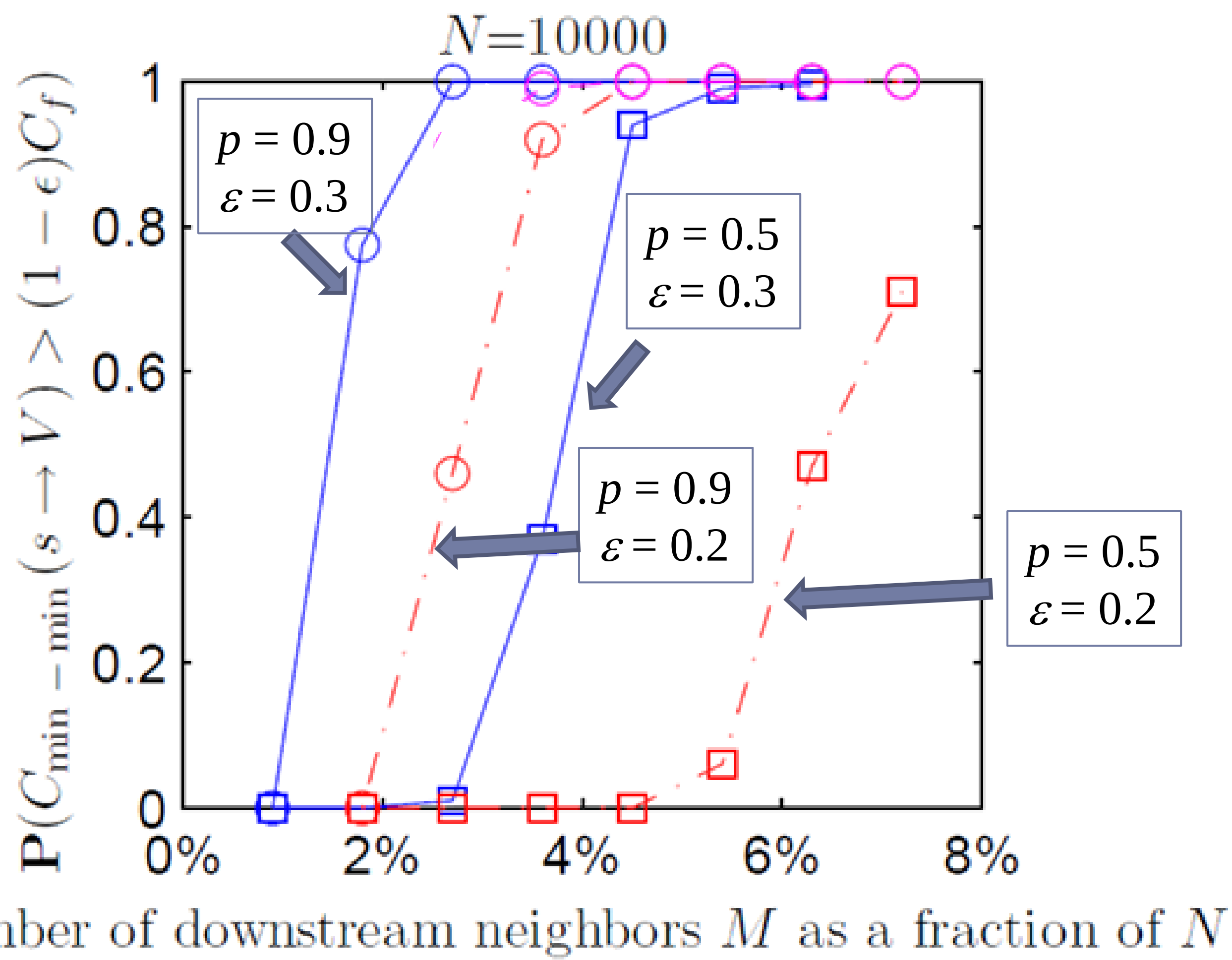
$$P(C_{\min-\min}(s \to V) \leq (1-\varepsilon)E[C_f]) \leq O\left(\frac{1}{N^{2d-1}}\right)$$

the constant α must be

$$\boxed{\alpha \geq \frac{4du_s}{pu\varepsilon^2}}$$

- Require a larger number of neighbors when
  - faster convergence rate (larger d)
  - fewer high bandwidth users (smaller p)
  - higher streaming rate requirement (smaller ε)
- This factor may be further reduced by improving the capacity of the last cut

Simulation Result – Single Channel



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- ***Single-Channel: Adaptive Rate Allocation***
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Adaptive Rate Allocation: Motivation

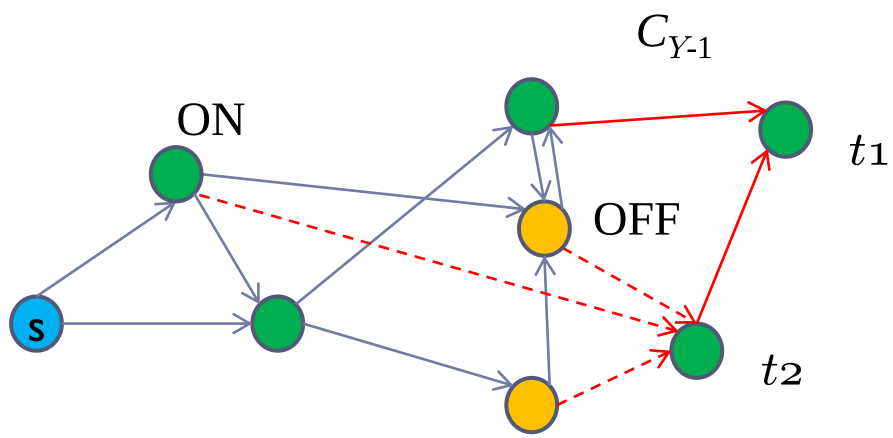
- Number of neighbors each peer needs $M = \alpha \log N$

$$\alpha \geq \frac{4du_s}{pu\varepsilon^2}$$

  - As $\epsilon \to 0$, α increases inversely proportional to ϵ^2
  - The number of neighbors of each peer can still be quite large
- Recall that the most critical cut is the last cut $C_{N\text{-}1}$
  - The capacity that each peer receives directly from its immediate upstream neighbors

- Will improving the capacity of the last cut reduce α?

From Uniform to Adaptive Rate Allocation



Uniform rate-allocation:

- Each edge from an ON peer contributes u/M capacity
- However, the number of such edges to a peer is random

- ***Adaptive rate-allocation***: Balance the capacity of the last cut by carefully assigning C_{ij} (the upload rate from peer i to peer j)

$$\boxed{\sum_{j:\, i \to j} C_{ij} \le u_i, \text{ for all } i,} \quad \text{and} \quad \boxed{\sum_{i:\, i \to j} C_{ij} \ge (1-\varepsilon) C_f, \text{ for all } j}$$

Caveat: no capacity guarantee on all other cuts!

Uniform versus Adaptive Rate Allocation: Pros and Cons

- Uniform rate allocation
  - The last cut is the most difficult
  - Other cuts have larger capacity
- Adaptive rate allocation
  - Balance the capacity for the last cut
  - No capacity guarantee for other cuts

- Hybrid scheme
  - Reserve a fraction of the upload capacity of each peer for uniform rate allocation
  - Perform adaptive rate allocation with the remaining upload capacity

Hybrid Scheme - Details

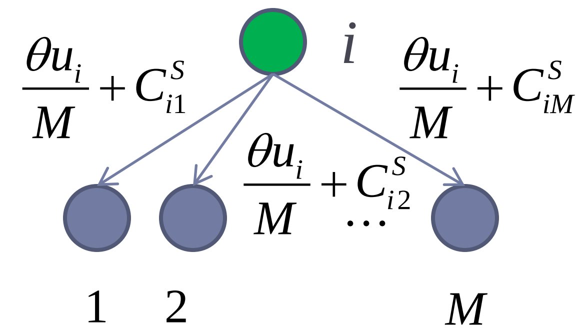
- Still perform *random peer-selection*
- Each link capacity C_{ij} consists of two parts

$$C_{ij} = C_{ij}^U + C_{ij}^S$$

- Reserve a fraction θ of the upload capacity for uniform allocation

$$C_{ij}^U = \theta u_i / M$$

  - Take care of all other cuts with high probability



- The capacity C_{ij}^S for adaptive rate allocation is given by the the solution of

$$\sum_{j:i \to j} C_{ij}^S \le (1-\theta)u_i, \text{ for all } i$$

$$\sum_{i:i \to j} C_{ij}^U + C_{ij}^S \ge (1-\varepsilon)C_f, \text{ for all } j$$

  - The solution exists with high probability $\Rightarrow$ take care of the last cut.
  - There exist fully-distributed algorithms to compute the solution.

Hybrid Scheme - Main Result

- For $0.5 < \theta < 1$, the hybrid scheme could achieve a close-to-optimal streaming rate with high probability

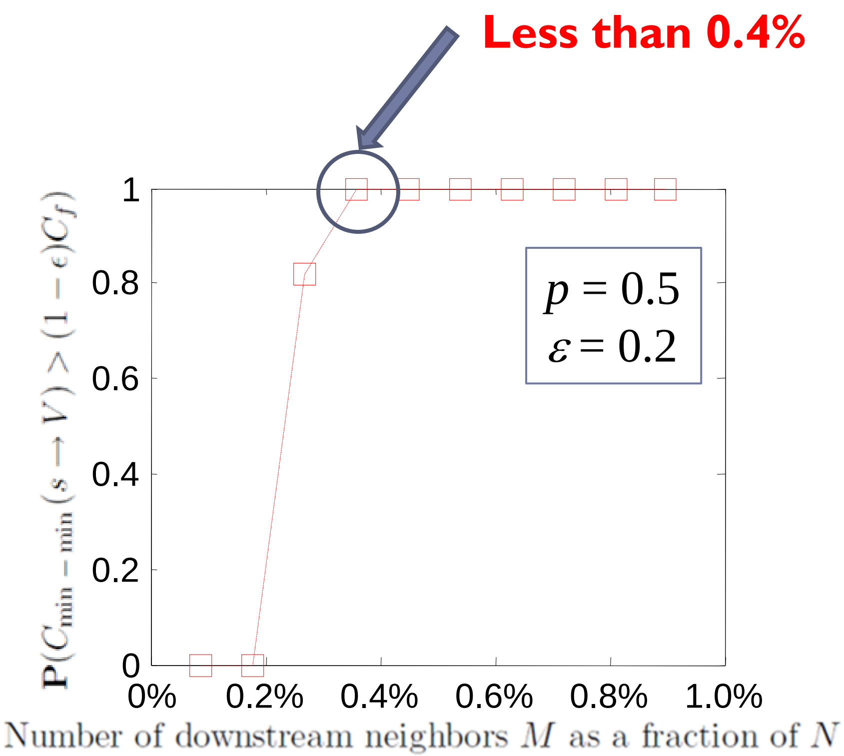
$$P(C_{\min-\min}(s \rightarrow V) \leq (1-\varepsilon)E[C_f]) \leq O\left(\frac{1}{N^{2d-1}}\right)$$

if

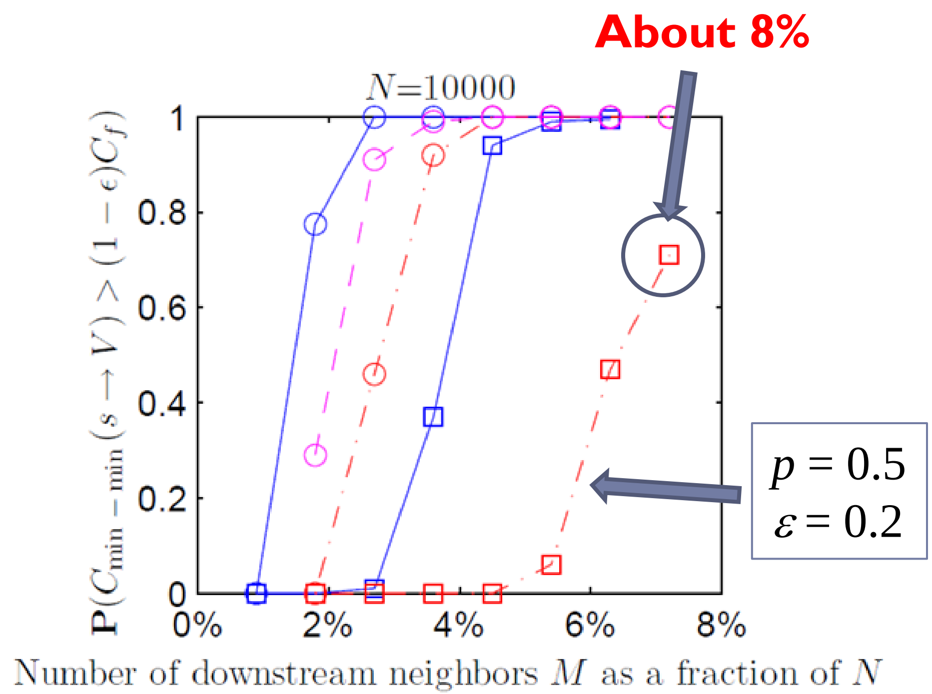
$$\alpha \geq \max\left\{\underbrace{\frac{2d}{\max\left\{\frac{\varepsilon^2}{2}, \frac{(2\theta-1)^2}{8\theta^2}\right\}p}}_{\text{For other cuts}}, \underbrace{\frac{16d}{(1-\varepsilon)p}}_{\text{For the last cuts}}\right\}\frac{u_s}{u}$$

- The dependency on small ε is virtually eliminated!
- Assume $\theta = 0.9$, $\varepsilon = 0.1$
  - Uniform rate allocation: $\alpha > 400 du_s/pu$
  - Hybrid Scheme: $\alpha > 17.8 du_s/pu$

Hybrid Scheme – Simulation Result



Hybrid (N=10000)



Uniform (N=10000)

Overview

- System Model
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- ***Multi-Channel P2P Live Streaming***
- Conclusion and Discussion

Multi-Channel P2P networks

- Existing P2P systems typically serve a large number of channels/videos at the same time
- Traditionally, each channel is treated separately
  - Peers viewing a channel only serve other peers in the same channel
- View-Upload Decoupling (VUD [Wu et. al. 2009])
  - Peers can view one channel but serve/upload videos for peers in a different channel
  - Streaming capacity for multi-channel P2P system is improved
  - Still assume complete connectivity and centralized operation
- Our work
  - We propose a simple distributed scheme that has a similar flavor of VUD
  - Close-to-optimal streaming capacity region can still be achieved for multi-channel systems

Multi-channel - System Model

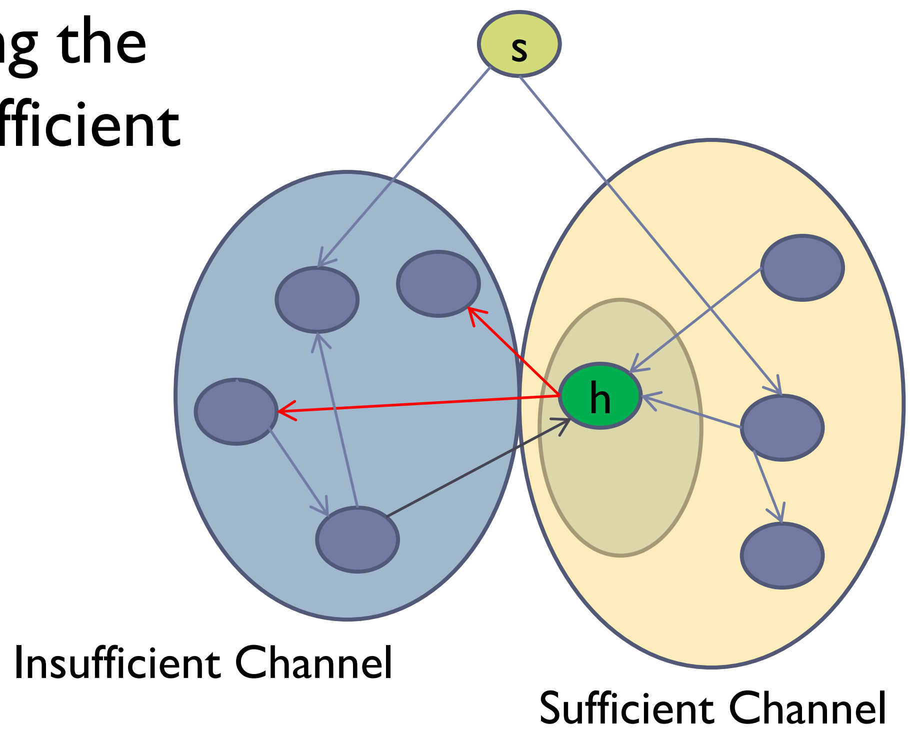
- Consider a multi-channel P2P system with J different channels
- $\mathcal{N}_j$: the set of peers that are viewing channel j
  - $N_j = |\mathcal{N}_j|$: The number of peers in channel j
- $u_{s,j}$: the capacity that server allocates to channel j
- R_j: the targeted streaming rate of channel j
- For each single channel, the optimal achievable streaming rate is

$$C_{f,j} = \min\left\{ u_{s,j}, \frac{u_{s,j} + \sum_{i \in \mathcal{N}_j} u_i}{N_j} \right\}$$

- For a given $\mathbf{R}$,
  - some channels may have a $C_{f,j} > R_j$, ➡ sufficient channels
  - some channels may have a $C_{f,j} < R_j$ ➡ insufficient channels

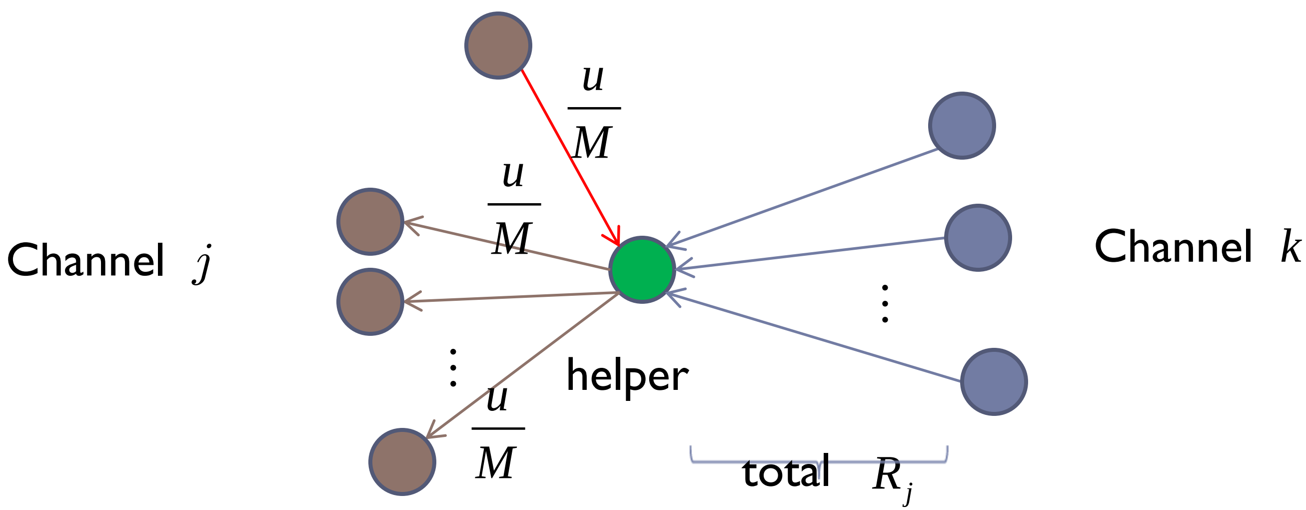
Multi-channel – View-Upload Decoupling

- VUD: Some peers from the sufficient channels become helpers to help improving the performance of the insufficient channels



Multi-channel - Helper

- A helper that is viewing channel k and helping channel j
  - Receives full streaming rate R_k of the content of channel k
  - Must be ON
  - Receives a rate u/M of the content of channel j
  - All of its downstream neighbors are peers viewing channel j



Multi-channel: Capacity Region

- R_j : the targeted streaming rate of channel j
- We can define the capacity region Λ as the set of streaming rate vectors $\mathbf{R} = [R_1, R_2, \ldots, R_J]^{\mathrm{T}}$ such that any $\mathbf{R} \in \Lambda$ is supportable by some control algorithm.
- The largest possible capacity region

$$\Lambda = \left\{ \mathbf{R} \,\middle|\, \sum_{j=1}^{J} N_j R_j \le u_s + \sum_{i \in V} u_i, \sum_{j=1}^{J} R_j \le u_s \right\}$$

Total capacity demand

Total upload capacity

- Given $\mathbf{R} \in (1-\epsilon)\,\Lambda$, can this rate vector $\mathbf{R}$ be achieved by a simple and distributed control scheme?

Multi-channel - Algorithm

- Let H_j be the number of helpers that channel j needs
- We would like to choose H_j so that

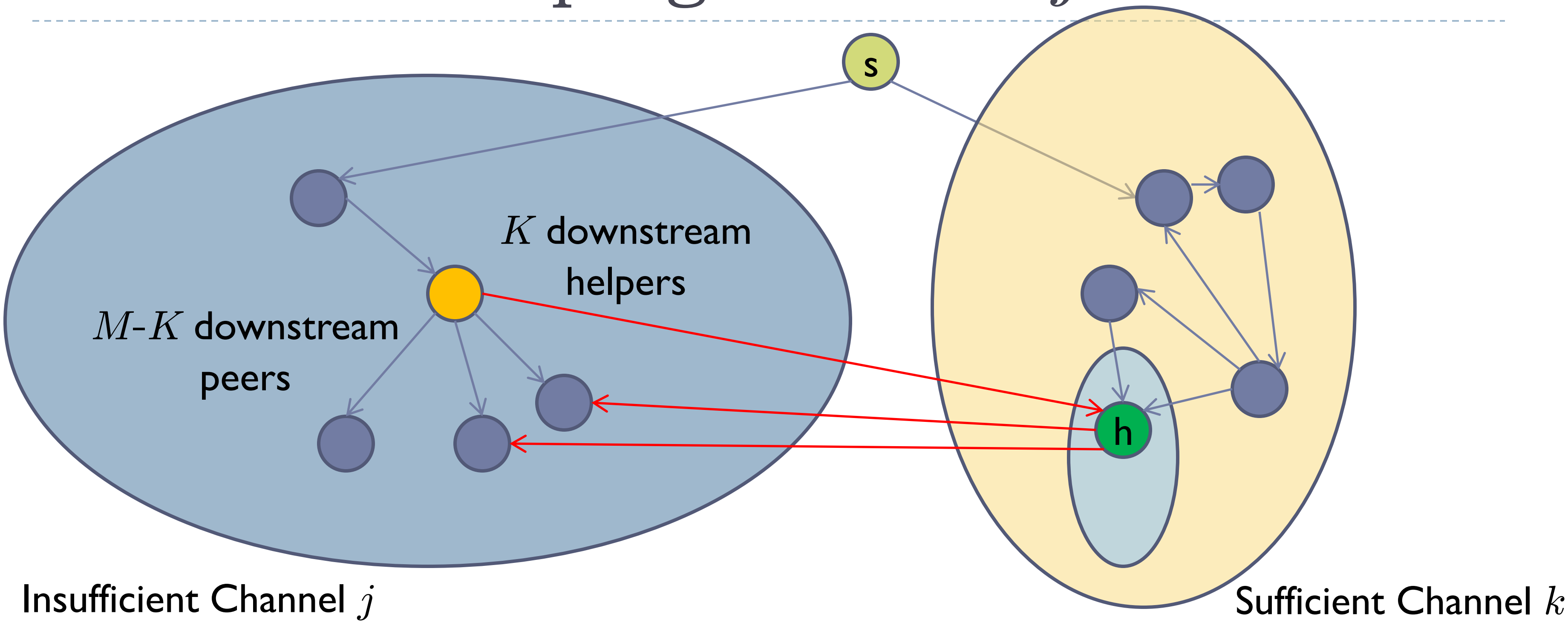
$$C_{f,j} = \min\left\{u_{s,j}, \frac{u_{s,j} + \sum_{i\in\mathcal{N}_j} u_i + \sum_{i\in\mathcal{H}_j} u_i}{N_j}\right\} = \frac{R_j}{1-\varepsilon}$$

- One solution:

$$H_j = \left\lfloor \frac{N_j R_j}{(1-\varepsilon)u} - \frac{u_{s,j}}{u} - pN_j \right\rfloor$$

  - $H_j > 0$ for an insufficient channel (needing helpers)
  - $H_j < 0$ for a sufficient channel (providing helpers)

Channel k Helping Channel j



- Each helper behaves like an OFF peer in channel k
- Each ON peer in channel j reserves K (downstream) slots for helpers
- Each helper finds a normal ON peer randomly from channel j as its upstream neighbor
- Each helper picks M downstream peers randomly from channel j
- Uniform rate allocation. Helpers do not connect to helpers

Multi-channel – Main Result

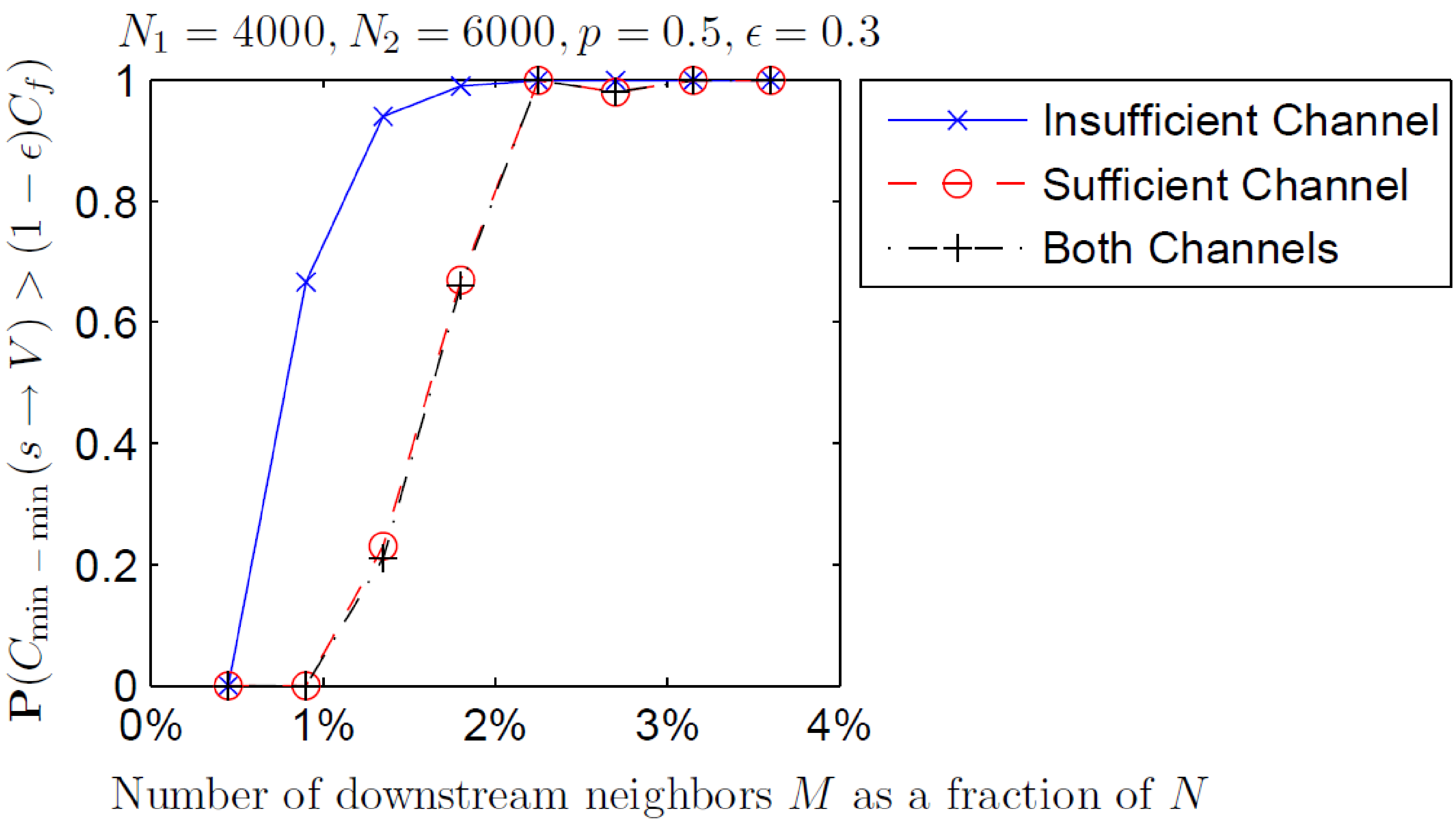
- For any $\varepsilon > 0$, $d > 1$ and $\mathbf{R} \in (1-\varepsilon)\Lambda$, there exists α such that if $M = \alpha \log N$, then for all channel j

$$P(C_{\min-\min}(s \to \mathcal{N}_j) \le R_j) \le O\left(\frac{1}{N^{2d-1}}\right)$$

  - $\mathcal{N}_j$: The set of peers that are viewing channel j
  - Λ is the largest possible capacity region.

- Our proposed scheme can achieve close-to-optimal capacity with sparse connectivity and decentralized control.
  - Each peer still needs only $O(\log N)$ neighbors
  - Helpers are chosen randomly

Simulation Result – Multi-Channel



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Summary

- Close-to-optimal streaming capacity can be achieved with high probability using
  - $O(\log N)$ downstream neighbors for each peer
  - Random peer-selection
  - Uniform rate-allocation
- Our results reveal important insights into the dynamics of large P2P streaming systems
- Based on these insights, we design a hybrid scheme that further improves the system performance.
- With "helpers", a similarly simple scheme could also achieve a close-to-optimal streaming capacity region for multi-channel P2P systems

On-Going and Future Work

- P2P Video-on-Demand (VoD) Systems
  - Timing of each neighbor is important
  - Users may jump forward/backward
  - Cache placement policy is also critical
  - We show that simple and distributed control with sparse-connectivity will still suffice

On-Going and Future Work

- The packet scheduling problem
  - May use generation-based random linear network coding.
  - There is a tradeoff between rate, delay, and overhead
  - BATS code?
- Incorporating scalable video
  - Video encoding rate may be adjusted based on the optimal streaming rate
  - Layered video
- Multiple ISPs
  - Cross-ISP traffic may encounter new bottlenecks
  - Will random peer-selection and simple rate-allocation strategies still be sufficient?
- Wireless versus wireline

Thank You!

Can Zhao, Xiaojun Lin and Chuan Wu ``The Streaming Capacity of Sparsely-Connected P2P Systems with Distributed Control," in *IEEE INFOCOM*, Shanghai, China, April 2011

https://engineering.purdue.edu/~linx