



ΟΙΚΟΝΟΜΙΚΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΘΗΝΩΝ  
ATHENS UNIVERSITY OF ECONOMICS AND BUSINESS

# Incentive-based Caching Mechanisms for Overlay Traffic Management

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Department of Informatics,

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EUROPEAN SOCIAL FUND

# Outline

1. Context and motivation
2. Design of the economic mechanism
3. Contribution
4. Metrics of interest
5. Cost modeling
6. Performance modeling
7. Simulation environment
8. Evaluation results
9. Game-theoretic analysis of ISPs' dynamics
10. Conclusions and future work

# Roadmap

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# Context

- Applications forming overlay networks generate significant traffic volumes in the Internet
  - P2P file sharing,
  - Video streaming,
  - Cloud applications, etc.
  
- What is an overlay?
  - A network lying over the IP network performing application layer routing
  
- Focus of this research work is on **Peer-to-Peer** (P2P) traffic
  - ~80% of total IP traffic in 2008
  - ~20-30% in 2012-2013 (but still very high in absolute volumes) \*

Focus on p2p file sharing, and especially **BitTorrent**

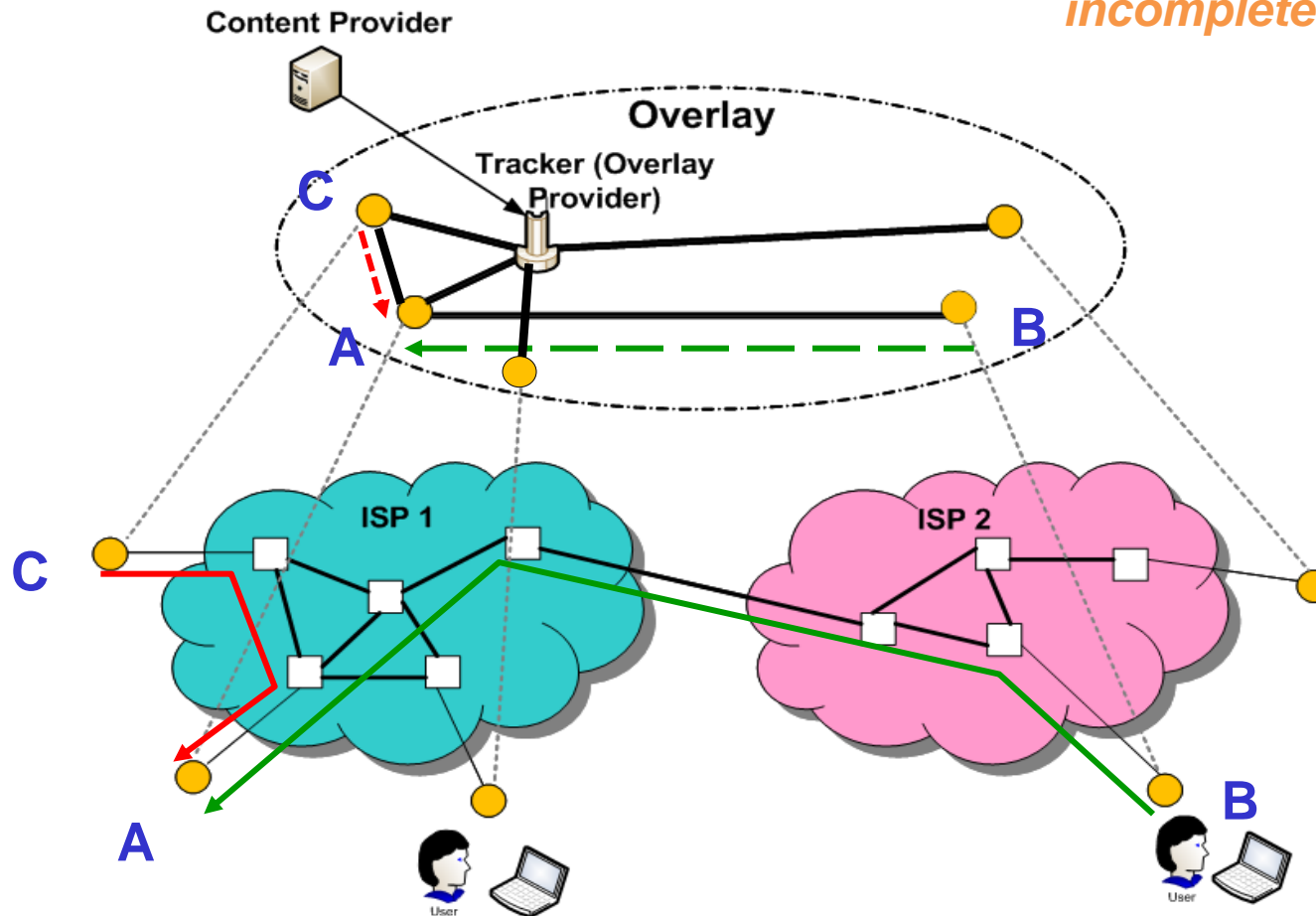
\* Source: Index, Cisco Visual Networking. "Forecast and Methodology, 2011–2016, 2012."

# Motivation

- Overlays have nice inherent capabilities
  - Scalability, Self-organization, Robustness
- But, they are usually built independently of the physical network (underlay)
  - Due to **incomplete information** and **misalignment of incentives/objectives**
- Result: increase of the operating **cost** of the ISPs, due to
  - Congestion in ISPs' networks and possibly degradation of the performance of other applications/overlays
  - Increase of traffic in costly inter-domain links
- ISPs take countermeasures to deal with the overlay traffic:
  - DPI techniques
  - Traffic shaping/throttling
- Thus, the system is led to a **suboptimal** operating situation for both players

# Example

- i. A does not know C → *incomplete information*



- ii. But even if A knew, he might still prefer B due to B's higher upload bandwidth → *misalignment of objectives*

# Question ...

- Can we design a Traffic Management (TM) mechanism that will
  - provide incentives to the overlay to make decisions also in favor of the underlay,
  - and lead the system to a **mutually beneficial situation**, i.e., *win-win*?
    - In contrast to traditional TM where a global optimum would be sought
    - Following the **Economic Traffic Management** paradigm proposed by FP7 project **SmoothIT**\*

\* The SmoothIT project: <http://www.smoothit.org/>

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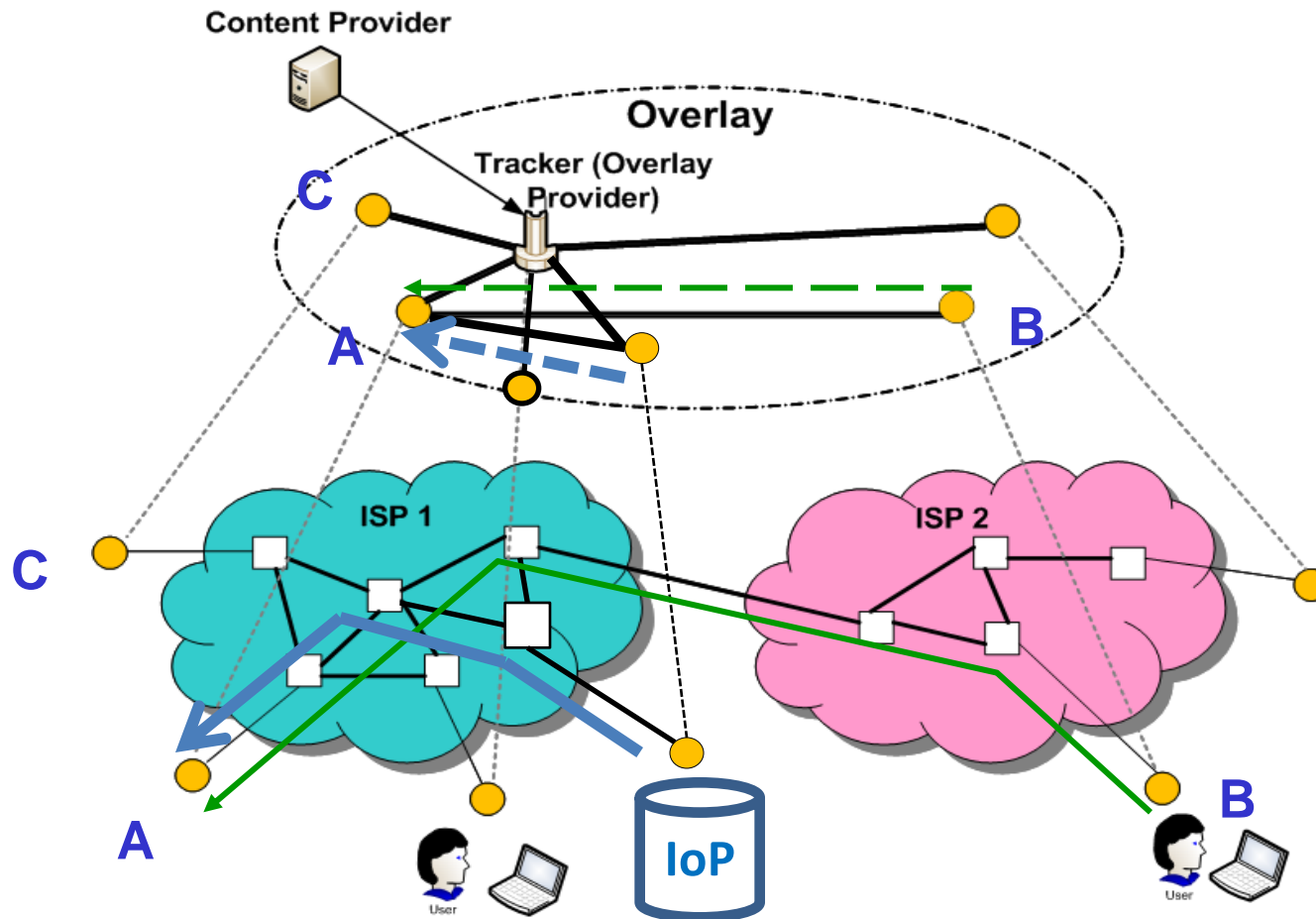
# Idea: Use of caching in the P2P context



- Insertion of a cache in the overlay by the ISP
  - Simple and low overhead
  - Does not require modification of the overlay client, the overlay tracker, or the communication protocol between them
- Requirements for the cache:
  - Act as a regular peer running the overlay protocol  
... hence called **ISP-owned Peer (IoP)**
  - Be resourceful to exploit BitTorrent's **reciprocation algorithm**, to become known and preferred by other to download from
- Variations: Transparent vs. promoted/advertised
- Unchoking Policy: Serves only local peers – in the same AS
- Swarm Selection: Select the swarm(s) to serve
- Bandwidth Allocation to selected swarms

I. Papafili, S. Soursos, G. D. Stamoulis, “*Improvement of BitTorrent Performance and Inter-Domain Traffic by Inserting ISP-owned Peers*”, 6th International Workshop on Internet Charging and QoS Technologies (ICQT'09), Aachen, Germany, May 2009

# Insertion of the IoP



**IoP preferred as a source by regular peers due to its rich resources**

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# Contribution of this thesis

- Development of an incentive-based mechanism for management of the traffic by P2P overlays
- Development of a set of models and tools to analyse and evaluate the impact of the mechanism in P2P content delivery scenarios
  1. Economic modeling of cost incurred by P2P in ISPs
  2. Performance modeling by means of a Markov model
  3. Game-theoretic modeling to investigate ISPs' dynamics
- Proposal of policies to enhance the impact of caching
- Extensive evaluation of the mechanism and its policies
  - In both simple and complex topologies
  - In multi-swarm environments

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# Metrics of interest

Overlay	Underlay
<p><b>Performance of users</b></p> <ul style="list-style-type: none"><li>○ Quality of Experience (QoE) → Average time to complete a file's download (in seconds)</li></ul>	<p><b>Inter-domain traffic</b></p> <ul style="list-style-type: none"><li>○ Use of 95<sup>th</sup> percentile (in Mbps) for a multitude of charging schemes → Directly related to inter-connection costs</li></ul>

- Investigation of the IoP's impact on: the ISP that deploys it, and on its users/peers
- Investigation of IoP's impact also on neighbouring ISPs
  - Consider potential **reactions** and **free-riding** effect!

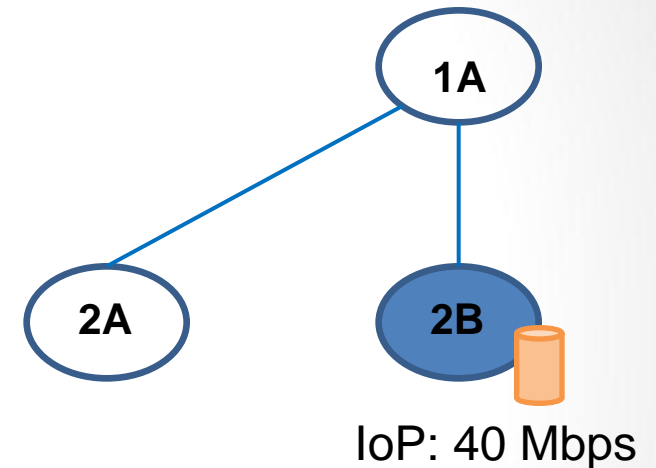
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# Cost of ISP buying Transit

- Translate traffic savings to cost savings
- Focus on charging scheme based on incoming traffic only, for simplicity

- Transit link: 6 Gbps
- Link utilization: 75% → 4 Gbps average
- P2P traffic share: 21%\*



- Cost of IoP's capacity per swarm: € 10.19
- Price for transit: € 1.18/Mbps (\$1.57/Mbps)\*\*

$z$  : traffic savings by  
IoP per swarm

- Net profit if savings per swarm, if  $z \geq 10.7$  Mbps

\* Source: Index, Cisco Visual Networking. "Forecast and Methodology, 2011–2016, 2012."

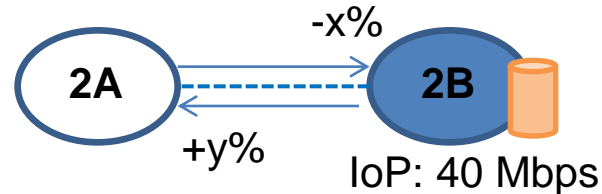
\*\*DrPeering.net



# Cost of ISP under a (Paid) Peering agreement

- Potential peering ratio violation due to traffic asymmetry
- Need to consider also **background** traffic
- P2P traffic share: 21%\*

- Background traffic:  $T_{back} = \left( \frac{1}{0.21} - 1 \right) \cdot T_{P2P} = 3.7 \cdot T_{P2P}$



$x\%$ : reduction in 2A2B  
 $y\%$ : increase in 2B2A  
 $r_p$  : peering ratio (1.1, 1.2)

- Traffic violation if:  $y \geq 4.7 \cdot (r_p - 1) - r_p \cdot x$
- Excessive traffic to be charged:  $T_{exc} = \left( 4.7 \cdot (1 - r_p) + y + r_p \cdot x \right) \cdot T_{P2P}$

\* Source: Index, Cisco Visual Networking. "Forecast and Methodology, 2011–2016, 2012."

# Roadmap

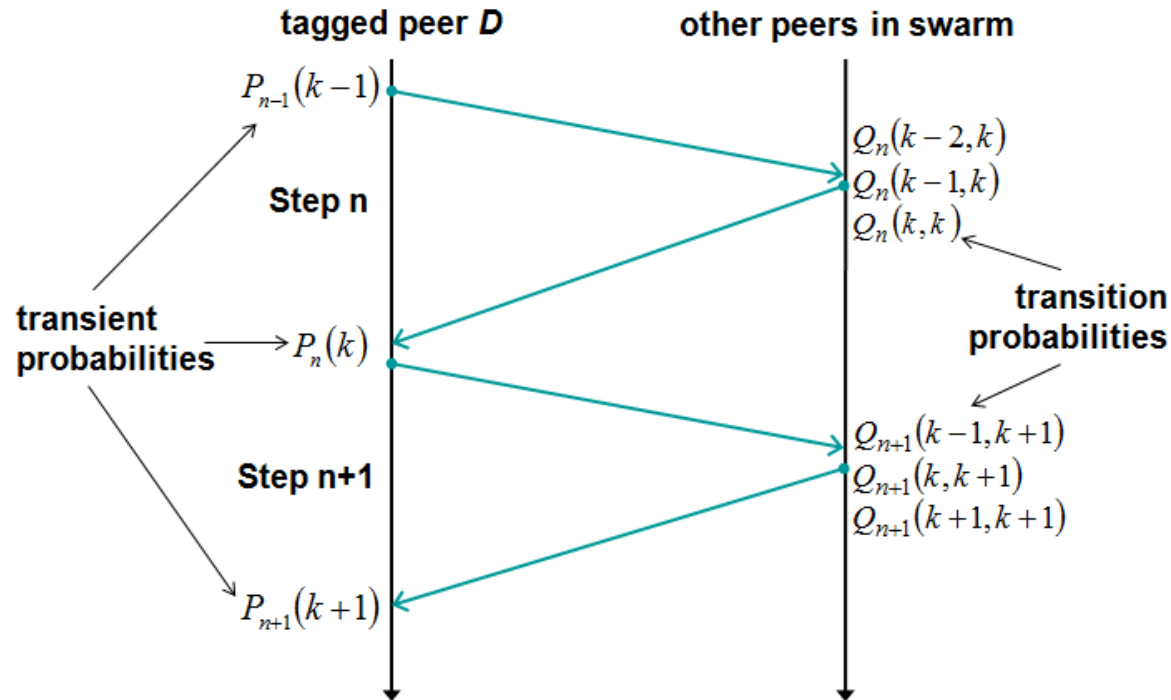
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# Modeling of a BitTorrent swarm's performance

- P2P systems have high complexity!
- Development of an approximation model that employs a **Markov chain** to:
  - Analyse and evaluate the performance of the P2P overlay
  - Dimension the IoP and evaluate its insertion
- State of tagged peer  $D$  at step  $n$ : number of chunks  $k$  obtained by step  $n$
- Transient distribution:  $P(n) = [P_n(0), P_n(1), \dots, P_n(K)]$
- Size of the complete content file:  $K$
- Key idea: Due to symmetry, distribution of tagged peer  $D$  characterizes all peers

Papafili, Ioanna, and George D. Stamoulis. "A Markov model for the evaluation of cache insertion on peer-to-peer performance." *Next Generation Internet (NGI), 2010 6th EURO-NF Conference on*. IEEE, Paris, France, June 2010.

# Markov chain evolution



Terminal condition:  
 $n^* : P_{n^*}(K) > 0.99$

**2-step Markov chain**

- Calculation of transient probability at step  $n+1$ :

$$P_{n+1}(k) = P_n(k-2)Q_{n+1}(k-2, k) + P_n(k-1)Q_{n+1}(k-1, k) + P_n(k)Q_{n+1}(k, k)$$

- Probabilities of the only 3 feasible transitions at each step  $n$  sum to 1:

$$Q_{n+1}(k-2, k-2) + Q_{n+1}(k-2, k-1) + Q_{n+1}(k-2, k) = 1$$

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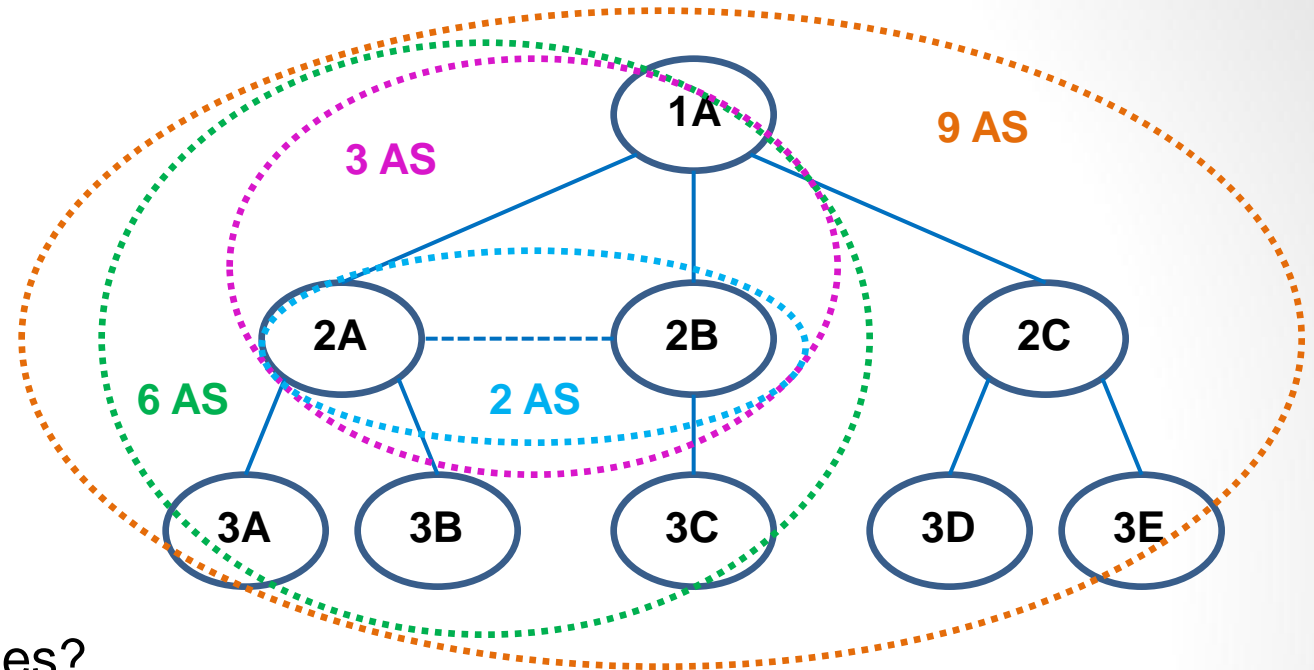
# Simulator

- Use of SmoothIT simulator
  - Developed by FP7 project **SmoothIT**\*
  - Built on top of ProtoPeer\*\* developed by EPFL
  - Java-based
  - Highly modular
  - Modeling of network and overlay
  - Alternative peer/chunk selection processes
  - Support of multi-swarm simulation

\* The SmoothIT project: <http://www.smoothit.org/>

\*\* The ProtoPeer simulator: <http://protopeer.epfl.ch/index.html>

# Evaluation topologies roadmap



Why simple topologies?

- Gain insight on the effect of IoP and its variations, combination with BNS and swarm selection

Why complex topologies?

- Gain insight on IoP's impact on the cost of a tier-2 ISP (2B)
  - Consider inter-connection agreements
- Take into account traffic from/to customer Ases
- More **realistic!**

# Comparison / Combination of IoP with Biased Neighbor Selection (BNS)\* by Bindal *et al.*

- Alternative policy for peer selection, to perform P2P traffic localization
  - $k$  remote,  $35-k$  local
  - Tracker – client modification required
- Achieves significant reduction of inter-AS traffic
- But, no improvement and potential performance deterioration
- In our evaluations:
  - Comparison of IoP (both transparent and promoted) against BNS
  - Combination of IoP with BNS

\* Bindal, R., Cao, P., Chan, W., Medved, J., Suwala, G., Bates, T., & Zhang, A. (2006). Improving traffic locality in BitTorrent via biased neighbour selection. In *Distributed Computing Systems, 2006. ICDCS 2006. 26th IEEE International Conference on* (pp. 66-66). IEEE.



# IoP variations examined

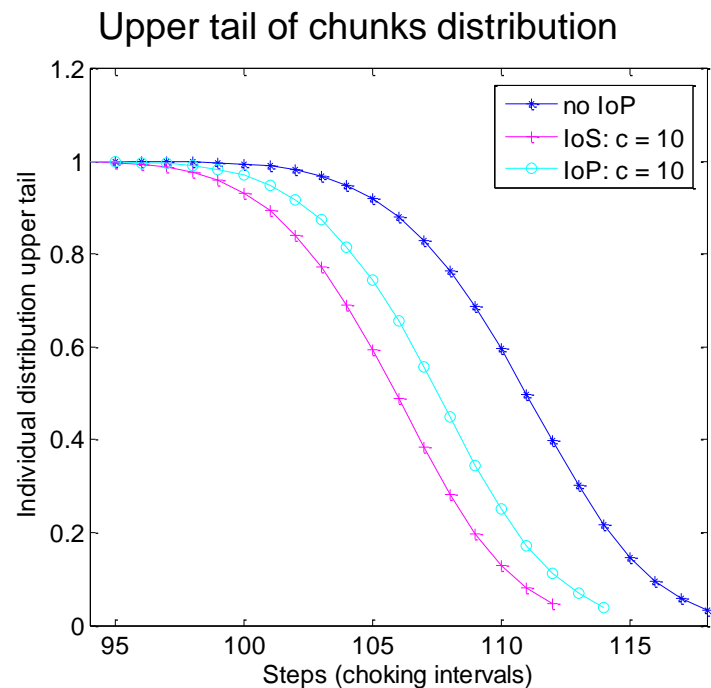
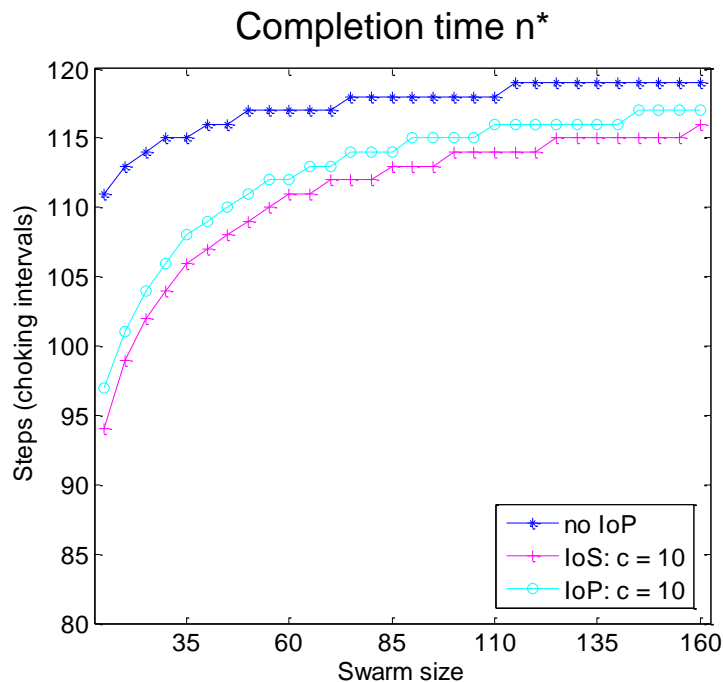
Abbreviation	Description of IoP variation
IoP	Transparent IoP insertion
IoPUP	Transparent IoP insertion with unchoking policy
IoPCT	Promoted IoP insertion – CT: cache-aware tracker
IoPCTUP	Promoted IoP insertion with unchoking policy
IoPBNS	Transparent IoP combined with BNS approach
IoPCTBNS	Promoted IoP combined with BNS approach

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# Evaluation of loP's impact on download time

- Significant improvement of performance compared to the 'no loP' case  
→ **benefit** for peers
- Even higher improvement, when the loP starts as a seeder



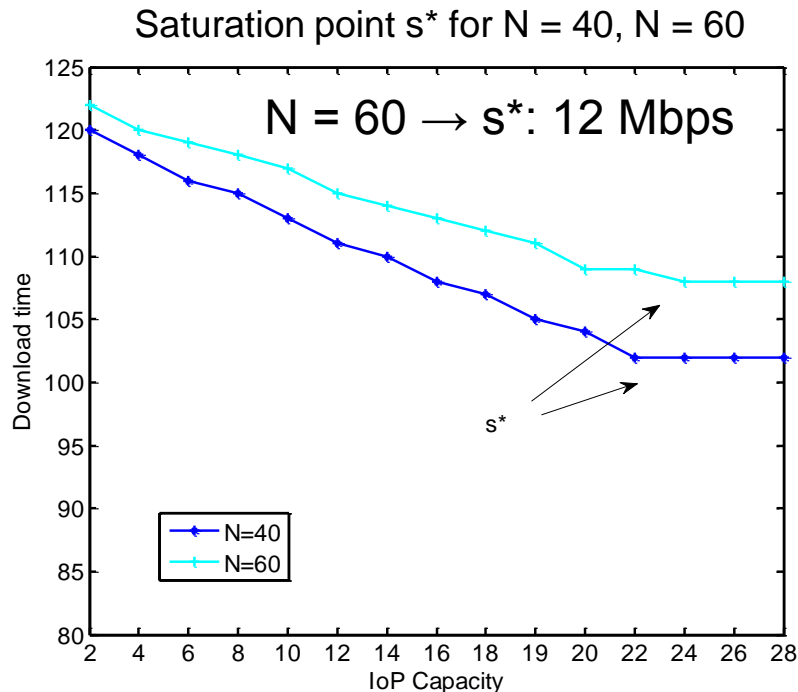
Results obtained by the Markov model

# Dimensioning of IoP

- Tradeoff: IoP's capacity should
  - be adequate to have notable impact
  - not be wasted!
- Select capacity by means of the Markov model
  - to save time from simulations

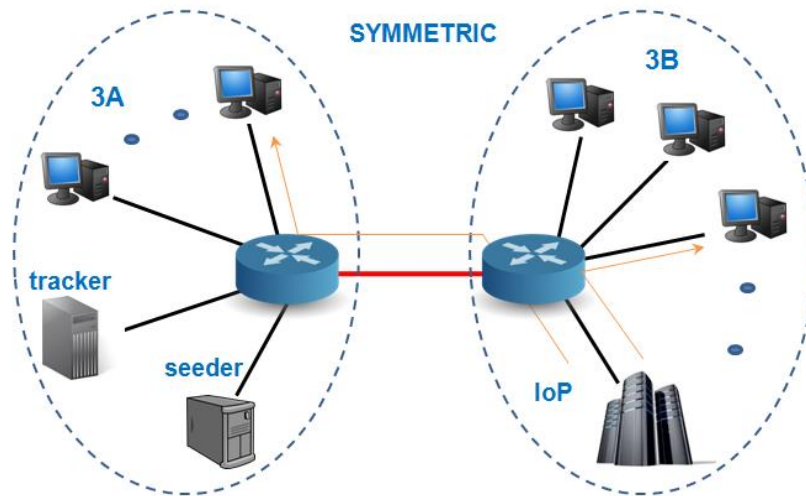
Peer population for {3, 6, 9}-AS topologies by simulation

Topology	Peers (seeders+leechers)		Leechers	
	Swarm	2B	Swarm	2B
	3 AS	120-150	55-65	45-90
6 AS	<b>180-230</b>	60-70	80-150	25-40
9AS	<b>210-230</b>	35-45	100-150	15-30



- Conservative transformation to address larger swarms
  - $N=180$  ( $3 \cdot 60$ ) →  $s^*$ : 33 Mbps
  - $N=210$  ( $3.5 \cdot 60$ ) →  $s^*$ : 42 Mbps
- Decision to use:
  - 6-AS: **40 Mbps**
  - 9-AS: **50 Mbps**

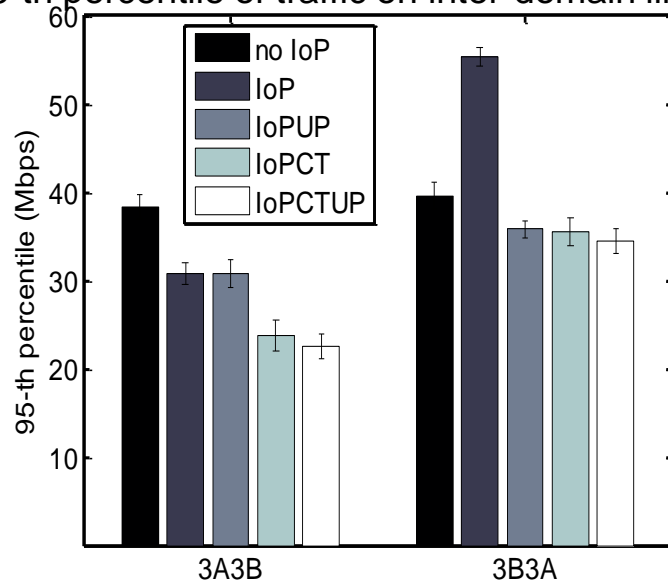
# Evaluation of IoP and its variations - peering



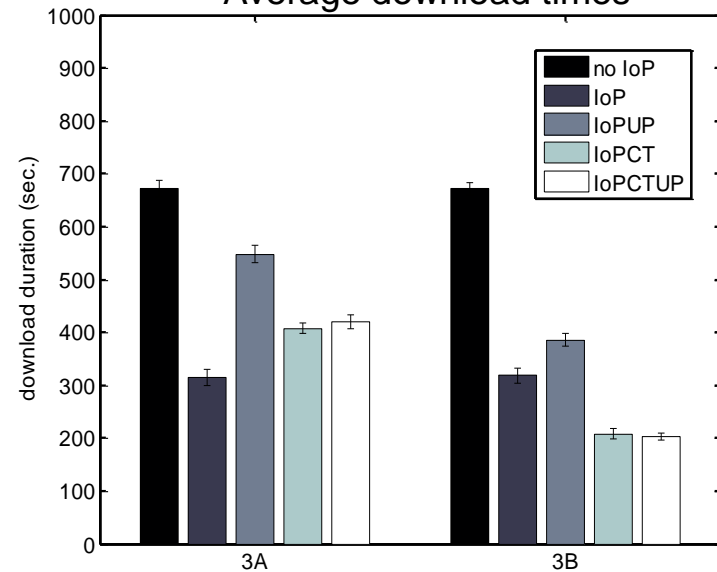
peering ratio = 1.1

- Promoted IoP
  - Higher capacity utilization (without/with policy)
  - Double incoming traffic reduction than transparent IoP
- Peering violation only for transparent IoP
- Excessive traffic: <8 Mbps

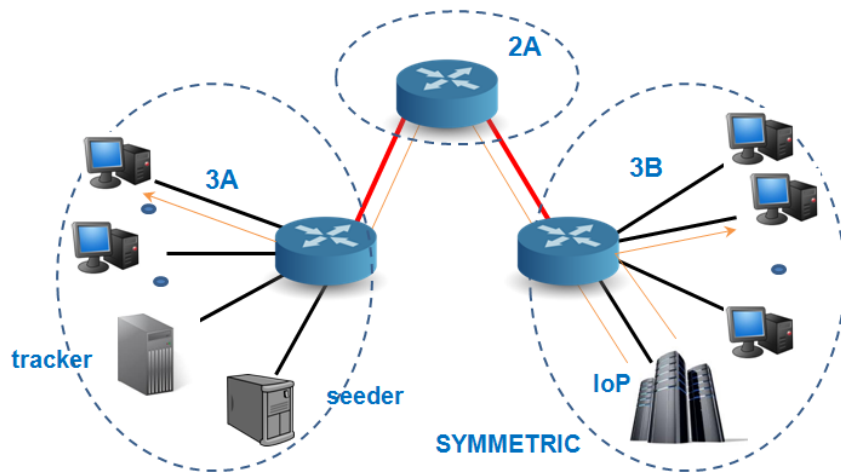
95-th percentile of traffic on inter-domain links



Average download times



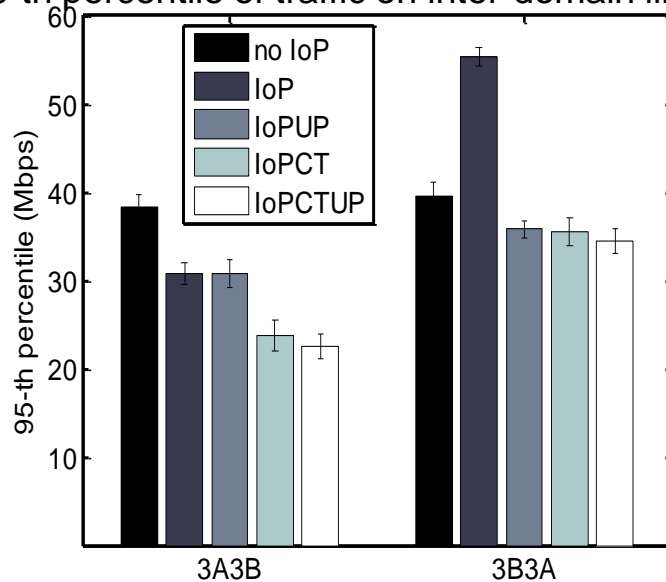
# Evaluation of IoP and its variations - transit



- Net profit if:  $z \geq 10.7$  Mbps

3B's traffic savings (Mbps)			
IoP	IoPUP	IoPCT	IoPCTUP
7.59	7.55	14.65	15.84

95-th percentile of traffic on inter-domain links

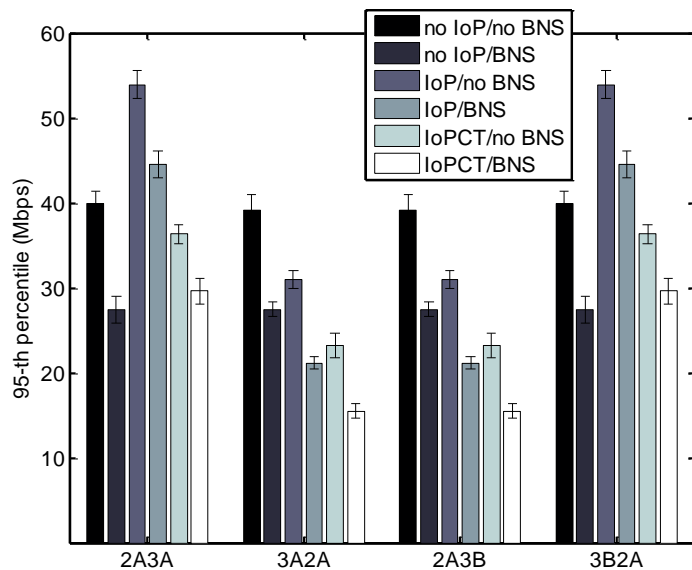


- Net profit when a promoted ISP is in place

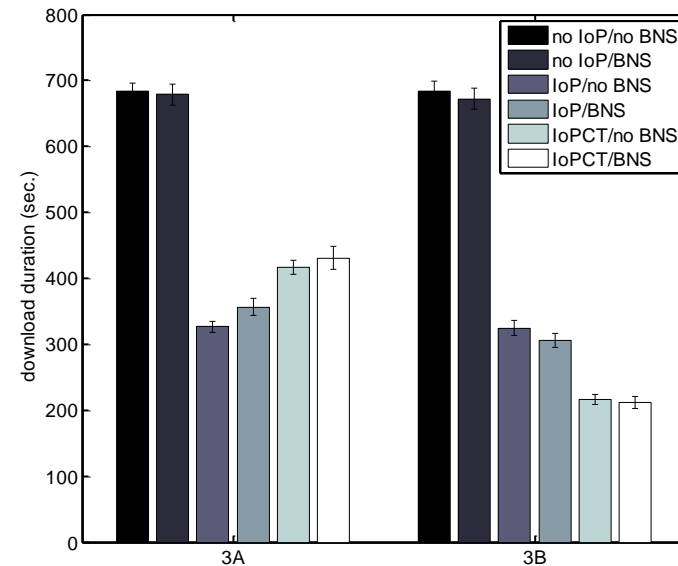
3A's traffic savings (Mbps)			
IoP	IoPUP	IoPCT	IoPCTUP
-15.74	3.80	4.03	5.15

- Savings also for 3A together with performance improvements  
→ **free-riding**

# Comparison / combination with BNS



95-th percentile of traffic on inter-domain links



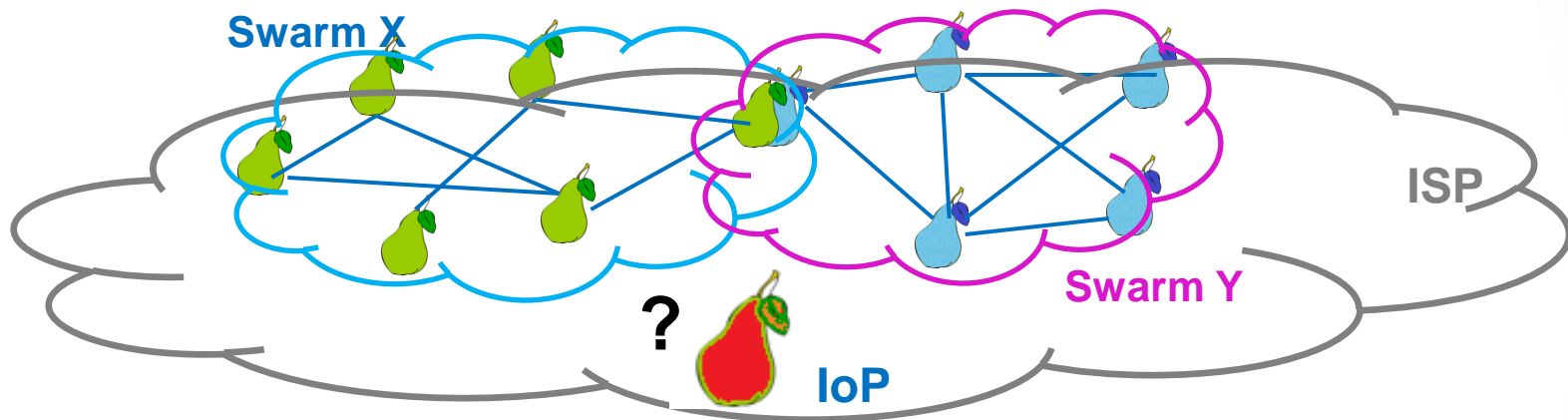
Average peers' download duration

- Combination with BNS
  - Reduces outgoing traffic by IoP
  - Eliminates potential performance deterioration by BNS
  - Higher benefits for all when promoted IoP is employed

# Swarm selection

- Large number of swarms active in an ISP
- Only few large swarms generate up to 80% of total P2P traffic\*

\* Source: Hoßfeld, T., Lehrieder, F., Hock, D., Oechsner, S., Despotovic, Z., Kellerer, W., Michel, M. (2011). "Characterization of BitTorrent swarms and their distribution in the Internet". *Computer Networks*, 1197 -1215.



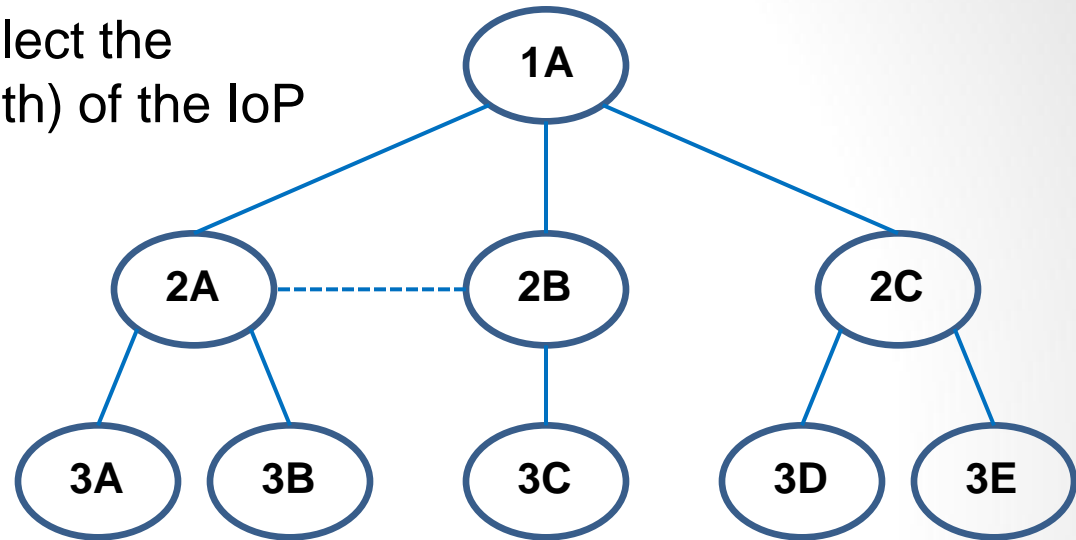
- IoP's capacity is not unlimited!  
→ Need to select in which swarms to step in
- Selection based on the **size** of either the **content file** or the **swarm**

Papafili, I., Stamoulis, G. D., Lehrieder, F., Kleine, B., Oechsner, S. (2011). "Cache capacity allocation to overlay swarms". In *Self-Organizing Systems* (pp. 68-80). Springer Berlin Heidelberg



# Evaluation of IoP in complex topologies

- Dimensioning of IoP by the Markov model was employed to decide to select the capacity (i.e., upload bandwidth) of the IoP



## Observations

- Similar traffic and performance patterns as in 3-AS topology
- Much higher traffic savings, which lead to higher cost savings
  - Higher net profit when promoted IoP
- Peering violation only in 9-AS topology with transparent IoP
- Important: Free-riding effect diminished!
  - Increase of external to IoP peers reduces both traffic savings and performance improvements for other ISPs

# Questions again ...

1. If ISP 2B introduces an IoP, how will ISP 2A be affected? and respond?
  - Should 2A insert an IoP too, or a variation of it?
  - How will 2B respond then?
2. How is traffic from/to customer ISPs and respective revenues affected?

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# Investigation of dynamics of ISPs

- Proposal of a novel game theoretic framework  
..., where ISPs anticipate users' reaction
    - Performance deterioration not adequately considered in related work
    - Use of a combined metric with ISP's cost can still lead to performance deterioration
  
  - In the proposed framework:
    - Performance deterioration is considered to lead to infinite ISP cost
      - Churn model
    - Our ultimate target is win-win!
  
  - Decision-making process:
    1. Performance to define feasible strategies
    2. Cost to select best-response strategy
- + Memory of previous states' payoffs

I. Papafili, S. Soursos, G. D. Stamoulis, *A Novel Game-Theoretic Framework for Modeling Interactions of ISPs Anticipating Users' Reactions*, in Proc. of the 6<sup>th</sup> International Conference on Performance Evaluation Methodologies and Tools, VALUETOOLS'12, Cargese, France, October 2012

# Proof of concept

Performance payoff for 2 tier-3 ISPs\*

	3B		
3A		no loP	loPUP
no loP		20 6.66	17.97 7.09
loPUP		20.43 4.63	18.46 4.99

Traffic cost payoff for 2 tier-3 ISPs\*

	3B		
3A		no loP	loPUP
no loP		5 5	5.26 4.62
loPUP		5 4.46	3.57 3.81 4.36

equilibrium under  
cost metric only

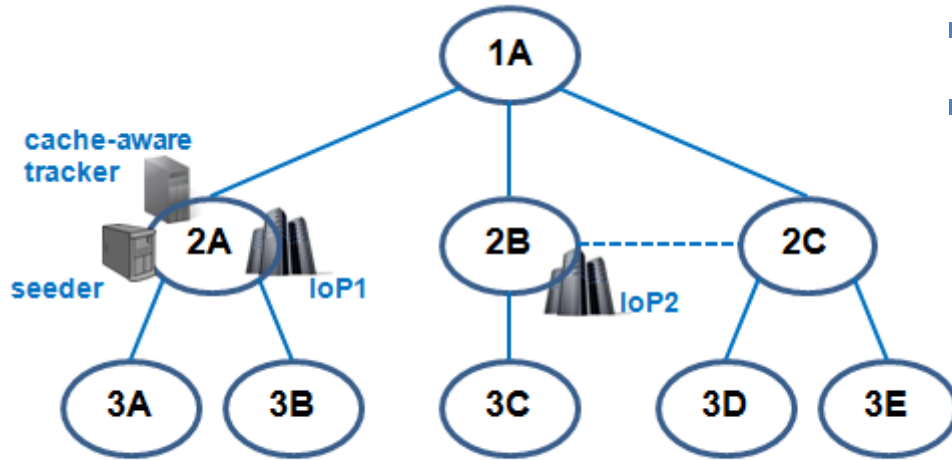
equilibrium under  
the two metrics

- Different equilibrium if only cost were considered
- Use of two metrics result in
  - Avoidance of performance degradation
  - System led to mutually beneficial situation (win-win)

\* Results obtained by a theoretical model proposed in:

Lehrieder, F., Dán, G., Hoßfeld, T., Oechsner, S., Singeorzan, V. (2010, August). The impact of caching on BitTorrent-like peer-to-peer systems. In *Peer-to-Peer Computing (P2P), 2010 IEEE Tenth International Conference*. IEEE.

# Strategy decision w.r.t. customer ASes



- No peering ratio violation in 2B2C
- ISPs' costs:

$$C_{2A} = T_{1A2A}^{95} - T_{2A3A}^{95} - T_{2A3B}^{95}$$

$$C_{2B} = T_{1A2B}^{95} - T_{2B3C}^{95}$$

Performance payoff for 2 tier-3 ISPs (sec)

	2B			
2A		no IoP	IoPCT	IoPCTUP
no IoP		651	174	168
	650	542	562	
IoPCT		545	162	157
	173	159	162	
IoPCTUP		555	161	157
	167	156	158	

Traffic cost payoff for 2 tier-3 ISPs (Mbps)

	2B			
2A		no IoP	IoPCT	IoPCTUP
no IoP		39.3	27.5	21.9
	16.0	10.6	10.2	
IoPCT		33.9	24.4	21.4
	-7.6	-10.8	-8.8	
IoPCTUP		34.5	17.6	14.5
	-2.4	-15.8	-5.8	

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# Conclusions

- Significant reduction of incoming traffic and performance improvement
- Increase of outgoing traffic by the transparent cache without policy
  - Potential peering ratio violation, but low exceeding traffic
  - Solution: unchoking policy or advertisement only to local peers
- More capacity in the cache leads only to further performance improvements, but only until a saturation point
- High traffic savings and net economic profit when the cache is advertised/promoted
- ISPs have incentives not to employ the unchoking policy when they sell transit to other ISPs
  - Revenues by charging them for extra incoming traffic



# Caching as an economic mechanism?

- Yes!
- Provides **incentives** to regular peers
  - Higher capacity → enhanced performance
  - Still, peers are free to 'defect' and choose other resources
- Potential **externalities?**
  - Improvement of performance of the entire swarm
  - Indirectly, also peers not connected to it get benefit
- The cache is a ***public good***



# Future extensions

- Address also other types of traffic
  - Cloud traffic,
  - Traffic stemming from social networks, etc.
- Extend the game-theoretic framework
  - Take into account new metrics, e.g., energy efficiency
  - Include other players, e.g., cloud operators

**Thank you for your attention!**

Questions?

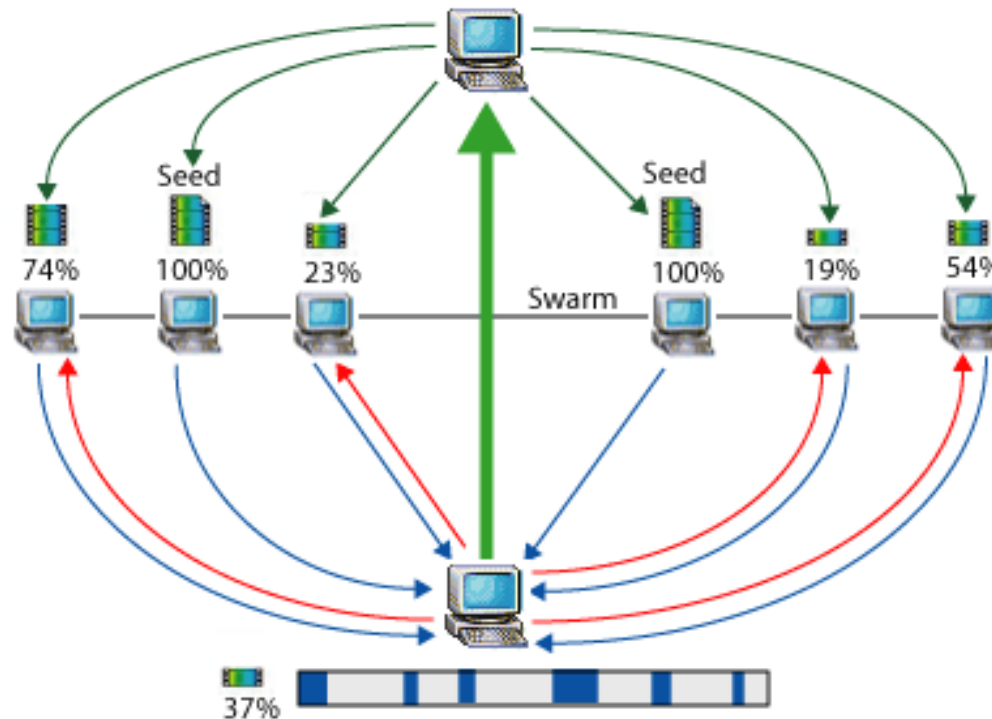
Network Economics & Services Laboratory

<http://nes.aueb.gr>

# Back-up slides

# BitTorrent basics

BitTorrent tracker identifies the swarm and helps the client software trade pieces of the file you want with other computers.



Computer with BitTorrent client software receives and sends multiple pieces of the file simultaneously.


©2005 HowStuffWorks

# Assumptions and simplifications on the BitTorrent protocol

... for the purposes of the Markov model

- Random chunk selection instead of ‘rarest first replication’
- Random peer selection instead of ‘tit-for-tat’
- Up to two chunks downloaded by a peer at each step
- Unique original seeder in the swarm
  - Up to two chunks downloaded by a peer at each step
    - 3 feasible transitions:  $\{k \rightarrow k, k \rightarrow k+1, k \rightarrow k+2\}$
- *Key idea*: Due to *symmetry*, transient distribution of tagged peer  $D$  characterizes all other peers too

# Multi-swarm simulations

- Evaluation of the impact of overlay parameters on swarm selection
  - **Size of content-file** (FS)
  - Size of swarm → 
    - **leechers' mean inter-arrival time** (mIAT)
    - **seeders' mean seeding time** (mST)
- Tunable parameters in our simulation framework
  - Swarms: X, Y
    - X: use of default values for FS, mIAT, mST
    - Y: tune parameters

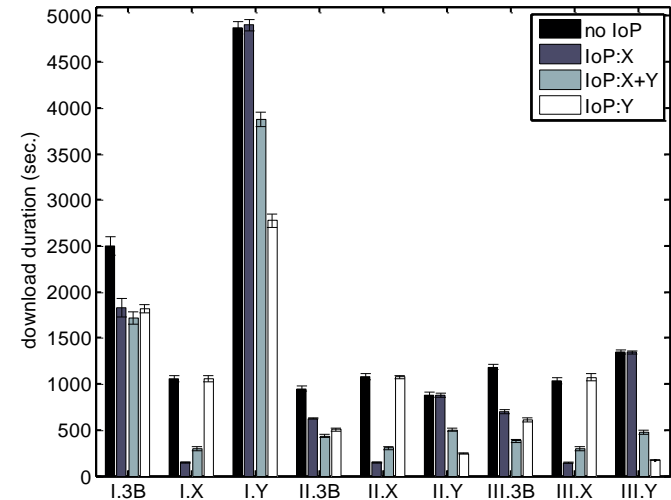
Scenario	I	II	III
<b>Default values</b>	mIAT: 60.0s mST: 600.0s	FS: 150 MB mST: 600.0s	FS: 150 MB mIAT:10.0s
<b>Modified values for swarm Y</b>	FS: 450 MB	mIAT: 20.0s	mST: 200.0s

# Evaluation in two-swarm environment

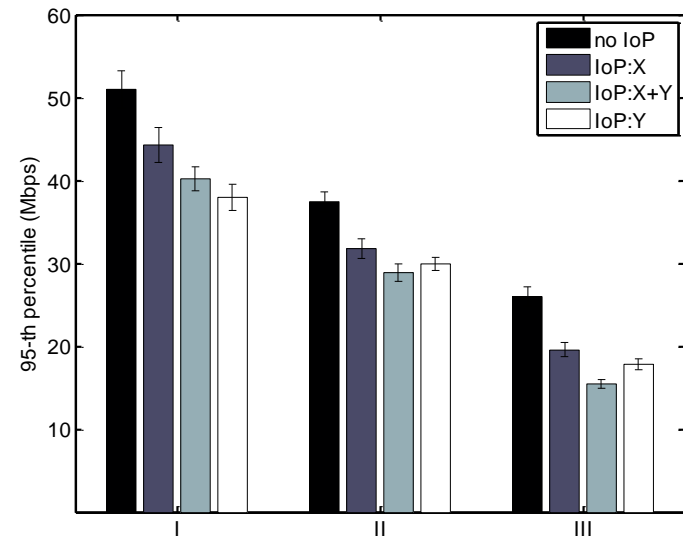
- If IoP joins both swarms (X+Y):
  - Higher incoming traffic reduction
  - Higher performance improvement
  
- Except the case of a large content file (scenario I)
  - Higher traffic reduction when IoP serves only swarm Y
  
- Pair-wise tuning of overlay parameters
  - Impact is higher for:

*Size of content file* >  
*number of leechers* >  
*number of seeders*

Average peers' download duration



95-th percentile of traffic on inter-domain links





# Peer-reviewed publications on the subject

## Journals

1. G. Dan, T. Hossfeld, S. Oechsner, P. Cholda, R. Stankiewicz, I. Papafili, G. D. Stamoulis, *Interaction patterns between P2P content distribution systems and ISPs*, IEEE Communications Magazine, Vol. 49, Is. 5, pp. 222-230, May 2011

## Conferences / Workshops

2. I. Papafili, S. Soursos, G. D. Stamoulis, *A Novel Game-Theoretic Framework for Modeling Interactions of ISPs Anticipating Users' Reactions*, in Proc. of the 6<sup>th</sup> International Conference on Performance Evaluation Methodologies and Tools, VALUETOOLS'12, Cargese, France, October 2012.
3. I. Papafili, S. Soursos, G.D. Stamoulis, *A game-theoretic Framework for ISP Interactions in the Context of ETM*, EuroNF Workshop on Traffic and Congestion Control for the Future Internet (TCCFI), Volos, Greece, March 2011 (extended abstract).
4. I. Papafili, G.D. Stamoulis, F. Lehrieder, B. Kleine, S. Oechsner, *Cache Capacity Allocation to Overlay Swarms*, 5th International Workshop on Self-Organizing Systems (IWSOS'2011), Karlsruhe, Germany, February 23<sup>th</sup>-25<sup>th</sup>, 2011.
5. I. Papafili, G. D. Stamoulis, *A Markov Model for the Evaluation of Cache Insertion on Peer-to-Peer Performance*, EuroNF NGI Conference, Paris, France, June 2<sup>nd</sup>-4<sup>th</sup>, 2010.
6. I. Papafili, S. Soursos, G. D. Stamoulis, *Improvement of BitTorrent Performance and Inter-Domain Traffic by Inserting ISP-owned Peers*, 6th International Workshop on Internet Charging and QoS Technologies (ICQT'09), Aachen, Germany, May 2009.

# Peer-reviewed publications in general

## Book chapters / Journals

7. D. Papadimitriou, T. Zahariadis, P. Martinez-Julia, I. Papafili, V. Morreale, F. Torelli, B. Sales, P. Demeester, *Design Principles for the Future Internet Architecture* in FIABook Future Internet – From Technological Promises to Reality, Editor(s): F. Alvarez, et al., IOS Press Books Online, May 2012
8. A. Kostopoulos, I. Papafili, C. Kalogiros, T. Leva, N. Zhang, D. Trossen, *A Tussle Analysis for Information-centric Networking architectures* in FIABook Future Internet – From Technological Promises to Reality, Editor(s): F. Alvarez, et al., IOS Press Books Online, May 2012
9. Ioanna Papafili, George Stamoulis, Rafal Stankiewicz, Simon Oechsner, Konstantin Pussep, Robert Wojcik, Jerzy Domzal, Dirk Staehle, Frank Lehrieder, Burkhard Stiller, *Assessment of Economic Management of Overlay Traffic: Methodology & Results* in FIABook The Future Internet: Achievements and Technological Promises, ISBN 978-3-642-20897-3. Editor(s): J. Domingue, et al., IOS Press Books Online, May 2011
10. T. Hoßfeld, D. Hausheer, F. Hecht, F. Lehrieder, S. Oechsner, I. Papafili, P. Racz, S. Soursos, D. Staehle, G. D. Stamoulis, P. Tran-Gia, B. Stiller, *An Economic Traffic Management Approach to Enable the TripleWin for Users, ISPs, and Overlay Providers* in FIABook Towards the Future Internet - A European Research Perspective, ISBN 978-1-60750-007-0. Editor(s): G. Tselentis, et al., pp.:24, IOS Press Books Online, May 2009

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11. I. Papafili, J. Rueckert, P. Poullie, S. Soursos, T. Bocek, K. Wajda, D. Hausheer, G. D. Stamoulis, B. Stiller, *SmartenIT Cloud Traffic Management: Approach and Architectural Considerations*, Future Network and Mobile Summit 2013, FuNeMS 2013, Lisbon, Portugal, July 2013.
12. M.Á.C. Rodríguez, J.A.S. García, A.M. Martín-Carnerero, P. Racz, F. Hecht, S. Spirou, I. Papafili, G.D. Stamoulis, W. Kellerer, K. Wajda, *NGN Usage in Future Internet Scenarios*, MobileSummit 2010, Florence, Italy, June 16<sup>th</sup>-18<sup>th</sup>, 2010.
13. P. Racz, F. Hecht, Hasan, B. Stiller, S. Soursos, G. D. Stamoulis, I. Papafili, M. A. Callejo Rodriguez, S. Spirou, *Economic Traffic Management for Overlay Networks*, CT-MobileSummit 2009, Conference, Santander, Spain, June 10<sup>th</sup>-12<sup>th</sup>, 2009.
14. S. Oechsner, S. Soursos, I. Papafili, T. Hossfeld, G. D. Stamoulis, B. Stiller, M. A. Callejo, D. Staehle, *A Framework of Economic Traffic Management Employing Self-Organization Overlay Mechanisms*, 3rd International Workshop On Self-Organizing Systems, (IWSOS'08), Vienna, Austria, December 2008.