Distributed Algorithms
Peer-to-Peer Systems

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Introduction

Definition

A peer-to-peer system is a collection of peer nodes, that act both as servers and as clients

- Provide resources to other peers
- Consume resources from other peers

Characteristics

- Put together resources at the edge of the Internet
- Share resources by direct exchange between nodes
- Perform critical functions in a decentralized manner

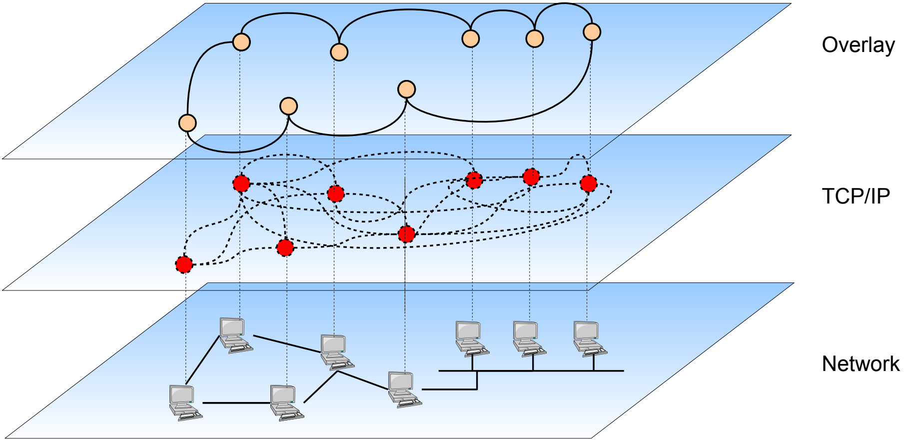
Motivation for P2P

- Cost-effective
  - Exploit the “dark matter” of the Internet constituted by “edge” resources
- No central point of failure
  - Control and resources are decentralized
- Scalability
  - Since every peer is alike, it is possible to add more peers to the system and scale to larger networks

It's a broad area. . .

- P2P file sharing
  - Gnutella
  - eMule
  - BitTorrent
- P2P communication
  - Instant messaging
  - Voice-over-IP: Skype
- P2P computation
  - Seti@home
- DHTs & their apps
  - Chord, CAN, Kademlia, . . .
- P2P wireless
  - Ad-hoc networking

Overlay networks



Overlay networks

Virtual edge

- TCP connection
- or simply a pointer to an IP address

Overlay maintenance

- Periodically ping to make sure neighbor is still alive
- Or verify liveness while messaging
- If neighbor goes down, may want to establish new edge
- New node needs to bootstrap

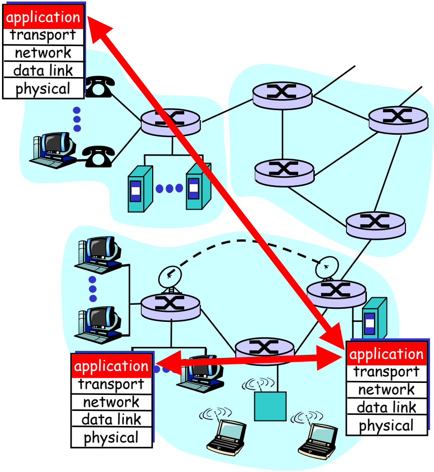
Overlay networks

Tremendous design flexibility

- Topology
- Message types
- Protocols
- Messaging over TCP or UDP

Underlying physical net is transparent to developer

- But some overlays exploit proximity



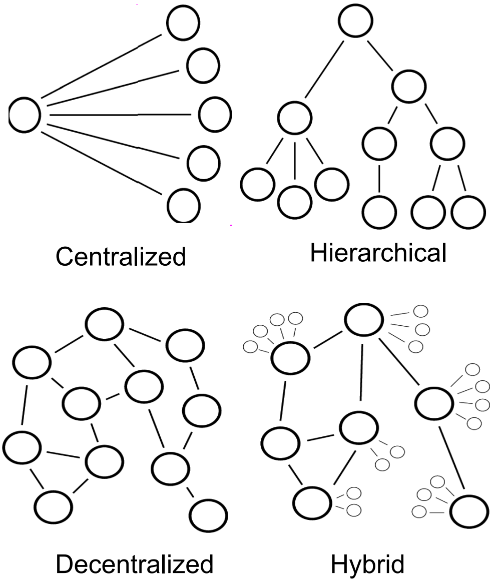
Overlay Topology

Unstructured:

- No explicit topology
- Observed rather than engineered
- Example: Gnutella, BitTorrent

Structured:

- An explicit "shape" is maintained
- Examples: Rings, Trees, DHTs
- Random topologies are "structured" as well



Criteria for topology selection

- Does it simplify location of data?
- Does it
  - balance the load, if nodes are equal?
  - exploit heterogeneity, otherwise?
- Is it robust?
  - Can it work if part of it is suddenly removed?
  - Can it be maintained in spite of churn?
- Has some correspondence with the underlying network topology?
  - Proximity (latency-based)
  - e.g., Pastry, Kazaa, Skype

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Distributed Hash Table (DHT)

A peer-to-peer algorithm that offers an associative Map interface:

- *put*(KEY k, VALUE v): associate a value v to the key k
- VALUE *get*(KEY k): returns the value associated to key k

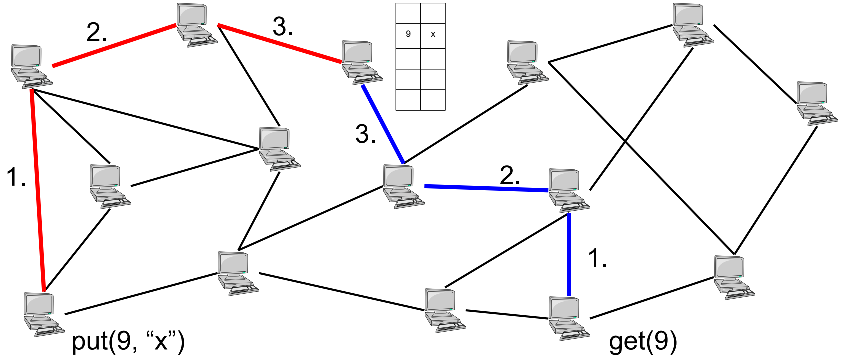
(Distributed) Hash Tables:

- Hash tables map keys to memory locations
- Distributed hash tables map keys to nodes

Organization:

- Each node is responsible for a portion of the key space
- Messages are routed between nodes to reach responsible nodes
- Replication used to tolerate failures

Routing in DHTs



DHT Implementations

- The founders (2001):
  - Chord
  - CAN
  - Pastry
  - Tapestry
- The ones which are actually used:
  - Kademlia and its derivatives (up to 4M nodes!)
    - BitTorrent
    - Kad (eMule)
    - The Storm Botnet
  - Cassandra DHT
    - Part of Apache Cassandra
    - Initially developed at Facebook
- The ones which are actually used, but we don't know much about:
  - Microsoft DHT based on Pastry
  - Amazon's Dynamo key-value store

Step 1: From Keys and Nodes to IDs

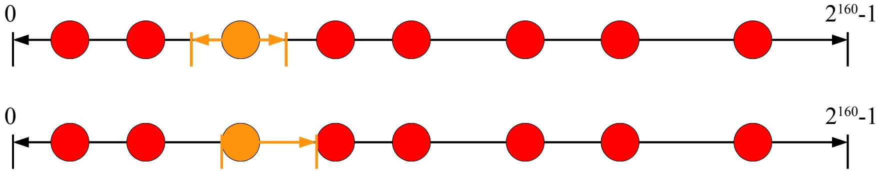
- Keys and nodes are represented by identifiers taken from an ID space
  - Key identifiers: computed through an hash function (e.g., SHA-1)
    - e.g., $ID(k) = SHA1(k)$
  - Node identifiers: randomly assigned or computed through an hash function
    - e.g., $ID(n) = SHA1(\text{IP address of } n)$

Why?

- Very low probability that two nodes have exactly the same ID
- Nodes and keys are mapped in the same space

Step 2: Partition the ID space

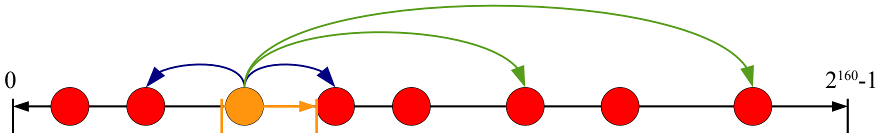
- Each node in the DHT stores some k, v pairs
- Partition the ID space in zones, depending on the node IDs:
- A pair (k, v) is stored at the node n such that (examples):
  - its identifier $ID(n)$ is the closest to $ID(k)$;
  - its identifier $ID(n)$ is the largest node id smaller than $ID(k)$



Step 2: Build overlay network

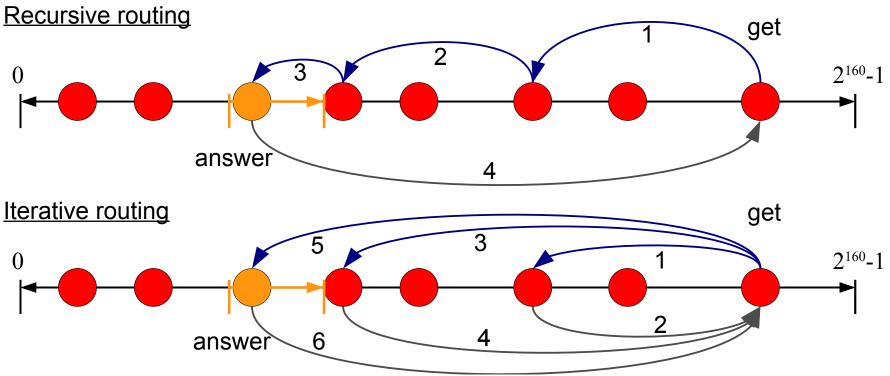
Each node has two sets of neighbors:

- Immediate neighbors in the key space (leafs)
  - Guarantee correctness, avoid partitions
  - If we had only them, linear routing time
- Long-range neighbors
  - Allow sub-linear routing
  - If we had only them, connectivity problems



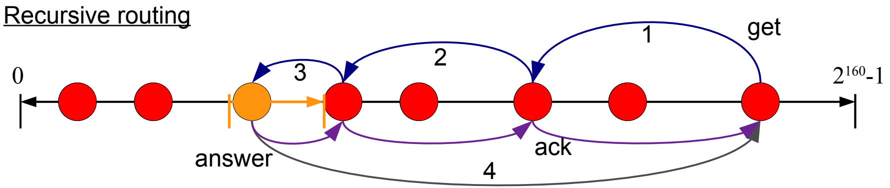
Step 3: Route puts/gets through the overlay

- Recursive routing: the initiator starts the process, contacted nodes forward the message
- Iterative routing: the initiator personally contact the nodes at each routing step



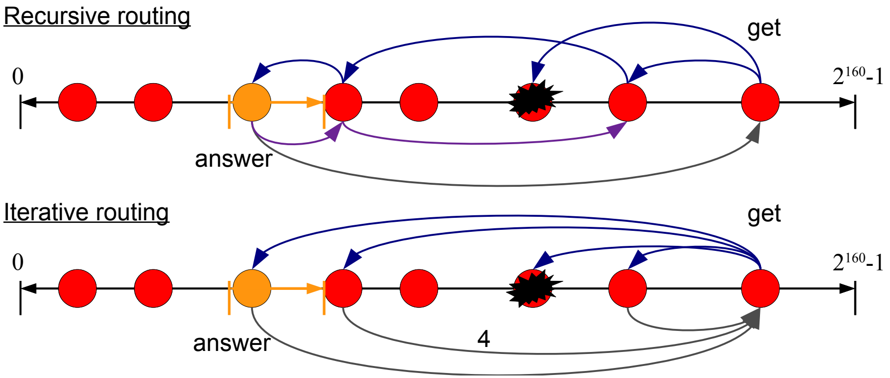
Routing around failures (1)

- Under churn, neighbors may have failed
- To detect failures, acknowledge each hop (recursive routing)



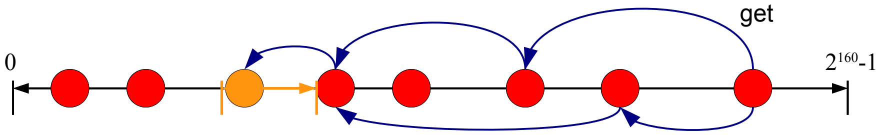
Routing around failures (2)

- If we don't receive ack or response, resend through a different neighbor



Routing around failures (3)

- Must compute timeouts carefully
  - If too long, increase put/get latency
  - If too short, get message explosion
- Parallel sending could be a design decision – see Kademlia

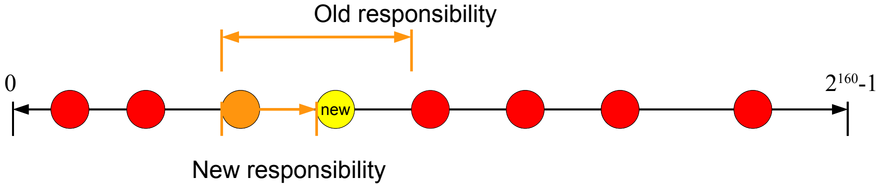


Computing good timeouts

- Use TCP-style timers
  - Keep past history of latencies
  - Use this to compute timeouts for new requests
- Works fine for recursive lookups
  - Only talk to neighbors, so history small, current
- In iterative lookups, source leads the entire lookup process
  - Must potentially have good timeout for any node

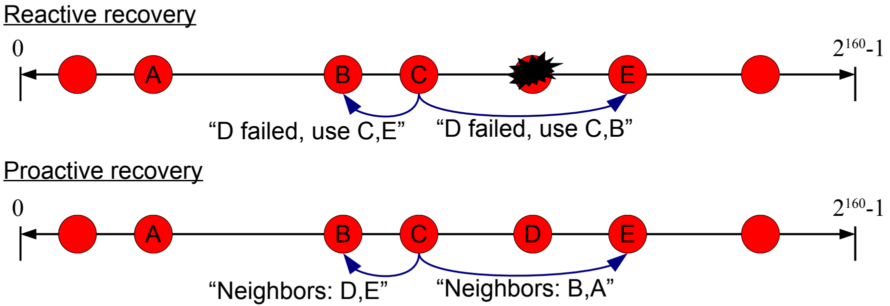
Recovering from failures

- Can't route around failures forever
  - Will eventually run out of neighbors
- Must also find new nodes as they join
  - Especially important if they're our immediate predecessors or successors



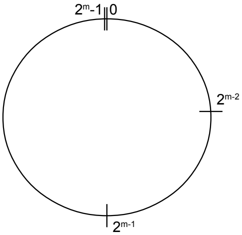
Recovery from failures

- Reactive recovery
  - When a node stops sending acknowledgments, notify other neighbors of potential replacements
- Proactive recovery
  - Periodically, each node sends its neighbor list to each of its neighbors



Chord

- ID space: uni-dimensional ring in $[0, 2^m - 1]$ $(m = 160)$
- Routing table size: $O(\log n)$
- Routing time: $O(\log n)$



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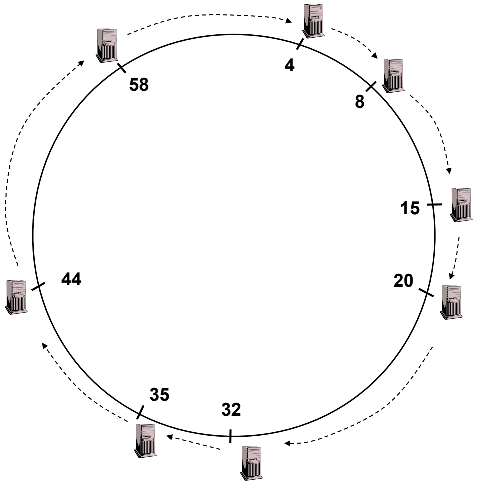
http://www.disi.unitn.it/~montreso/ds/papers/chord.pdf

Identifier mapping

Example:

- Node 8 maps $[5, 8]$
- Node 15 maps $[9, 15]$
- Node 20 maps $[16, 20]$
- ...
- Node 4 maps $[59, 4]$

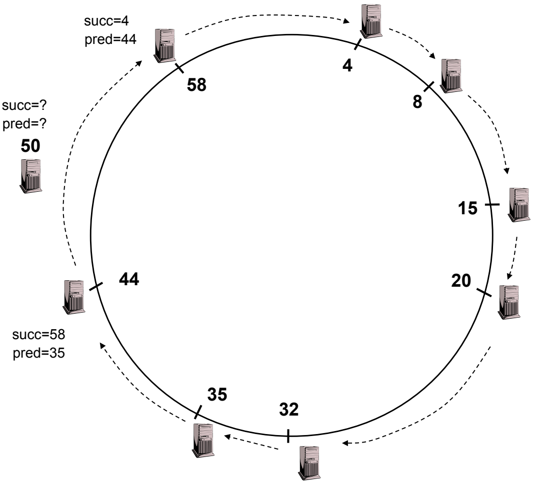
- Random ID assignment
- Each node maintains a pointer to its successor



Join procedure (1)

Example:

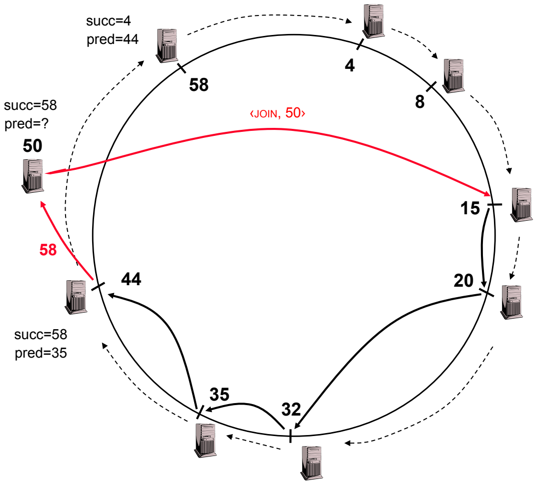
- Node with $id = 50$ joins the ring
- Node 50 needs to know at least one node already in the system
- Assume known node is 15



Join procedure (2)

Example:

- Node 50: send ⟨JOIN, 50⟩ to node 15
- Message is routed to node 44
- Node 44: returns node 58
- Node 50: updates its successor to 58



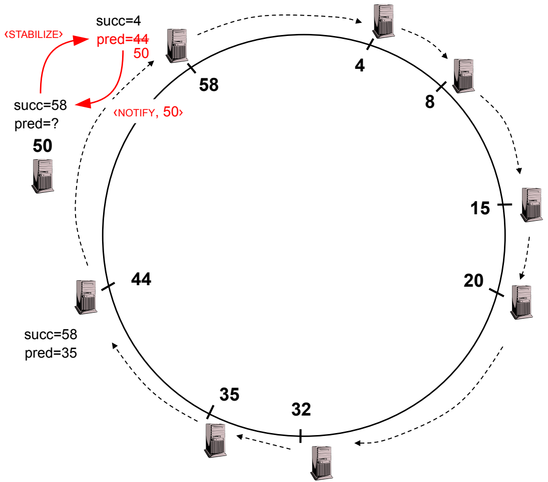
Stabilization

- Periodically, each node A:
  - sends a $\langle$STABILIZE$\rangle$ message to its successor B
- Upon receiving $\langle$STABILIZE$\rangle$ message from A, node B:
  - returns its predecessor $B' = \mathit{pred}(B)$ to A by sending a $\langle$NOTIFY$, B'\rangle$ message
  - updates its predecessor to A, if A is between B' and B
- Upon receiving $\langle$NOTIFY$, B'\rangle$ message from B, node A:
  - updates its successor to B', if B' is between A and B

Join procedure (4)

Example:

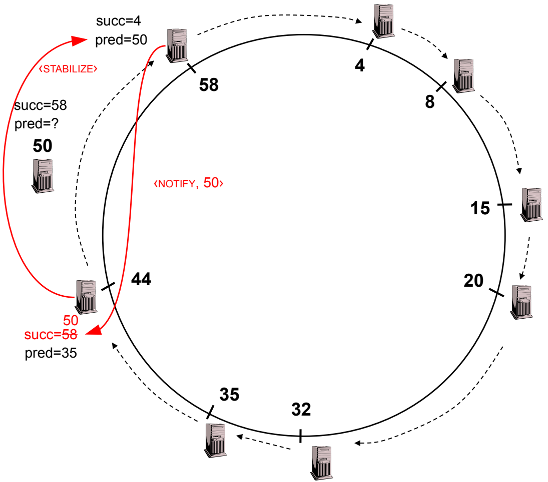
- Node 50: send ⟨STABILIZE⟩ to node 58
- Node 58: update predecessor to 50
- Node 58: send ⟨NOTIFY, 50⟩ back



Join procedure (5)

Example:

- Node 44: send ⟨STABILIZE⟩ to its successor node 58
- Node 58: replies with ⟨NOTIFY, 50⟩
- Node 44: updates it successor to 50

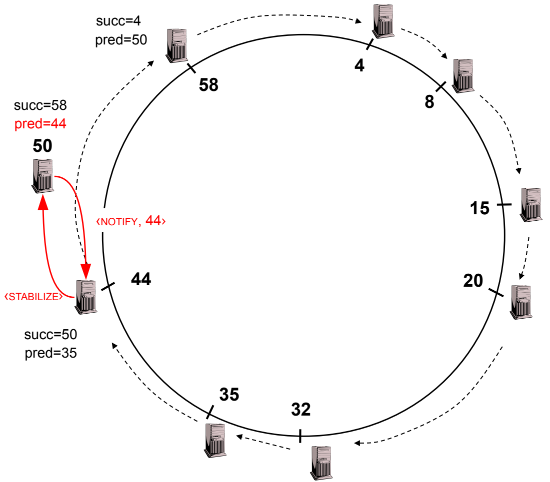


Join procedure (6)

Example:

- Node 44: send ⟨STABILIZE⟩ to its new successor, node 50
- Node 50: updates it predecessor to 44

This completes the joining operation!

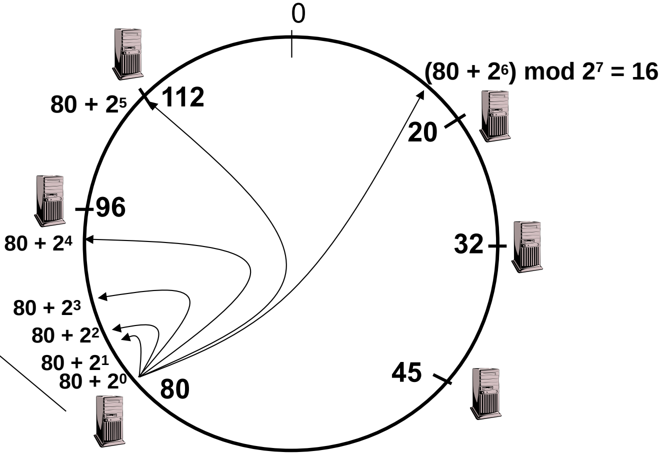


Achieving efficiency

- Chord requires each node to keep a finger table containing up to m entries
- The i-th entry $(0 \leq i \leq m-1)$ of node n will contain the address of the successor of $(n + 2^i) \bmod 2^m$
- Fingers are used in routing to reduce the number of hops to $O(\log N)$

Achieving efficiency

i	*ft[i]*
0	96
1	96
2	96
3	96
4	96
5	112
6	20



Achieving robustness

- To improve robustness, each node maintains $k > 1$ immediate successors instead of only one
- In the ⟨NOTIFY⟩ message, node A can send its $k - 1$ successors to its predecessor B
- Upon receiving the ⟨NOTIFY⟩ message, B can update its successor list by concatenating the successor list received from A with A itself

Optimizations

- Reduce latency
  - Choose finger that reduces expected time to reach destination
  - Choose the closest node from range $[n + 2^{i-1}, n + 2^i)$ as successor
- Accommodate heterogeneous systems
  - Multiple virtual nodes per physical node

CAN

- Associate to each node and item a unique ID in an d-dimensional Cartesian space on a d-torus
- Routing table size is constant: $O(d)$
- Guarantees that a key is found in at most $d \cdot n^{1/d}$ steps, where n is the total number of nodes

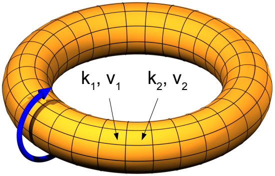


Figure: A 2-torus

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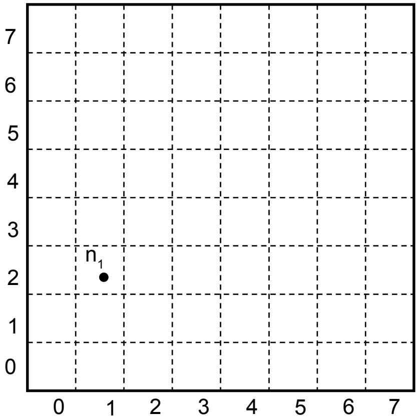
In *Proc. of SIGCOMM'01*, pages 161–172, San Diego, California, USA, 2001. ACM.
http://www.disi.unitn.it/~montreso/ds/papers/CAN.pdf

Example: 2-dimensional space

- Space divided between nodes
- All nodes cover the entire space
- Each node covers either a square or a rectangular area of ratios 1 : 2 or 2 : 1

Example:

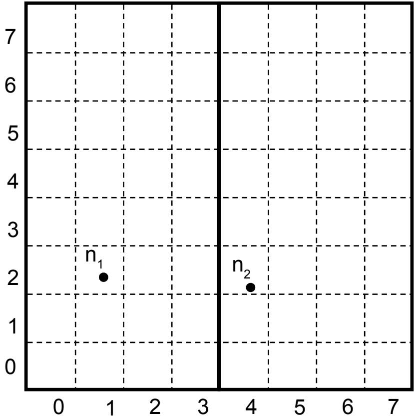
- Node $n_1 : (1, 2)$ – first node that joins – cover the entire space



Example: 2-dimensional space

Example:

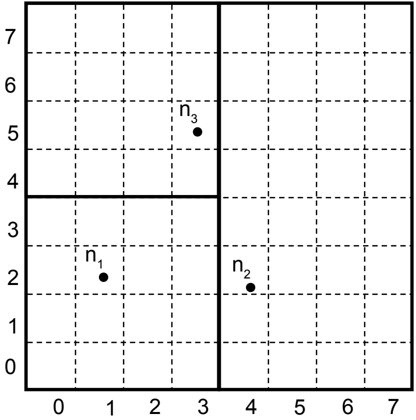
- Node $n_2 : (4, 2)$ joins: space is divided between n_1 and n_2



Example: 2-dimensional space

Example:

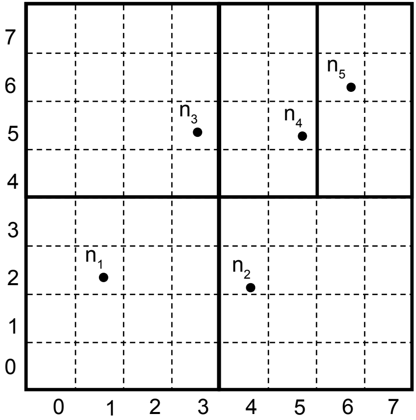
- Node $n_3 : (3, 5)$ joins



Example: 2-dimensional space

Example:

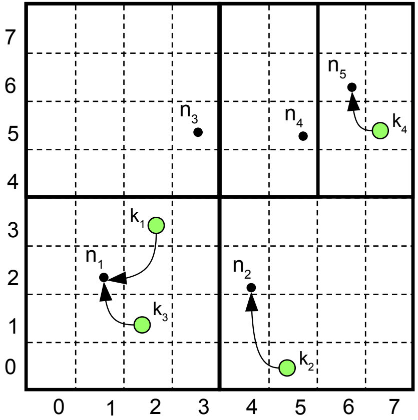
- Nodes $n_4 : (5, 5)$ and $n_5 : (6, 6)$ join



Example: 2-dimensional space

Example:

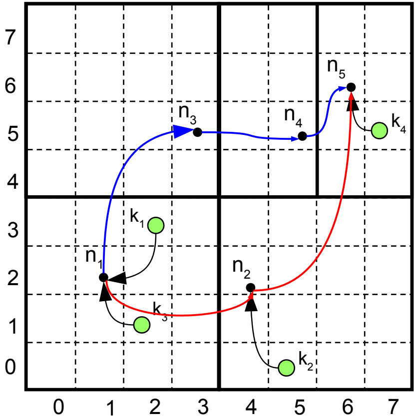
- Nodes: $n_1 : (1, 2)$, $n_2 : (4, 2)$, $n_3 : (3, 5)$, $n_4 : (5, 5)$, $n_5 : (6, 6)$
- Items: $k_1 : (2, 3)$, $k_2 : (5, 1)$, $k_3 : (2, 1)$, $k_4 : (7, 5)$
- Each item is stored by the node who owns its mapping in the space



Example: 2-dimensional space

Example:

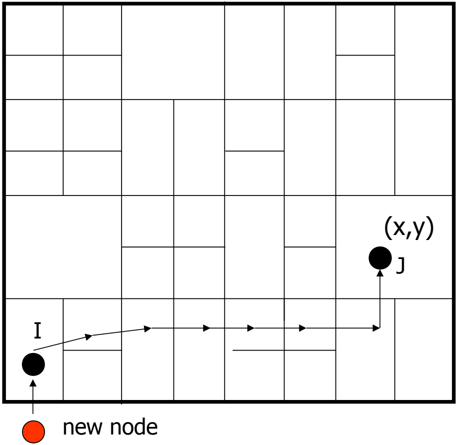
- Each node knows its neighbors in the d-space
- Forward query to the neighbor that is closest to the query id
- Example: assume n_1 queries k_4
- Can route around some failures



Example: 2-dimensional space

Node joining:

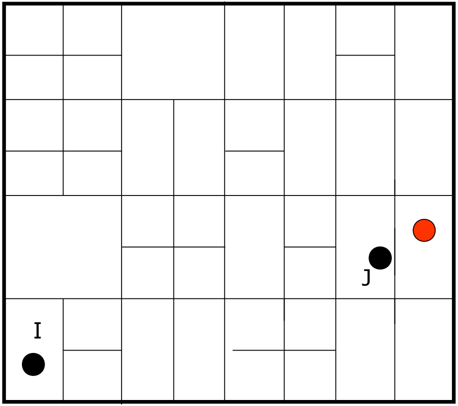
1. Discover some node I already in CAN
2. Pick random point (x, y) in space
3. I routes to (x, y), discovers node J



Example: 2-dimensional space

Node joining:

1. Split J zone in half
2. New node owns one half



Node departures

Take-over mechanism:

- Node explicitly hands over its zone and the associated (key,value) database to one of its neighbors
- A maximum of $2d$ nodes need to be contacted
- Problem: in case of network failure, no regeneration of data
- Solution: every node has a backup of its neighbors

Multi-verse?

Increasing availability:

- Each key is mapped into r different realities
- Each reality is associated with a different hash function
- A key is not available only when the r nodes hosting it in different realities are down at the same time

Kademlia

Key points

- Kademlia uses tree-based routing
- SHA-1 hash function in a 160-bit address space
- Every node maintains information about keys close to itself
  - Distance based on the XOR metric: $d(a,b) = a \oplus b$
- Uses parallel asynchronous queries to avoid timeout delays
- Routes are selected based on latency

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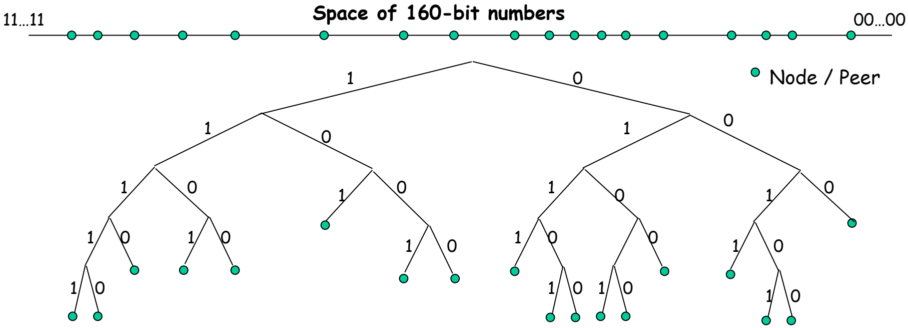
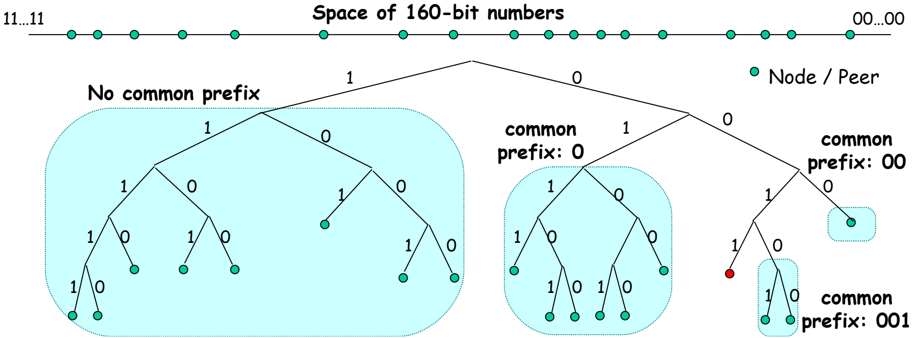
In *Proc. of the* 1^{st} *International Workshop on Peer-to-Peer Systems (IPTPS'02)*, pages 258–263. Springer, 2002.
http://www.disi.unitn.it/~montreso/ds/papers/kademlia.pdf

Kademlia Tree



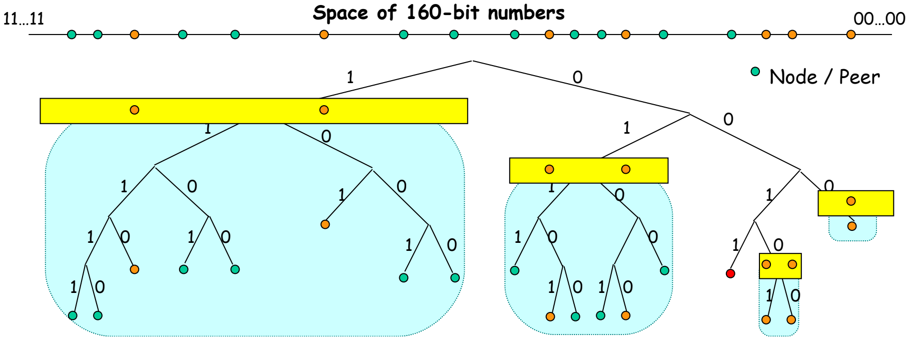
- Nodes are treated as leafs in binary tree
- Node's position in the tree is determined by the shortest unique prefix of its ID
- A node is responsible for all "closest" IDs (those having same prefix as itself)

Kademlia Tree



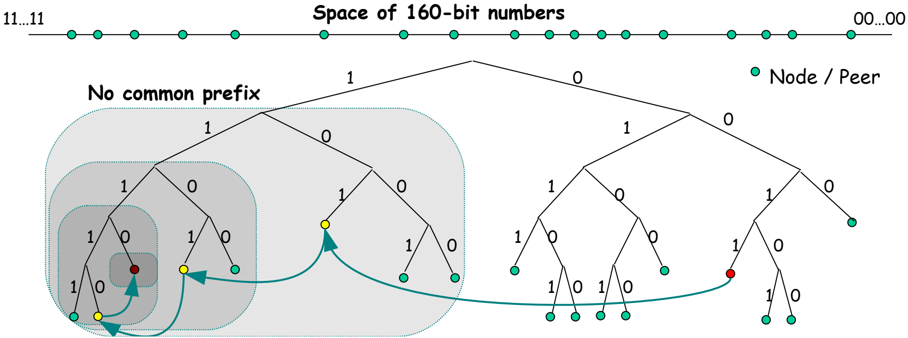
- From the point of view of each node, the tree is divided into a series of maximal subtrees that do not contain the node
- Example: the red node with prefix `0011`
- A node must know at least one node in each of these subtrees

Routing table



- Consider routing table for a node with prefix `0011`
- The routing table is composed of a series of *k*-buckets corresponding to each of the subtrees
- Consider a 2-bucket example, each bucket will have at least 2 contacts for each subtree

Kademlia Tree



- Consider a query for ID 111010… initiated by node 0011100…

Messages

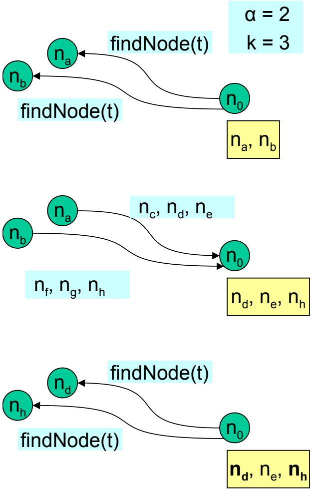
Kademlia protocol consists of 4 RPCs:

- $ping_{n \to m}()$
  - Probe node m to see if it is online
- $store_{n \to m}(k, v)$
  - Instruct node m to store a $\langle k, m \rangle$ pair
- $findNode_{n \to m}(t)$
  - Returns the k contacts "closest" to t
- $findValue_{n \to m}(k)$
  - Returns the value associated to k, if present, or
  - Returns k contacts closest to k

Routing

Goal: find k nodes closest to ID t – Protocol executed by n_0

- Initial phase :
  - insert in a set S all the nodes in the routing table
- Iteration
  - select a subset $T \subseteq S$ of the α nodes closest to t
  - invoke *findNode*(t) on nodes in T, in parallel
  - collect the replies in a new set S
  - repeat until no new node is discovered
- Final phase
  - invoke *findNode*(t) to all of k closest nodes not already queried
  - return when have results from all the k-closest nodes



Kademlia summary

Strengths:

- Low control message overhead
- Tolerance to node failure and leave
- Capable of selecting low-latency path for query routing
- Unlike Chord, Kademlia is symmetric: $a \oplus b = b \oplus a$
  - Peers receive lookup queries from precisely the same set of neighbors contained in their routing tables

Weaknesses:

- Balancing of storage load is not truly solved
- No experimental results provided

Cassandra

Few information available:

- $O(1)$ routing hops
- $O(N)$ routing state
  - Thanks to a routing protocol that guarantees that eventually every node knows every other node

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http://www.disi.unitn.it/~montreso/ds/papers/Cassandra.pdf

Security aspects of DHTs

Security weaknesses specific to DHTs

- Sybil attacks
  - an attacker introduces a large number of bogus nodes that can subvert protocols based on redundancy
- Eclipse attacks
  - an attacker tries to corrupt the routing tables of honest nodes by filling them with references to malicious nodes
- Routing and storage attacks
  - various attacks where malicious nodes do not follow the routing and storage protocols correctly

Bibliography

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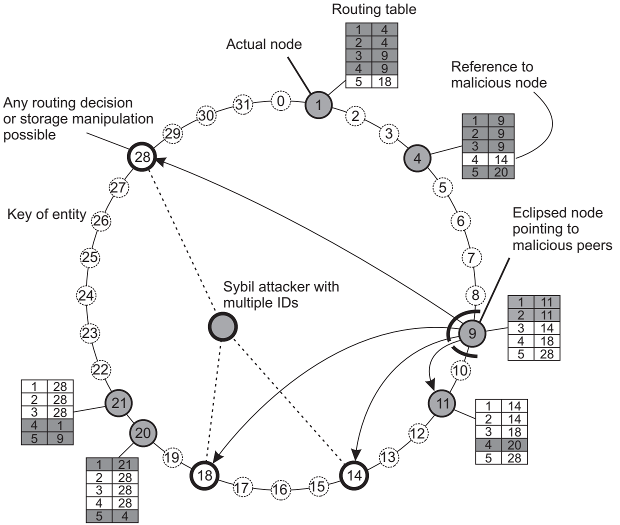
http://www.disi.unitn.it/~montreso/ds/papers/DhtSecuritySurvey.pdf

Example of attacks



Defenses against Sybil attacks

- Collusion is easier
- Possible defenses:
  - Centralized certification
  - Distributed registration
  - Physical network characteristics
  - Social networks
  - Computational puzzles
- You can only reduce the impact of Sybil attacks, not eliminate them completely

Defenses against eclipse attacks

- Effect of eclipse attack ("table poisoning") is measured by:

$$\frac{\text{percentage of malicious entries in routing tables}}{\text{percentage of malicious users in the network}}$$

- Possible defenses:
  - Constrained neighbor selection
    - Original Chord: only one node may fit in a finger table entry – good
    - Random Chord: several nodes may fit in finger table entry – bad
    - Pastry: some table entries may be filled by any node sharing a short prefix – bad
    - Kademlia: table entries are filled by fast-responding peers – good
  - In-degree anonymous auditing
    - Malicious nodes have larger in-degree

Defenses against routing and storage attacks

- Redundant routing
  - Possible approaches:
    - Multiple paths
    - Wide paths
    - Multiple wide paths
  - Wide paths require one good node per hop, multiple paths require a path with only good nodes
- Redundant storage
  - Storing replicas "numerically close" to each other
    - Chord, Pastry, Kademlia
    - Pros: easier to maintain consistency
    - Cons: malicious node may control a region of space
  - Storing replicas spread over the identifier space
    - Tapestry, several other proposals
    - Pros: most difficult to subvert an area
    - Cons: requires additional tables

Why Kademlia?

Generic reasons

- Relative security: wide searches
- Replicated storage

The reality is that Kademlia is insecure

- Successful (academic) attacks on Kad/BitTorrent
- Successful infiltrations on the Storm BotNet

The real reasons

- For BitTorrent, damage is limited anyway (decentralized tracking)
- Many alternative ways to obtain peers (PEX, multiple trackers)

Comparison

	CAN	**Chord**	**Tapestry**	**Pastry**
Architecture	d-dimens. space	ring	Plaxton tree	Plaxton tree
Routing hops	$O(dN^{1/d})$	$O(\log N)$	$O(\log_b N)$	$O(\log_b N)$
Routing state	$2d$	$\log N$	$\log_b N$	$B \log_b N$
Join cost	$2d$	$(\log N)^2$	$\log_b N$	$\log_b N$

	Kademlia	**Viceroy**	**Koorde**	**Kelips**
Architecture	Tree	Butterfly network	de Brujin graph	n-dimens. space
Routing hops	$O(\log N)$	$O(\log n)$	$O\left(\frac{\log n}{\log \log n}\right)$	$O(1)$
Routing state	$k \log N$	$\log N$	$\log N$	$\sqrt{n}$
Join cost	$k \log N$	$\log N$	$\log N$	$\sqrt{n}$

Conclusions

- The DHT abstraction is doing well, both inside clouds and in P2P networks
- Kademlia seems to be the winner. Main reasons:
  - Performance
  - Relative security

Table of contents

Gnutella: brief history

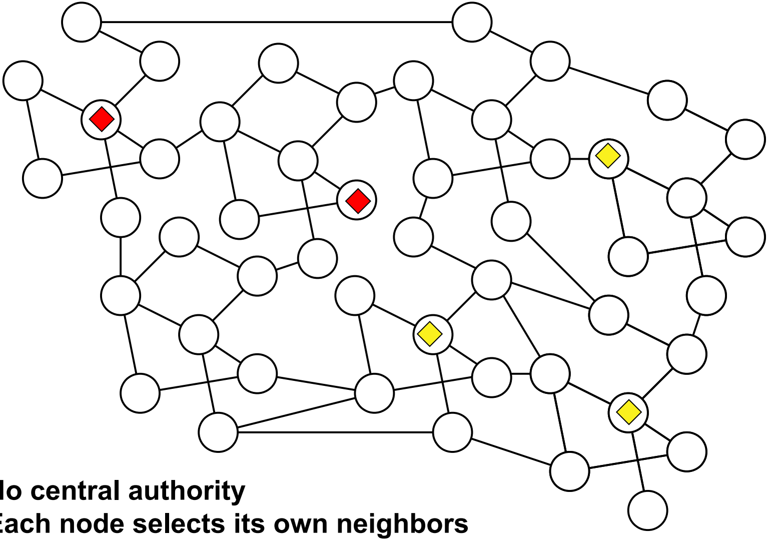
- Nullsoft (a subsidiary of AOL) released Gnutella on March 14th, 2000, announcing it on Slashdot
- AOL removed Gnutella from Nullsoft servers on March 15th, 2000
- After a few days, the Gnutella protocol was reverse-engineered
- Napster was shutdown in early 2001, spurring the popularity of Gnutella
- On October 2010, LimeWire (a popular client) was shutdown by court's order

Gnutella

Gnutella is a protocol for peer-to-peer search, consisting of:

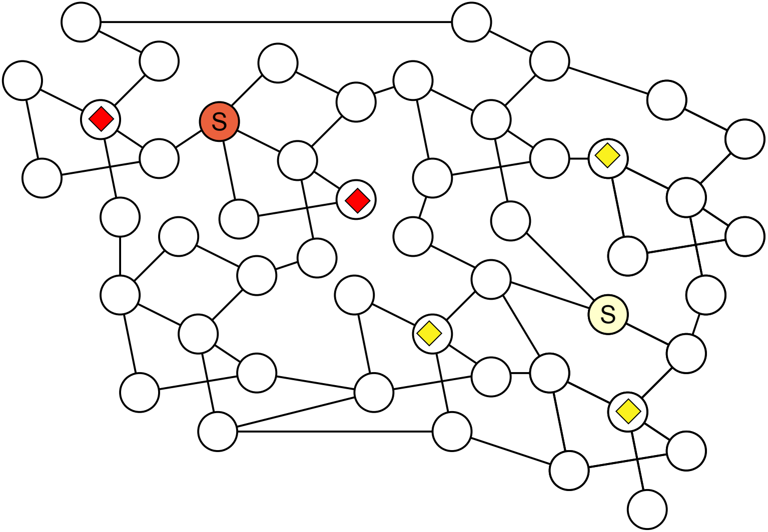
- A set of message formats
  - 5 basic message types
- A set of rules governing the exchange of messages
  - Broadcast
  - Back-propagate
  - Handshaking
- An hostcache for node bootstrap

Gnutella topology: unstructured

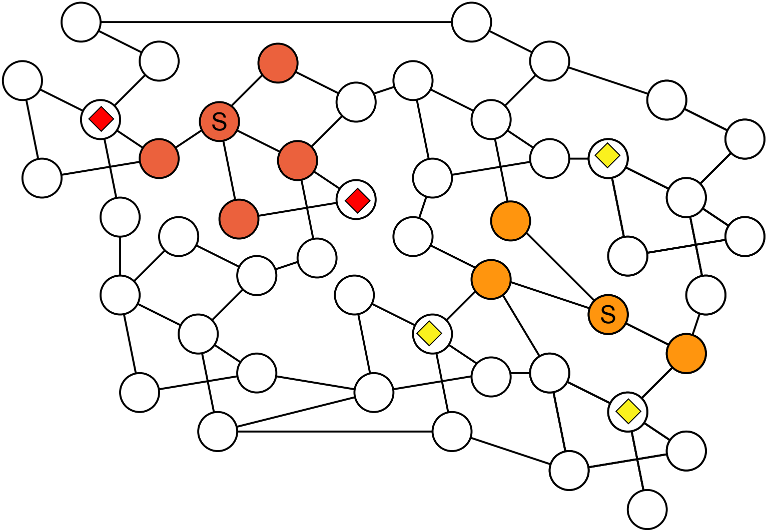


No central authority
Each node selects its own neighbors

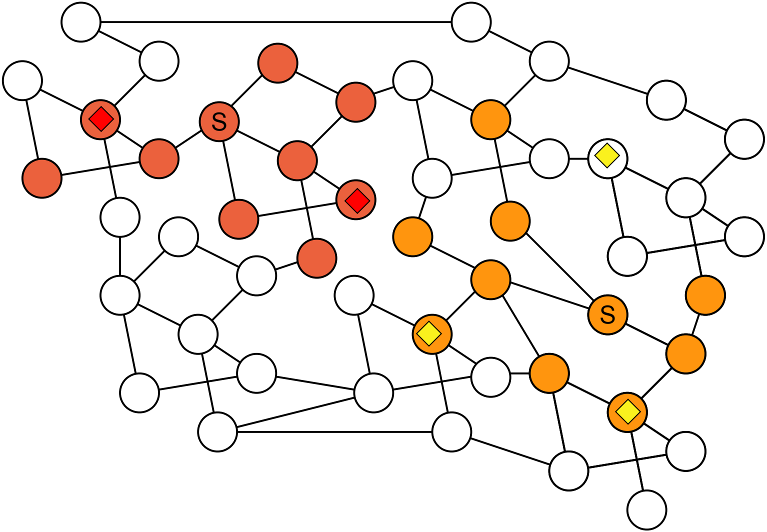
Gnutella routing



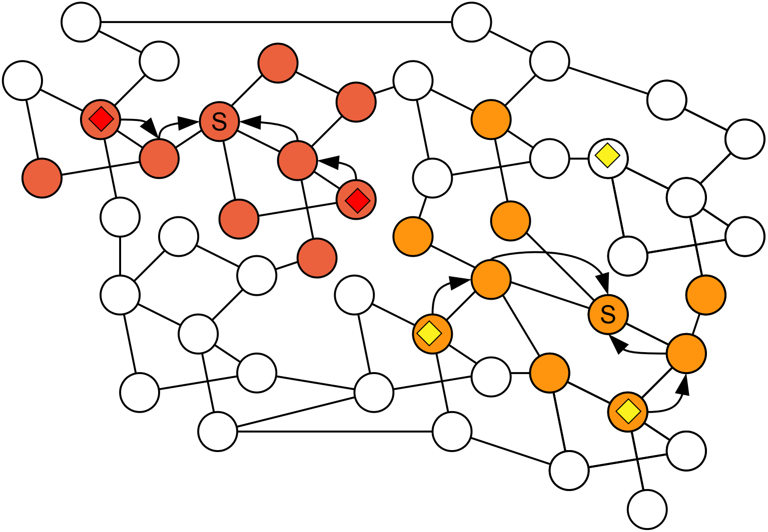
Gnutella routing



Gnutella routing



Gnutella routing



Gnutella messages

Each message is composed of:

- A 16-byte ID field uniquely identifying the message
  - randomly generated
  - not related to the address of the requester (anonymity)
  - used to detect duplicates and route back-propagate messages
- A message type field
  - PING, PONG
  - QUERY, QUERYHIT
  - PUSH (for firewalls)
- A Time-To-Live (TTL) Field
- Payload length

Gnutella messages

- PING (broadcast)
  - Used to maintain information about the nodes currently in the network
  - Originally, a "who's there" flooding message
  - A peer receiving a PING is expected to respond with a PONG message
- PONG (back-propagate)
  - A PING message has the same ID of the corresponding PING message
  - Contains:
    - address of connected Gnutella peer
    - total size and total number of files shared by this peer

Gnutella messages

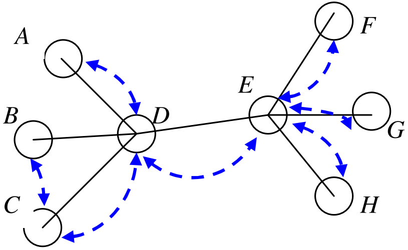
- QUERY (broadcast)
  - The primary mechanism for searching the distributed network
  - Contains the query string
  - A servent is expected to respond with a QUERYHIT message if a match is found against its local data set
- QUERYHIT (back-propagate)
  - The response to a query
  - Has the same ID of the corresponding QUERY message
  - Contains enough information to acquire the data matching the corresponding query
    - IP Address + port number
    - List of file names

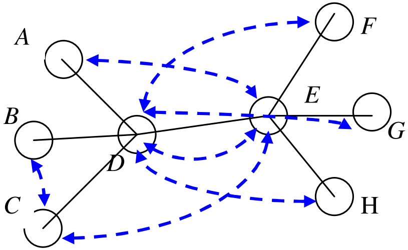
Beyond the original Gnutella

Several problems in Gnutella 0.4 (the original one):

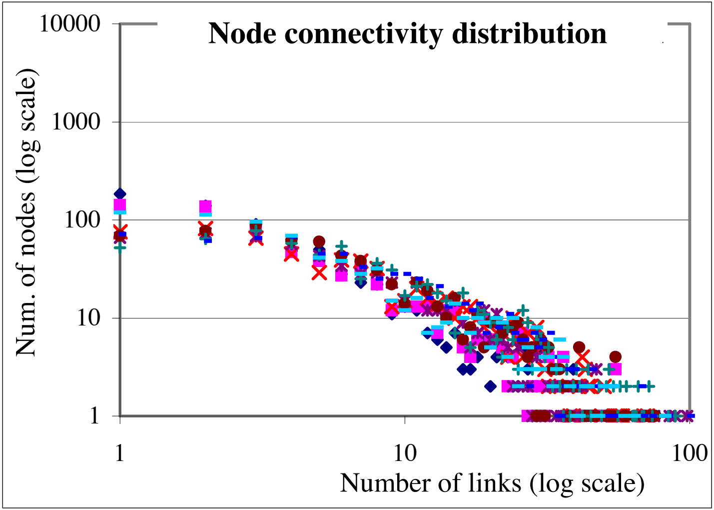
- What kind of topology is generated?
  - Is it planned ("engineered")?
  - Is it good?
- PING-PONG traffic
  - More than 50% of the traffic generated by Gnutella 0.4 is PING-PONG related
- Scalability
  - Each query generates a huge amount of traffic
    - e.g. $TTL = 6, d = 10 \Rightarrow 10^6$ messages
  - Potentially, each query is received multiple times from all neighbors

Gnutella overlay vs underlying topology

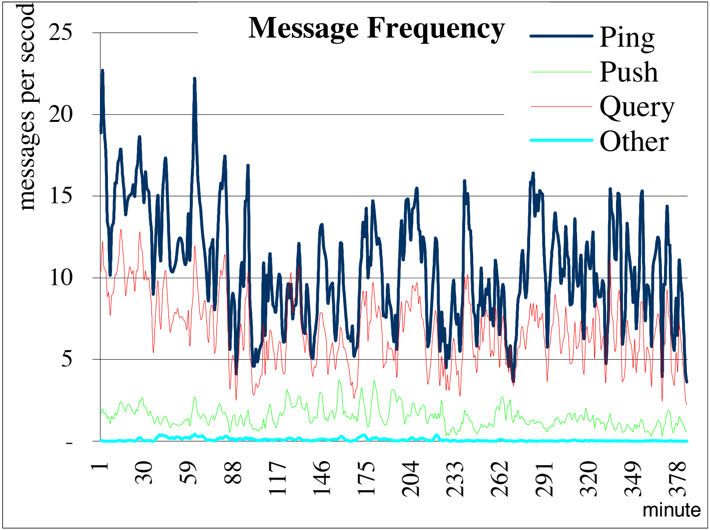




Traffic


Node connectivity distribution
Num. of nodes (log scale)
10000
1000
100
10
1
1
10
100
Number of links (log scale)

Connectivity (and robustness)



Gnutella conclusions

Gnutella 0.6:

- Superpeer-based organization
- Ping/pong caching
- Query routing

Summary:

- A milestone in P2P computing
  - Gnutella proved that full decentralization is possible
- But:
  - Gnutella is a patchwork of hacks
  - The ping-pong mechanism, even with caching, is just plain inefficient

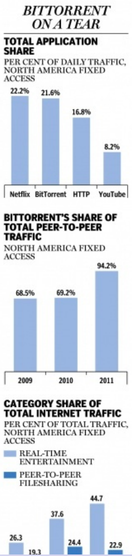
BitTorrent

- Interest on P2P system driven by file sharing applications
  - end users become content provider
- Main focus is to efficiently discover content
  - different generations of P2P…
    - centralized (Napster), unstructured (Gnutella), structured (DHT)
  - …with different problems
    - single point of failure (centralized), low success rate (unstructured), high management traffic (structured)

But…what happens when you find the content?

BitTorrent

- Designed for efficient content download
- Search features not included
- Large portion of the Internet traffic is due to BitTorrent
- Basic concept: file swarming



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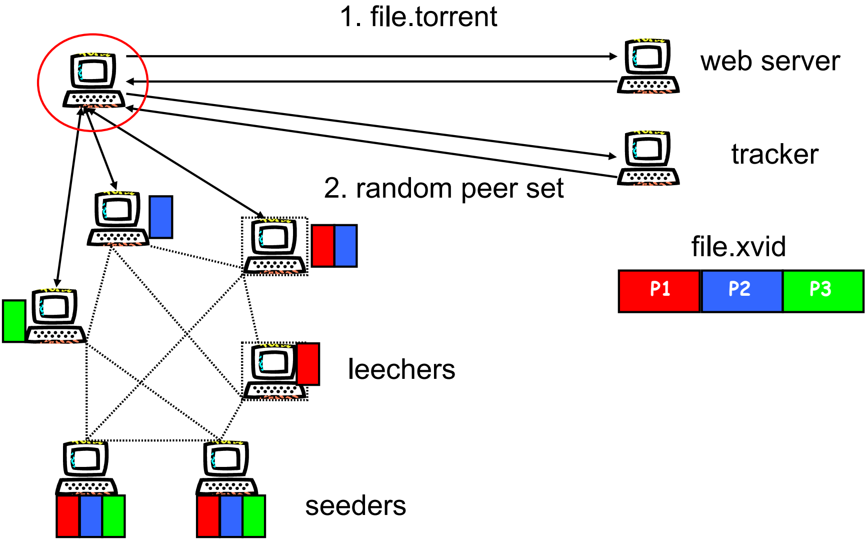
B. Cohen. Incentives build robustness in BitTorrent. In *Proc. of the Workshop on Economics of P2P Systems*, 2003.
http://www.disi.unitn.it/~montreso/ds/papers/BitTorrent.pdf

Legal (!) applications

- Music, video and the like
  - BitTorrent Inc
  - SubPop Records
  - Norwegian Broadcasting Corporation
- Software
  - Linux distributions
  - Blizzard: Diablo III, StarCraft II, World of Warcraft (game updates)
- Web services
  - Amazon S3 equipped with built-in BitTorrent support
  - Facebook, Twitter use BitTorrent to distribute updates to their servers

BitTorrent architecture



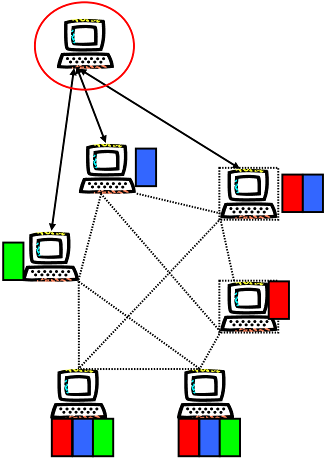
Torrent file

A torrent file is a *bencoded* dictionary with the following keys:

- `announce` – the URL of the tracker
- `name` – suggested file/directory name
- `piece length` – number of bytes per piece (commonly 256KB)
- `pieces` – a concatenation of each piece's SHA-1 hash.
- Exactly one of `length` or `files`:
    - `length` – size of the file (in bytes)
    - `files` – a list of files with the following keys:
        - `path` - pathname of the file
        - `length` - size of the file (in bytes)

BitTorrent architecture

- Peer Selection
  - "Which peers to upload to"
  - Efficiency criteria:
    - Maximize service capacity
    - Foster reciprocation and prevent free riders
- Piece selection
  - "Which pieces to download from selected peer"
  - Should guarantee *piece diversity*
    - Always find an interesting piece in selected peer
    - Do not bias peer selection



Piece selection

- The order in which pieces are selected by peers is critical
- A bad algorithm could create a situation where all peers have all pieces that are currently available and none of the missing ones
- If the original seed disappears, the download cannot be completed!

Policies

- Strict Priority
  - A piece is broken into sub-pieces (typically 16KB in size)
  - Policy: *Until a piece is assembled, only download sub-pieces for that piece from the same source*
  - This policy lets complete pieces assemble quickly
- Rarest first
  - Policy: *Determine the pieces that are most rare among your peers and download those first*
  - This ensures that the most common pieces are left till the end to download
  - Rarest first also ensures that a large variety of pieces are downloaded from the seed

Policies

- Random first piece
  - Initially, a peer has nothing to trade
  - Important to get a complete piece ASAP
  - Rare pieces are typically available at fewer peers, so downloading a rare piece initially is not a good idea
  - Policy: *Select a random piece of the file and download it*
- Endgame mode
  - Policy: *When all the sub-pieces that a peer doesn't have are actively being requested, these are requested from* ***every*** *peer*
  - When the sub-piece arrives, the replicated requests are canceled
  - This ensures that a download doesn't get prevented from completion due to a single peer with a slow transfer rate
  - Some bandwidth is wasted; in practice, not too much

Peer selection

Choking

- Choking is a temporary refusal to upload; download occurs as normal
- One of BitTorrent's most powerful idea
- It ensures that nodes cooperate and eliminates(?) the free-ride problem
- When a node is unchoked, upload restart
- Connection is kept open to reduce setup costs
- Based on game-theoretic tit-for-tat strategy in repeated games

Prisoner's Dilemma

Two men are arrested, but the police do not possess enough information for a conviction. Following the separation of the two men, the police offer both a similar deal:

	Prisoner B stays silent	Prisoner B confesses
Prisoner A stays silent	Both serve 1 months	A serves 1 year B goes free
Prisoner A confesses	B serves 1 year A goes free	Both serve 3 months

Prisoner's Dilemma

Single-iteration game

- What is the best strategy?

Prisoner's Dilemma

Single-iteration game

- What is the best strategy?
- "Confessing" is a dominant strategy
  - If the other prisoner confesses, the best move is to confess
  - If the other prisoner stay silent, the best move is to confess

Prisoner's Dilemma

Single-iteration game

- What is the best strategy?
- "Confessing" is a dominant strategy
  - If the other prisoner confesses, the best move is to confess
  - If the other prisoner stay silent, the best move is to confess

What about iterated games?

Prisoner's Dilemma

Single-iteration game

- What is the best strategy?
- "Confessing" is a dominant strategy
  - If the other prisoner confesses, the best move is to confess
  - If the other prisoner stay silent, the best move is to confess

What about iterated games?

- Robert Axelrod's "The evolution of cooperation"
- Tournament of computer programs playing PD
- The winner: Tit-for-tat, Anatol Rapoport

Prisoner's Dilemma

Tit-for-tat

- Be nice at the beginning
- Do onto others as they do onto you:
- If the other prisoner confesses, you must retaliate back
- Have a recovery mechanism to ensure eventual cooperation

How to translate this in BitTorrent?

Choking/unchoking

Goal: have several bidirectional connections running continuously

- Upload to peers who have uploaded to you recently
  - "Do onto others as they do onto you"
- Unused connections are uploaded to on a trial basis to see if better transfer rates could be found using them
  - "Be nice at the beginning"
  - "Have a recovery mechanism to ensure eventual cooperation"

Choking/unchoking specifics

- A peer always unchokes a fixed number of its peers (default: 4)
- Decision to choke/unchoke done based on current download rates, averaged over the last 20s
- Evaluation on who to choke/unchoke is performed every 10s
  - Prevents wasting of resources by rapidly choking/unchoking peers
  - Enough for TCP to ramp up transfers to their full capacity
- Which peer is the optimistic unchoke is rotated every 30s
  - Used to discover if a currently choked peer would be better

Additional details

Anti-snubbing:

- A peer is said to be snubbed if each of its peers chokes it
- To handle this, snubbed peer stops uploading to its peers
- Optimistic unchoking done more often
  - Hope is that will discover a new peer that will upload to us

Seeding:

- Once download is complete, a peer has no download rates to use for comparison nor has any need to use them
- The question is, which nodes to upload to?
- Policy: Upload to those with the best upload rate.
  - This ensures that pieces get replicated faster

Improvements over the tracker bottleneck

- Trackerless BitTorrent (i.e., w/o a centralized tracker):
  - Based on variants of Kademlia DHT
  - Tracker run by a normal end-host
  - Vuze DHT vs Mainline DHT
- Peer Exchange (PEX):
  - Each peer directly update other peers as to which peers are currently in the swarm
  - Epidemic sampling!
  - Three incompatible version of PEX (Vuze, BitComet, Mainline)
- Multitracking
  - Multiple trackers in the torrent file

Five months in a torrent's lifetime

- Analysis of a tracker log
- 1.77GB Linux Redhat 9 distribution
- Five months - April-August 2003
- 180.000 downloads

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Dissecting bittorrent: Five months in a torrent's lifetime.
In *Passive and Active Network Measurement*, volume 3015 of *Lecture Notes in Computer Science*, pages 1–11. Springer.

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Network: Number of active peers over time

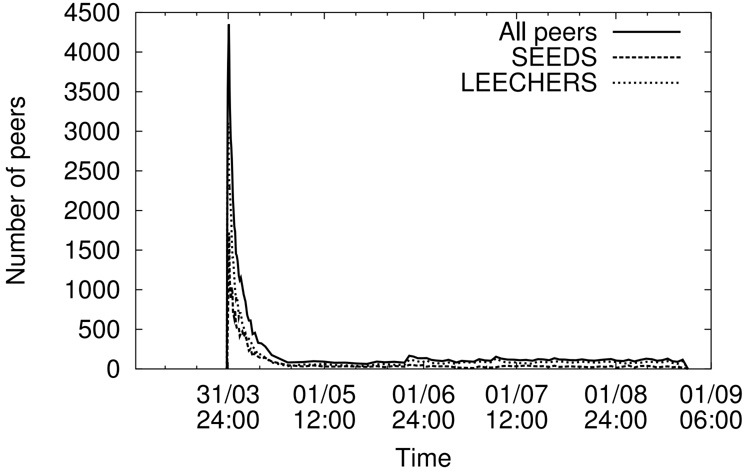

Figure: Complete trace

Network: Number of active peers over time

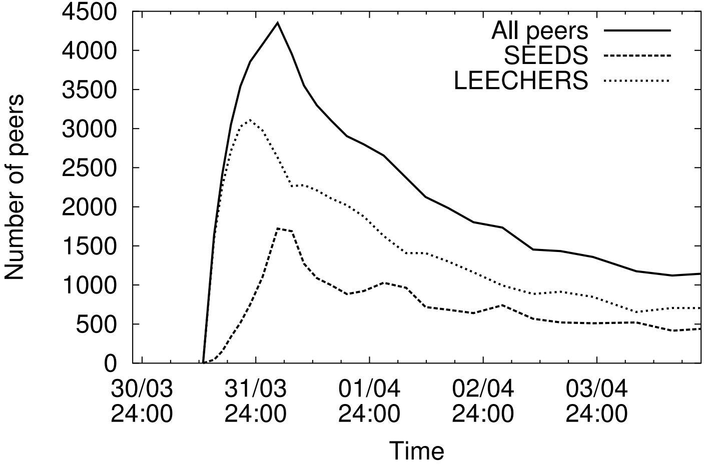

Figure: First five days

Network: Proportion of seeders and leechers

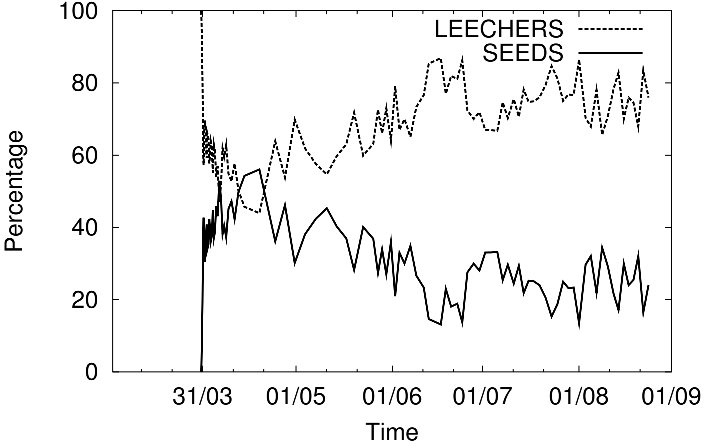

Figure: Complete trace

Client: Cumulative download and upload evolution

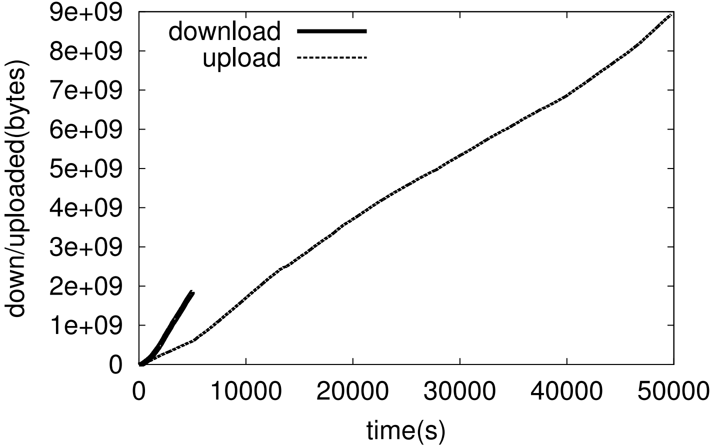

Figure: Complete torrent

Client: Cumulative download and upload evolution

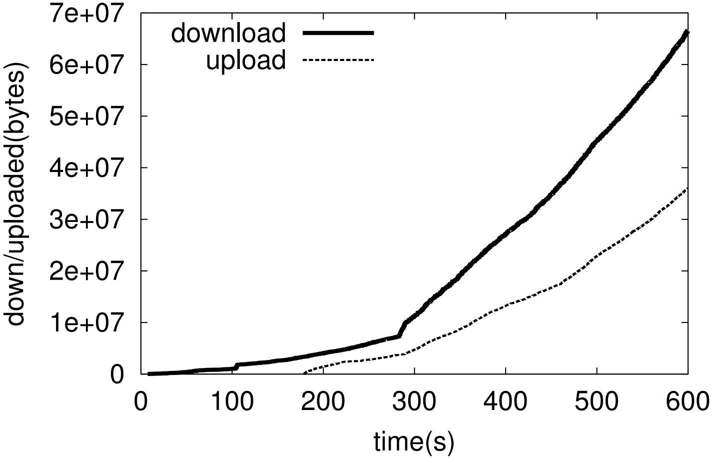

Figure: First ten minutes

Client: Number of connected peers

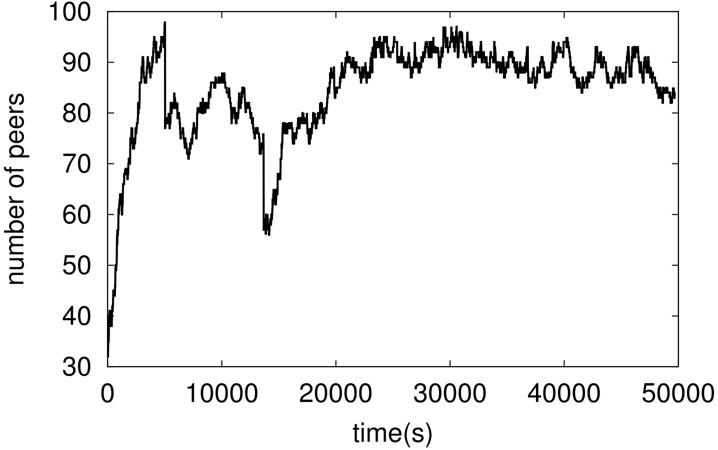

Figure: Around 14 hours

Cheating BitTorrent

- Tit-for-tat strategy has been designed to foster reciprocation
- Nevertheless, its incentives are not robust to strategic clients
- Two examples:
  - BitTyrant
    - a strategic client that tries to improve download/upload rate
  - BitThief
    - a client that never uploads anything

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  In *Proc. of HotNets-V*, Irvine, USA, Nov. 2006. Usenix.
  http://www.disi.unitn.it/~montreso/ds/papers/BitThief.pdf

BitTyrant

How to improve performance?

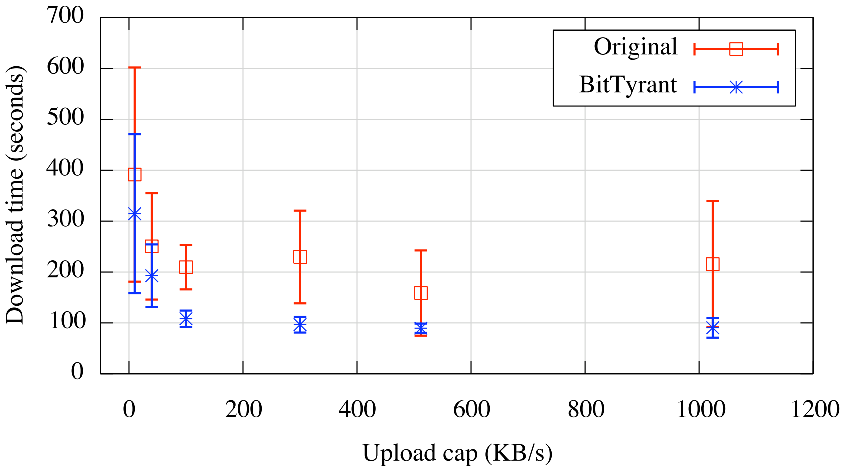
- Maximize reciprocation bandwidth per connection
- Maximize number of reciprocating peers
- Deviate from equal split

Unchoking algorithm

- d_p: download rate of connection p
- u_p: upload rate of connection p
- Each round, rank peers by the ratio u_p/d_p and unchoke the first k such that the upload capacity is reached:

$$\sum_{i=1}^{k} u_i \leq cap$$

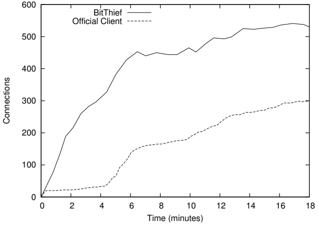
BitTyrant


Original
BitTyrant
Download time (seconds)
Upload cap (KB/s)
0
100
200
300
400
500
600
700
0
200
400
600
800
1000
1200

BitThief

Download only: benefits

- no copyright issues (only contributors are sued)
- conserve resources
- spoil the community



Gains from optimistic unchoking:

- Ask for as many clients as possible
  - Increment tracker polling
  - Decentralized tracking, PEX
- Connect to all available clients
  - higher chance of being unchoked
- Always pretend to be a newcomer
  - Advertise no pieces
  - Download whatever available
  - Most clients are nice

Gains from free sharing of seeders:

- Seeders select peers in two ways:
  - highest bandwidth
  - round robin
- BitThief report high upload rate

BitThief

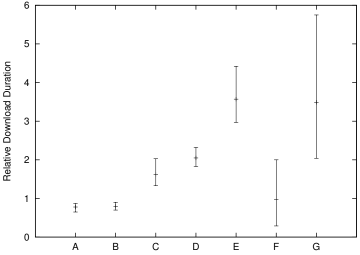


Figure: With seeders

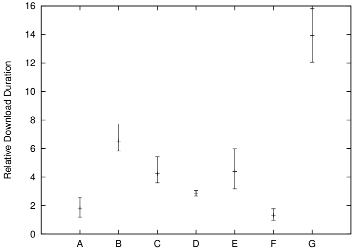


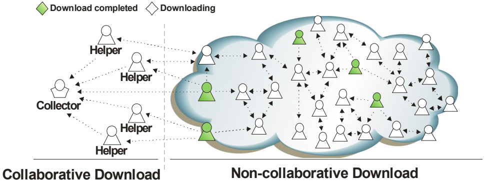
Figure: Without seeders

	Size	Seeders	Leechers	μ	σ
A	170MB	10518 (303)	7301 (98)	13	4
B	175MB	923 (96)	257 (65)	14	8
C	175MB	709 (234)	283 (42)	19	8
D	349MB	465 (156)	189 (137)	25	6
E	551MB	880 (121)	884 (353)	47	17
F	31MB	N/A (29)	N/A (152)	52	13
G	798MB	195 (145)	432 (311)	88	5

Tribler

Problem:

- Most users have different upload/download speeds
- Tit-for-tat may restrict the download speed
- Solution: let your friends help you for free



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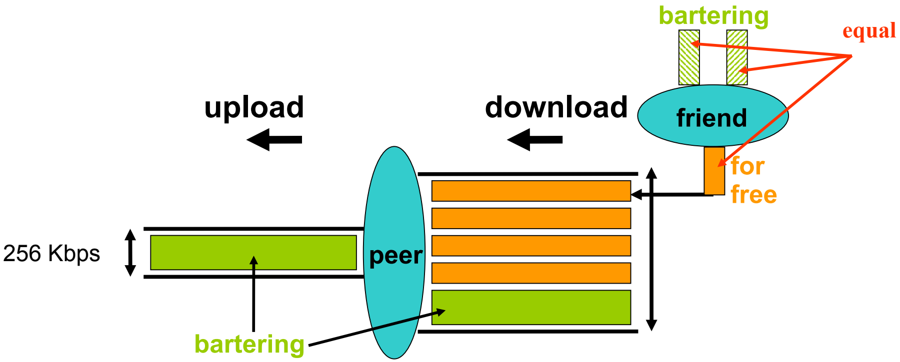
http://www.disi.unitn.it/~montreso/ds/papers/Tribler.pdf

Tribler


bartering
equal
upload
download
friend
for
free
256 Kbps
peer
bartering

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- E. K. Lua, J. Crowcroft, M. Pias, R. Sharma, and S. Lim. A survey and comparison of peer-to-peer overlay network schemes.
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