What If Some Peers Are More Equal than Others?

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Peer-to-Peer Technology

• Well-known p2p systems
  - Internet telephony: Skype
  - File sharing: BitTorrent, eMule, ...
  - Streaming: Zattoo, Joost, ...

• Other (well-known?) systems
  - Pulsar streaming system (e.g., tilllate clips?)
  - Wuala online storage system

• Impact: Accounts for much Internet traffic!
  (source: cachelogic.com)
The Paradigm

- **Key concepts**
  - Machines (peers) in the network: consumer and producer of resources
  - Use of decentralized resources on the edge of the Internet (e.g., desktops)

- **Benefits**
  - **Scalability**: More resources in larger networks („cake grows“)
  - **Robustness**: No single point of failure
  - Can outperform server-based solutions
  - **Cheap**: start-up vs Google

- **Therefore:**
  - No need for expensive infrastructure at content distributors
  - **Democratic aspect**: Anyone can publish media contents / speeches
A Challenge

• In practice, peer-to-peer is not synonym for „from equal to equal“
  - Rather some peers may be „more equal than others“!

• E.g.
  - Some peers want to be consumers only (but not producers) of resources
  - Some peers may be malicious
  - Some peers may be social
  - Different capabilities (e.g., better Internet connection)

• These differences must not be ignored
  - E.g., punish selfish behavior
  - E.g., ensure efficiency despite heterogeneity
State of the Art

- Peer-to-peer systems: no effective solutions for many inequality problems today

- Example 1: BitThief client downloads entire files from BitTorrent without uploading

- Example 2: Censorship attacks in the Kad network (malicious peer)
  - Peer assumes corresponding IDs

- Example 3: Solutions for heterogeneity challenge often simplistic
  - Cheated incentive mechanism: Kazaa Lite client hardwires user contribution to maximum
  - Limited heterogeneity: two peer type approach of Gnutella or Kazaa
Talk Outline

- Case Study 1: Non-Cooperation in BitTorrent Swarms (*HotNets 2006*)
- Case Study 2: Malicious Peers in the Kad Network (*under submission*)
- Analysis of Social Behavior in Peer-to-Peer Systems (*EC 2008*)
- SHELL: A Heterogeneous Overlay Architecture (*ongoing work*)
- Conclusion and Research Problems
Case Study BitThief: Free-riding Peers in BitTorrent
BitThief: BitTorrent

• BitTorrent = one of the most popular p2p systems
  - Millions of simultaneous users

• One of the few systems incorporating incentive mechanism

• Basic principle
  - Peers interested in same file are organized by a tracker in a swarm
  - File is divided into pieces (or „blocks“)
  - Distinguish between seeders (entire file) and leechers (not all pieces)
  - Peers have different pieces which are exchanged in a tit-for-tat like manner
  - Bootstrap problem: peers optimistically unchoke neighbors (round-robin = give some pieces „for free“)
BitThief: BitTorrent Swarms

Website with .torrent file
- tracker address
- verification data
- ....

Tracker

Seeder

Leecher

Leecher

Leecher

Leecher

Leecher

tit-for-tat
unchoking
seeding
BitThief: Goal

BitThief = proof of concept Java client (implemented from scratch) which achieves fast downloads without uploading at all – in spite of BitTorrent's incentive mechanism!
BitThief: Tricks

BitThief’s three tricks:
- Open as many TCP connections as possible
- Contacting tracker again and again, asking for more peers (never banned!)
- Pretend being a great uploader in sharing communities

=> Exploit optimistic unchoking
=> Exploit seeders
=> Exploit sharing communities
BitThief: Connect to More Neighbors…
BitThief: Results (with Seeders)

2. Compared to official client (with unlimited number of allowed connections).

3. • All downloads finished!
   • Fast for small files (fast startup), many peers and many seeders!

4. BitThief with public IP and open TCP port.

<table>
<thead>
<tr>
<th>Size</th>
<th>Number of Peers Announced by Tracker</th>
<th>Max Peers Found by BitThief</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 170MB</td>
<td>10518 (303)</td>
<td>7301 (98)</td>
</tr>
<tr>
<td>B 175MB</td>
<td>923 (96)</td>
<td>257 (65)</td>
</tr>
<tr>
<td>C 175MB</td>
<td>709 (234)</td>
<td>283 (42)</td>
</tr>
<tr>
<td>D 349MB</td>
<td>465 (156)</td>
<td>189 (137)</td>
</tr>
<tr>
<td>E 551MB</td>
<td>880 (121)</td>
<td>884 (353)</td>
</tr>
<tr>
<td>F 31MB</td>
<td>N/A (29)</td>
<td>N/A (152)</td>
</tr>
<tr>
<td>G 798MB</td>
<td>195 (145)</td>
<td>432 (311)</td>
</tr>
</tbody>
</table>
BitThief: Results (without Seeders)

- Seeders detected with bitmask / have-message
- Even **without seeder** it’s fast!
- Unfair test: **Mainline client** was allowed to use seeders!
BitThief: Sharing Communities (1)

• **Closed / private swarm**
  - Tracker requires user registration
  - Monitors contributions, bans peers with low sharing ratios

• **Client can report uploaded data itself! (tracker announcements)**
  - As tracker does not verify, it’s **easy to remain** in community...
  - ... and communities are often a **paradise** for BitThief.

![Graph showing download rate over time](image)

4 x faster!
(BitThief had a faked sharing ratio of 1.4; in both networks, BitThief connected to roughly 300 peers)
BitThief: Sharing Communities (2)

• In communities, contribution is more balanced

• Reason?
  - Peers want to boost ratio?
  - Users more tech-savvy? (less firewalled peers? faster network connections?)
Case Study Kad: Censorship in Kad

Under submission / PhD thesis
Kad: The Kad Network

- **Kad** = one of the first widely used distributed hash tables (DHT)
  - A **structured** peer-to-peer system where the index is stored distributedly
  - In literature, DHTs have been studied for years (Chord, Pastry, etc.)

- **Basic principle**
  - Consistent hashing
  - Peers and data items with identifiers chosen from [0, 1)
  - (Pointers to) data items stored on closest peers
Lookup only with **first keyword** in list. Key is **hash function** on this keyword, will be routed to peer with Kad ID closest to this hash value. This peer is **responsible** for files stored with this first keyword.
Kad: Keyword Request

Peer responsible for this keyword returns different sources (hash keys) together with keywords.
Kad: Source Request

Peer can use this hash to find peer responsible for the file.
Kad: Source Request

Peer provides requester with a list of peers storing a copy of the file.
Eventually, the requester can download the data from these peers.
Kad: Censorship

- Kad network has several **vulnerabilities**

- Example: **malicious peers** can perform censorship attack
  - Simply by assuming the corresponding IDs (**peer insertion attack**)
  - No prescribed ID selection method or verification
Kad: Censorship

- Censoring contents in Kad

If peer is inserted here, it can block (or spy on) keyword requests for „Simpsons“, „Simpsons Movie“, etc.
Kad: Censorship

• Censoring contents in Kad
Kad: Censorship

- Some results

- Similarly for source requests
- There are also other censorship attacks (e.g., pollute cache of other peers)
- Plus eclipse and denial of service attacks (e.g., pollute cache such that requests are forwarded to external peers)...
Easy to Fix?
BitThief and Kad Attacks

• BitThief
  - Optimistic unchoking can be exploited
  - Just do pure tit-for-tat? Bootstrap problem...  
  - Fast extension: subset of pieces only (limited „venture capital“)
  - What if participants are not directly interested in each other?

• Kad Attacks
  - Do not accept too much information from same peer (e.g., publish attack)
  - Bind ID to peer... But how?
  - Bind to IP? But what about NATs where many peers have same ID? And what about dynamic IP addresses? Lose credits?
  - Generate ID, e.g., by hashing a user phrase? But due to sparsely populated ID space, it’s still easy to generate IDs close to the object...
What is the Impact?
(Extended) Game Theory...
Modelling Peers (1)

- Game theory is formalism to study uncooperative behavior
  - mainly selfish individuals (e.g., Price of Anarchy)

- Model for peer-to-peer network?
Modelling Peers (2)

- Game theory models participants as selfish players
  - Seek to maximize their utility
Modelling Peers (3)

- We extended this model and introduced malicious players
  - seek to minimize social welfare

Hackers, Polluters,
Viruses, DOS attacks

Network
Impact of Selfish Players

- Study of strategic behavior in unstructured peer-to-peer topologies

- Some results of network creation game (PODC 2006)
  - Price of Anarchy can be large
  - Nash equilibria may not exist (instability!)
  - NP-hard to decide whether a given network will stabilize
Impact of Malicious Players

• What is impact of malicious players in selfish networks?

• Depends on
  - Knowledge of selfish players on malicious players
  - How selfish players react to this knowledge (neutral, risk-averse, etc.)

• Some results (PODC 2006) for a virus inoculation game
  - If selfish players are oblivious, malicious players reduce social welfare
  - If players non-oblivious and risk-averse, social welfare may improve!
  - Phenomenon called fear factor or windfall of malice
Impact of Social Players?

- In the following, we want to study social peers
- Motivation: Social networks
  - E.g., Skype contact lists

What is the effect of social behavior on the spread of a virus in social networks such as Skype?
A Sample Game

• Sample game: **virus inoculation**

• The game
  - Network of n peers (or **players**)
  - Decide whether to inoculate or not
  - **Inoculation** costs C
  - If a peer is **infected**, it will cost L>C

• At runtime: virus breaks out at a **random** player, and **(recursively) infects** all insecure adjacent players
Modelling Peers...

- Peers are **selfish**, maximize utility

- However, utility takes into account friends’ utility
  - „local game theory“

- **Utility / cost function** of a player
  - Actual individual cost:
    \[ c_a(i, a) = a_i \cdot C + (1 - a_i) L \cdot \frac{k_i}{n} \]
    
    \( a_i = \text{inoculated?} \)
    \( k_i = \text{attack component size} \)
  
  - Perceived individual cost:
    \[ c_p(i, a) = c_a(i, a) + F \cdot \sum_{p_j \in \Gamma(p_i)} c_a(j, a) \]
    
    \( F = \text{friendship factor, extent to which players care about friends} \)
Social Costs and Equilibria

• In order to **quantify** effects of social behavior...

• **Social costs**
  - Sum over all players’ **actual costs**

• **Nash equilibria**
  - Strategy profile where each player **cannot improve** her welfare...
  - ... given the strategies of the other players
  - **Nash equilibrium (NE):** scenario where all players are selfish
  - **Friendship Nash equilibrium (FNE):** social scenario
  - FNE defined with respect to **perceived costs**!
  - Typical assumption: selfish players end up in such an equilibrium (if it exists)
Evaluation

• What is the impact of social behavior?

• Windfall of friendship
  - Compare (social cost of) worst NE where every player is selfish (perceived costs = actual costs)...
  - ... to worst FNE where players take friends‘ actual costs into account with a factor F (players are „social“)
Windfall of Friendship

- Formally, the windfall of friendship (WoF) is defined as

\[ \gamma(F, I) = \frac{\max_{NE} C_{NE}(I)}{\max_{F,NE} C_{F,NE}(F, I)} \]

- \( WoF \gg 1 \) => system benefits from social aspect
  - Social welfare increased

- \( WoF < 1 \) => social aspect harmful
  - Social welfare reduced

instance I describes graph, C and L
Characterization of NE

• In regular (and pure) NE, it holds that...

• **Insecure player** is in attack component $A$ of size at most $Cn/L$
  - otherwise, infection cost
    $> (Cn/L)/n * L = C$

• **Secure player**: if she became insecure, she would be in attack component of size at least $Cn/L$
  - same argument: otherwise it’s worthwhile to change strategies
Characterization of Friendship Nash Equilibria

• In friendship Nash equilibria, the situation is more complex

• E.g., problem is asymmetric
  - One insecure player in attack component may be happy...
  - ... while other player in same component is not
  - Reason: second player may have more insecure neighbors

```plaintext
not happy, two insecure neighbors (with same actual costs)

happy, only one insecure neighbor (with same actual costs)
```
Bounds for the Windfall

Theorem 4.2. For all instances of the virus inoculation game and $0 \leq F \leq 1$, it holds that

$$1 \leq \gamma(F, I) \leq PoA(I).$$

- It is always beneficial when players are social!

- The windfall can never be larger than the price of anarchy
  - Price of anarchy = ratio of worst Nash equilibrium cost divided by social optimum cost

- Actually, there are problem instances (with large $F$) which indeed have a windfall of this magnitude ("tight bounds", e.g., star network)
Example for Star Graph

- In regular NE, there is always a (worst) equilibrium where center is insecure, i.e., we have \( \frac{n}{L} \) insecure nodes and \( n - \frac{n}{L} \) secure nodes (for \( C=1 \)):

\[
\text{Social cost} = \left( \frac{n}{L} \right) \frac{n}{n} \frac{n}{L} \frac{L}{} + \left( n - \frac{n}{L} \right) \sim n
\]

- In friendship Nash equilibrium, there are situations where center must inoculate, yielding optimal social costs of (for \( C=1 \)):

\[
\text{Social cost} = \text{"social optimum"} = 1 + \left( n - 1 \right) \frac{n}{n} \frac{L}{} \sim L
\]

WoF as large as maximal price of anarchy in arbitrary graphs (i.e., \( n \) for constant \( L \)).
A Proof Idea for Lower Bound

• $\text{WoF} \geq 1$ because...:

• Consider arbitrary FNE (for any $F$)

• From this FNE, we can construct (by a best response strategy) a regular NE with at least as large social costs
  - Component size can only increase: peers become insecure, but not secure
  - Due to symmetry, a player who joins the attack component (i.e., becomes insecure) will not trigger others to become secure
  - It is easy to see that this yields larger social costs

• In a sense, this result matches our intuitive expectations...
Monotonicity

But the windfall does not increase monotonously: WoF can decline when players care more about their friends!

- Example again in *simple star graph*...
Monotonicity: Counterexample

\[ n = 13 \]
\[ C = 1 \]
\[ L = 4 \]
\[ F = 0.9 \]

**total cost** = 12.23

(many inoculated players, attack component size two)
Monotonicity: Counterexample

\[ n = 13 \]
\[ C = 1 \]
\[ L = 4 \]
\[ F = 0.1 \]

Boundary players happy with larger component, center always inoculates, thus: only this FNE exists! total cost = 4.69
Further Results and Open Problem

• More results in paper…
  - e.g., better bounds for windfall on special graphs
  - e.g., NP hardness (best and worst FNE)

• Many exciting open problems!
  - Example 1: existence of equilibria and convergence time (asymmetry!)
  - Potential functions used for regular equilibria cannot be adopted directly...
  - Example 2: study of windfall on class of social networks
  - Example 3: multihop scenario (transitive friendship?)
  - Example 4: alternatives for worst case equilibria
  - Example 5: experimental verification in practice? Monotonicity in reality?
Other Forms of Inequality?
Heterogeneous Capabilities...
Heterogeneous Peers...

- Peer-to-peer machines have different
  - Internet connections
  - CPUs
  - Hard disks
  - Operating systems
  - ...

- But still, peers need to collaborate, in an efficient way

- Interesting problem
  - E.g., conflict with incentive compatibility
  - Should a (cooperative) weak peer be supported by stronger peers?
  - Threat: strategic behavior? Is peer weak or just selfish?
The Basic Problem

- Motivation: strong peers cannot make full use of the system if they can only interact indirectly via weak peers

- Idea: clustering of peers with roughly same capability! - in a heap-like manner

Warning: The following results are first ideas only!
The Distributed SHELL Heap

• What is a distributed heap?

• We assume that peers have a key / rank / order / id
  - for example: inverse of peer capability

• (Min-) heap property: peers only connect to peers of lower rank
  - for example: peers only connect to stronger peers
  - SHELL constructs a directed overlay
    (routing along these edges only)
The SHELL Topology (1)

- Continuous-discrete approach: de Bruijn network
- Problem: de Bruijn neighbor may have larger rank

- Solution
  - peer at position \( x \) connects to all lower-ranked peers in an interval around \( x/2 \) and \( (x+1)/2 \)
  - i.e., space divided into intervals
  - size of interval depends on number of low-rank peers there
  - larger degree, but still logarithmic diameter etc.
The SHELL Topology (2)

- Peer connects to all peers of lower order in
  - Level-i home interval (interval which includes position x of peer)
  - Adjacent level-i intervals to home
  - de Bruijn intervals: intervals which include position x/2 and (x+1)/2

- What is level i?
  - Level i chosen s.t. there are at least $c \log n_p$ lower order peers in interval
  - $n_p$ = total number of peers in system with lower order
  - $n_p$ can be estimated, in the following we assume it is given
Routing (1)

- Interesting **routing** properties on heap

- Routing paths: if peer \( p \) is weaker than peer \( p' \), a request sent from \( p \) to \( p' \) only traverses peers which are stronger than \( p \)
  - „augmenting paths“

- E.g., **live streaming**: quality of transmission depends on weaker of the two peers, but not on peers in-between

- General routing policy: route according to de Bruijn rules, and choose **highest-ranked** peer to forward message in interval
  - yields low congestion
Routing (2)

- **Congestion:** *each* peer makes a lookup of a *random* ID
  - Two phase routing: first forward along outgoing edges to a peer whose home interval includes ID, then make descent if necessary to higher-ranked peers

- **Proof idea** low congestion in first phase
  - Recall: among all lower-ranked peers, forward packet to highest-ranked peer
  - Thus, it can be shown that *w.h.p.*, reached peer whose interval includes ID is of *rank at least t/2* when starting from ranked t peer
  - I.e., packet does not travel to too low-ranked peers
  - Therefore, peer of order t only receives packets from peers of ranks t+1..2t!

![Diagram showing routing process](image-url)
Other Application: Robust Information System

- Approach also useful as robust distributed information system

- For instance, robustness to Sybil attacks

- Sybil attack: at time $t$, an arbitrary number of malicious peers join the system
  - E.g., try to overload system with bogus requests

- Idea: build same de Bruijn heap, but use different peer ranks
  - Instead of rank ~ peer capacity, we use rank ~ join time
  - Thus: peers only connect to older peers
  - i.e., we want to maintain join time order in our distributed system
Robustness to Sybil Attacks (1)

- Requests do not travel to younger peers
  - Path between old peers does not include any young / Sybil peers
  - Hence, older peers are immune against this Sybil attack!
  - Compare to heterogeneous SHELL system: paths without weak peers...

- Additional advantage: older peers have larger remaining session times
  - According to measurement studies
  - higher robustness to churn
Robustness to Sybil Attacks (2)

- Yields min heap

- In addition, in case of congestion, a rate control algorithm could be used towards „lower peers“ in order to prevent newly joined peers to overload the system
  - Traffic only from younger to older peers, i.e., upward the tree
Conclusion and Open Problems
Conclusion (1)

- Presence of unequal participants is interesting and important challenge in peer-to-peer computing
  - Unequal peers = peers which voluntarily or involuntarily do not contribute the same amount of resources as/to other peers
  - How to distinguish the two cases in a distributed environment?

- Reality check: are people selfish?
Conclusion (2)

- Solutions to this problem have **useful consequences**
  - Most importantly: **efficiency**
  - E.g., **side benefits**: heap structure can also be used to make information systems robust to Sybil attacks

- Many **open problems**...
Open Problems (1)

• **Incentive compatible** peer-to-peer computing?
  - Mechanism design...
  - E.g., how to prevent BitThief from free-riding in BitTorrent?
  - Tit-for-tat is good, but how to solve the **bootstrap problem** for newly joined peers?
  - E.g., fast extension: newly joined peers get a random **subset** of pieces for free (subset depends on peer ID) => venture capital
  - Unlike optimistic unchoking, BitThief could no longer download **entire files**...

• And what about **other systems** where peers are not directly interested in same file?
  - Difficulty depends on application, e.g., live streaming easier
Open Problems (2)

- **Robust** peer-to-peer computing?
  - How to prevent our attacks on Kad?
  - Idea: do not allow arbitrary IDs... E.g., ID may depend on **IP address** of peer!
  - But: What if many peers behind **NAT** share same IP?
  - And what about **dynamic** **IPs**? Kad ID should be stable (e.g., no loss of credits etc.)
  - Idea: **User generated phrase** which is hashed?
  - But: Attacks still possible, as generated Kad ID must only **approximately** match to be censored keyword (sparsely populated ID space)
  - General rule (e.g., against publish attack): do not accept too much information from same **IP address**...

- Why are these attacks not used today?
  - Measurement studies show that there are indeed large **ID clusters** (Sybil attack?)
Open Problems (3)

• Formal analysis with game theory?
  - Heterogeneous population (e.g., different BitTorrent clients)
  - Need to model different types of players
  - Effects of these players on social welfare?
  - How to exploit these phenomena?

• Insights can be relevant in other areas
  - e.g., how to foster cooperation / how to ensure high quality in Wikipedia?