Peer-to-Peer Systems

Security and Reliability

Michael Welzl michael.welzl@uibk.ac.at

DPS NSG Team http://dps.uibk.ac.at/nsg
Institute of Computer Science
University of Innsbruck, Austria

Outline

- This block addresses the question:
  What if something goes wrong?
- What can go wrong?
  - Attackers can infiltrate the system
  - Nodes can fail
- Why would nodes fail?
  - Technical reasons (e.g. link outage)
  - Denial-of-Service attacks
  - Censorship
- Reliability / resilience and security are related issues

Security in DHTs

- DHT architectures assumes a trusted system
  - True in corporate environments, but not on the Internet

- One solution: Central certificate-granting authority
  - Used by Pastry and its related projects
  - Constrains membership in DHT

- One attack: Return incorrect data
  - Easy to avoid through cryptographic techniques
  - Detect and ignore non-authentic data

- Focus: Attacks that prevent participants from finding the data
  - Threatens the liveliness of the system

DHT Components and adversary model

DHTs have the following components:

1. Key identifier space
2. Node identifier space
3. Rules for associating keys to nodes
4. Per-node routing tables that refer to other nodes
5. Rules for updating routing tables as nodes join and leave

- Any of the above may be the target of the attack from an adversary
  - Adversaries are participants in DHT that do not follow protocol correctly

Adeversary model - assumptions:

- Malicious node can generate arbitrary packets
  - Includes forged source IP address
- Can receive only packets addressed to itself
  - Not able to overhear communications between other nodes
- Malicious nodes can conspire together, but still limited as above

Types of Attacks

1. Routing attacks
2. Attack against data storage
3. Miscellaneous attacks

- First goal: Detect attack
  - Violation of invariants or contracts

- What to do when an attack is detected?
  - Is other node malicious?
  - Did other node simply not detect attack?

- Achieving verifiability is vital

Routing Attacks

- Routing is responsible for maintaining routing tables and sending messages to correct nodes
  - Routing must function correctly
  - Define invariants and check them

- Attacker can incorrectly forward messages
  - But: Each hop should get “closer” to destination
  - Querying node should check this
  - Allow querying node to observe lookup process
    - For example, processing messages recursively hides this

- Attacker can claim that wrong node is responsible node
  - Querying node is “far away”, cannot verify this
  - Assign keys to nodes in a verifiable way
  - Often: Assign node IDs in a verifiable way (e.g., IP address)
    - For example, CAN lets node pick its own ID…

More Routing Attacks

- Attacker can send incorrect routing updates
  - Blatantly wrong updates can be detected
  - If DHT allows several choices for next hop
    - Attacker can pick a "bad" node
    - Not necessarily a problem with correctness, only performance
    - Can be a problem for some applications (anonymity)
  - Server selection can be abused
- Attacker can partition network
  - If new node contacts attacker first, attacker can partition network (can even hijack nodes from real network)
  - Parallel network is consistent and "looks OK"
    - Attacker can track nodes
  - Bootstrap from a trusted source: Hard to get in dynamic networks, public keys might help
  - Cross check routing tables with random queries
    - Assumes we were part of network earlier, still not totally safe

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Storage and Retrieval Attacks

- Attacker can deny existence of data
  - Or return wrong data
- Must implement replication at storage layer
  - Who creates replicas?
  - Clients must be able to verify that all copies were created
- Avoid single points of responsibility
  - Replication with multiple hash functions is one good way
- Big problem if system does not verify IDs
  - Any node can become responsible for any data
  - For example, Chord allows virtual nodes

Miscellaneous Attacks

- Attacker can behave inconsistently
  - Some nodes see it as good, others as bad
  - Maintain good face to nearby nodes
  - How would a distant node convince neighbors of bad node?
    - Public keys and signatures could solve this
- Denial of service
  - Attacker floods a node with messages
  - Node appears failed to the rest of the network
  - Replication helps, but attacker may succeed if replication not sufficient
  - Replicas should be in physically different locations
    - DHT assigns keys to nodes randomly, should be OK
    - Large attacks require lot of resources

More Miscellaneous Attacks

- Attacker can join and leave the network rapidly
  - Causes lot of stabilization traffic in network
  - Loss of performance, maybe loss of correctness
  - Works well if stabilization requires lot of data transfer
    - For example, copying of large objects from node to node
  - DHT must handle this case anyway
- Attacker can send unsolicited messages
  - Q asks E and gets referred to A
  - E knows Q expects an answer from A
  - E forges message from A to Q
  - Public keys and signatures (heavy solution)
  - Random nonce in a message works also

Design Principles

Summary of design principles for secure DHT:

1. Define verifiable system invariants (and verify them!)
2. Allow querying node to observe lookup process
3. Assign keys to nodes in a verifiable way
4. Server selection in routing may be abused
5. Cross-check routing tables with random queries
6. Avoid single points of responsibility

Sybil Attack

- Entity: Real-world entity; Identity: Representation in the system
- Redundancy requires resources to be spread across several entities
  - Peer-to-peer systems work only with identities
- Sybil Attack: one entity creates multiple identities to attack the system
  - From book/movie telling the story of Sybil Isabel Dorsett who suffered from multiple personality disorder
- For example, data replication
  - A single copy might be on a malicious peer
  - But several copies on different peers are safe, right?
- How can we know that the "different" peers are really different and distinct physical entities?
- Answer: We need a (logically) centralized, trusted entity (e.g., CA)
  - Without central authority, problem was proven to be *unsolvable*

Examples of Solutions

- Real centralized authorities:
  - Certification Authorities, e.g., VeriSign
- Logically centralized authorities:
  - Hashing IP address to get DHT identifier (e.g., CFS)
  - Add host identifiers to DNS names (SFS)
  - Cryptographic keys in hardware (EMBASSY)
  - These appear distributed, but they all rely on some centralized authority (e.g., ICANN gives out IP addresses and DNS names)
- Identities vouching for other identities
  - For example, PGP web of trust for humans
  - NOT a solution!
  - Attacker can attack the system early and compromise generation of identities and break chain of vouchers

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Results

- Entity should accept identities only if they have been validated by central authority, itself, or others
  - In a fully distributed system, only entity itself and others
- The following can be shown under reasonably realistic assumptions for direct validation:
  1. Even when severely resource constrained, a faulty entity can counterfeit a constant number of multiple identities
  2. Each correct entity must simultaneously validate all the identities it is presented; otherwise, a faulty entity can counterfeit an unbounded number of entities
  - Similar results hold for indirect validation by others
- What resources can be used in identification?
  - Communication, CPU, storage

Resources as Proof

- Communication
  - Broadcast request for others to identify themselves and accept only responses which come within a certain time interval
  - Model had assumed broadcast communications

- CPU
  - Require other peer to perform some computationally intensive, but easily verifiable, task
  - This requires simultaneous identification (point 2 from above)

- Storage
  - Have others store some uncompressible data and periodically ask them to give back a small piece
  - Would eventually catch a Sybil attack
  - Problem: No storage space left for doing any real work…

Implications of Sybil Attack

- Need centralized authority for managing identities

- Logically centralized systems should be aware of their potential (future) vulnerabilities
  - For example, privacy extensions for IPv6 might break CFS

- Sybil attack can be avoided under the assumptions:
  - All entities operate under identical resource constraints
  - All presented identities are validated simultaneously by all entities, coordinated over the whole system
  - For indirect validation, the number of vouchers must exceed the number of failures in system

- Are these assumptions feasible or practical for a large-scale distributed system?
  - Answer would seem to be no

Byzantine Generals Problem

- Several divisions of the Byzantine army surround an enemy city. Each division is commanded by a general.
- The generals communicate only through messenger
  - Need to arrive at a common plan after observing the enemy
- Some of the generals may be traitors
  - Traitors can send false messages
- Required: An algorithm to guarantee that
  1. All loyal generals decide upon the same plan of action, irrespective of what the traitors do.
  2. A small number of traitors cannot cause the loyal generals to adopt a bad plan.

Theorem: (from L. Lamport)

- If no more than m generals out of $n = 3m + 1$ are traitors, everybody will follow the orders

Solution:

- Digital signatures; all generals sign their orders, inconsistent orders or forwarding of false messages can immediately be detected

Reliability / performance issues with DHTs

- DHTs trade-offs: performance vs. cost, reliability vs. cost
  - Cost: node state or number of bytes sent into network
  - Reliability / performance often connected
    - Performance = lookup latency = f(number of hops)
    - Assume random failures: long path = unreliable system

- It was shown that we can configure a DHT to give us “decent” performance (lookup latency) at “reasonable” cost (overlay maintenance overhead)

- Question: Is “decent” good enough for real applications?
- In other words, how does a DHT-based P2P application compare against a client/server-application?

- Let’s take Domain Name System (DNS) as example
  - Fundamental Internet-service
  - Very much a client/server application

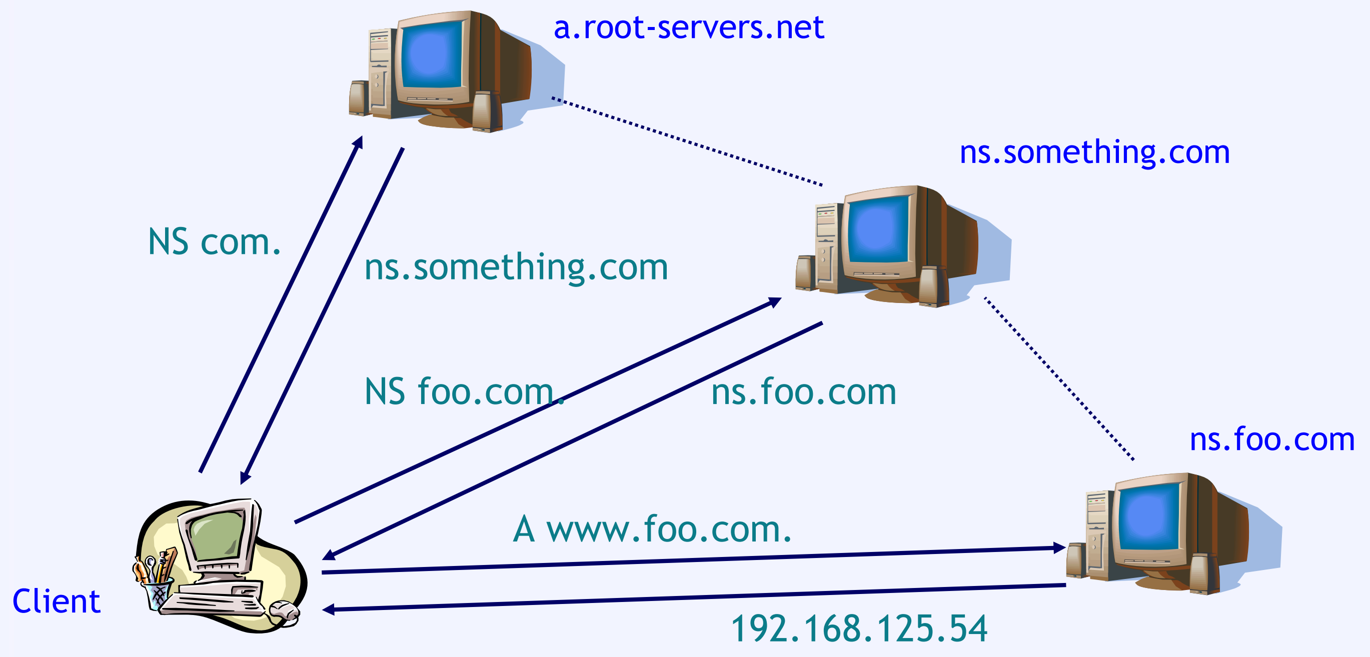
P2P DNS

- Domain Name System (DNS) very much client-server
- *Ownership of domain = responsibility to serve its data*
- DNS concentrates traffic on root servers
    - Up to 18% of DNS traffic goes to root servers
- A lot of traffic also due to misconfigurations
- P2P DNS
    - puts expertise in the system
        - No need to be an expert administrator
    - shares load more equally
- So why not replace standard DNS with P2P DNS?

DNS: Overview

- DNS organized in zones (≈ domain)
    - Actual data in resource records (RR)
    - Several types of RRs: A, PTR, NS, MX, CNAME, …
- Administrator of zone responsible for setting up a server for that zone (+ redundant servers at other domains)
- Queries resolved hierarchically, starting from root
- Owner of a zone is responsible for serving zone’s data
- DNS shortcomings:
    - Need skill to configure name server
    - No security (but added later to some degree)
    - Queries can take very long in worst case

DNS: Example



a.root-servers.net

ns.something.com

NS com.

ns.something.com

NS foo.com.

ns.foo.com

ns.foo.com

A www.foo.com.

Client

192.168.125.54

- Client wants to resolve www.foo.com
- Replies to queries have additional information (IP address + name)
- Queries can be iterative (here) or recursive

How to Do P2P DNS?

- Put DNS resource records in a DHT
- Key is hash of domain name and query type
  - For example, SHA1(www.foo.com, A)
- Values replicated for better performance (~ 5-7 copies)
- Can be built on any DHT, works the same way
- All resource records must be signed
  - Some overhead for key retrieval
- For migration, put P2P DNS server on local machine
  - Configure normal DNS to go through P2P DNS
  - No difference to applications

P2P DNS: Performance

- Current DNS has median latency of 43 ms
    - Measured at MIT
- Some queries can take a long time
    - Up to 1 minute (due to default timeouts)
- P2P DNS has median latency of 350 ms!
    - Simulated on top of Chord
- Conclusion:
  P2P DNS is much, much worse than standard DNS
    - But extremely long queries cannot happen

Why (not) P2P DNS?

Pros

- Simpler administration
    - Most problems in current DNS are misconfigurations
    - DNS servers not easy to configure well
- P2P DNS robust against lost network connectivity
    - Current DNS: first DNS server unavailable ⇒ all lookups fail
- No risk of incorrect delegation
    - Subdomains can be easily established
    - Signatures confirm

Cons

- All queries must be anticipated in advance
    - With current DNS, a local database could be queried as a request arrives
- Current DNS can tailor requests to client
    - Widely used in content distribution networks and load balancing
- Might be possible to implement above in client software
- But latency problem remains!

Future of DHT-Based Applications?

- DHT-based applications have to make several RPCs
  - 1 million node Chord = 20 RPCs, Tapestry 5 RPCs

- Experiments with DNS show even 5 is too much
  - Current DNS usually needs 2 RPCs
  - DNS puts a lot of knowledge at the top of the hierarchy
    - Root servers know about millions of domains

- Many RPCs is main weakness of DHTs

- DHT-based applications have all their features on clients
  - New feature ⇒ install new clients
  - Some kind of an "active" network as a solution?

Reliability of P2P Storage

- Example case: P2P storage system
  - Each object replicated in some peers
  - Peers can find where objects should be
    - Typically DHT-based, but DHT is not absolutely required
- No concern of consistency
  - Read-only storage system

Questions:

1. How many copies are needed for a given level of reliability?
   - Unconstrained system with infinite resources

2. What is the optimal number of copies?
   - System with storage constraints

Reliability of Data in DHT-Storage

- Storage system using a distributed hash table (DHT)
- Peer A wants to store object O
  - Create k copies on different peers
  - k peers determined by DHT for each object (k closest)
- Later peer B wants to read O
  - What can go wrong?
- Simple storage system: Object created once, read many times, no modifications to object
- Question: What is the value of k needed to achieve e.g., 99.9% availability of O?
  - Remember: Only probabilistic guarantees possible!

Assumptions

- Assume l peers in the DHT
  - Each peer has unlimited storage capacity
- Peer is up with probability p
  - Peers are homogeneous, i.e., all peers have same up-probability
- Peers uniformly distributed in hash space
  - Makes mathematical analysis tractable
- New peers can join the network
- Peers never permanently leave
- User may need to access several objects to complete one user-level action
  - For example, resolve path to file

What Can Go Wrong?

1. All *k* peers are down when *B* reads
   - Object is not available in any on-line peer
2. *k* closest peers were down when *A* wrote and are up when *B* reads
3. At least *k* peers join and become new closest peers
   - In above two cases, object is (maybe) still available in the peers where *A* wrote it
4. All *k* peers have permanently left the network
   - Assumed not to happen

- We only look at the first three cases
- What are the probabilities of each one of them?

Probabilities of Loss

1. All *k* peers are down when *B* reads

$$p_{l1} = (1-p)^k$$

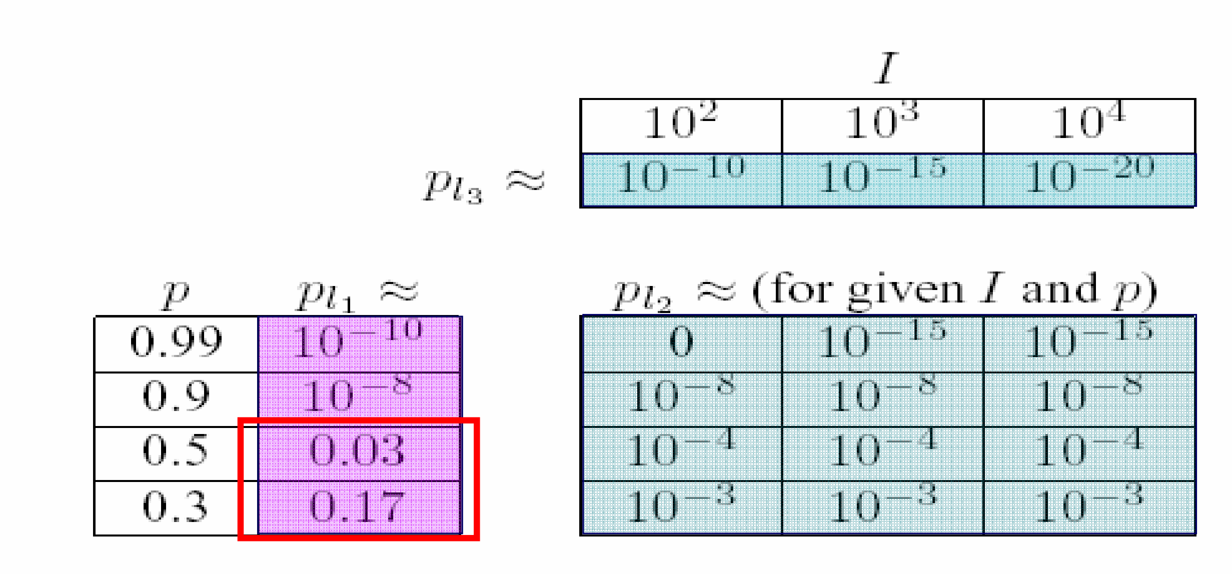
2. *k* closest peers were down when *A* wrote and are up when *B* reads

$$p_{l2} \approx \sum_{i=k}^{(1-p)I} \binom{(1-p)I}{i} \left(\frac{p(1-p)}{I} \right)^i$$

3. *N* peers join and at least *k* peers become new closest peers

$$p_{l3} = \sum_{i=k}^{N} \binom{N}{i} \frac{1}{I^i}$$

Numerical Values for Loss



	I		
	10^2	10^3	10^4
$p_{l_3} \approx$	10^{-10}	10^{-15}	10^{-20}

p	$p_{l_1} \approx$
0.99	10^{-10}
0.9	10^{-8}
0.5	0.03
0.3	0.17

$p_{l_2} \approx$ (for given I and p)

0	10^{-15}	10^{-15}
10^{-8}	10^{-8}	10^{-8}
10^{-4}	10^{-4}	10^{-4}
10^{-3}	10^{-3}	10^{-3}

- First case clearly dominates
  - In above tables, *k* = 5
  - Cases 2 and 3 may look good at first sight, but note: Often necessary to search more than *k* nodes to find object!

How to Improve?

- Maintain storage invariant → *O* always at *k* closest
  - Needs additional coordination
  - Possible if down-events controlled
  - Crash → others need to detect crash (before they crash)
  - Guarantees availability as long as invariant maintained
  - Possibly wastes storage if copies are not removed when peers come back into the system
  - This approach taken by PAST storage system
- Increase *k*
  - Create more copies, simple to implement
  - Wastes storage capacity?
  - Not good for changing objects (consistency)

What does the user see?

- Suppose: User’s action needs to access several objects
  - For example, resolve path for files one level at a time
- For each object: $p_s = 1 - p_{l1} = 1 - (1 - p)^k$

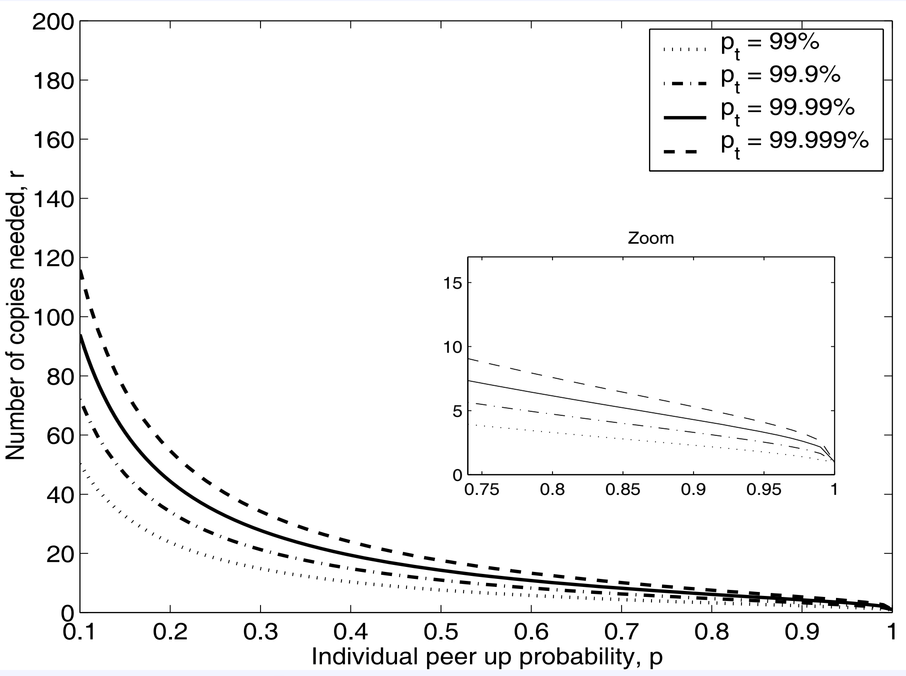
- What if we need to access 2 objects?

- Success for user: $p_t = (1 - (1 - p)^k)^2$
- Solving for k:

$$k = \frac{\log(1 - \sqrt{p_t})}{\log(1 - p)}$$

- In general for n objects: $p_t = (1 - (1 - p)^k)^n$

How Large Should k Be?



- Define target p_t
  - This is what user sees
  - Failures temporary

- When peers mostly up, k small

- Increase in p_t → small increase in k

Replication: how to do it?

- Replication in read-only system helps availability
- Main cause of unavailability is *k* peers being down at the same time when trying to read
- Create *k* copies of each object
  - If peers mostly up, *k* quite small (< 10)
  - Actively maintaining copies in right peers helps
- Where to place objects?
- Key assumption of DHTs: load evenly distributed across address space
  - Then storing replicas in local neighbors will preserve this property

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Two replication strategies for Chord

1. Successor list
   - Chord maintains 1 successor pointer, 1 predecessor pointer, finger table
   - Idea for storing replicas in (overlay) proximity:
     - Maintain pointers to next *S* successors
       (N*(S-1)) additional pointers in the whole system)
     - Store replica in all these nodes
     - Maintenance: copy / move replica as nodes come and go (or fail)
2. Multiple nodes in one interval
   - Assign interval responsibility to more than one node
   - Each node stores additional pointers to neighbors in the same interval
     - But only one finger pointer
   - Joining node announces itself to nodes responsible for the same interval

Shortcomings of proximity based methods

- Proximity based replica storage assumes that objects evenly distributed across address space
  - Not always true
- Prior analysis assumes all objects equally popular or important
  - Not always true
  - Zipf-distribution for object popularities
  - Also, some objects may require higher availability
- How should objects be replicated in this case?
- Algorithms based on notion of well connected P2P community (e.g. campus)
  - Replacement policies such as Most Frequently Requested (MFR)
  - Each object o has "attractor nodes"; Object o tends to get replicated in its attractor nodes; Queries for o tend to be sent to attractor nodes ⇒ tend to get hits

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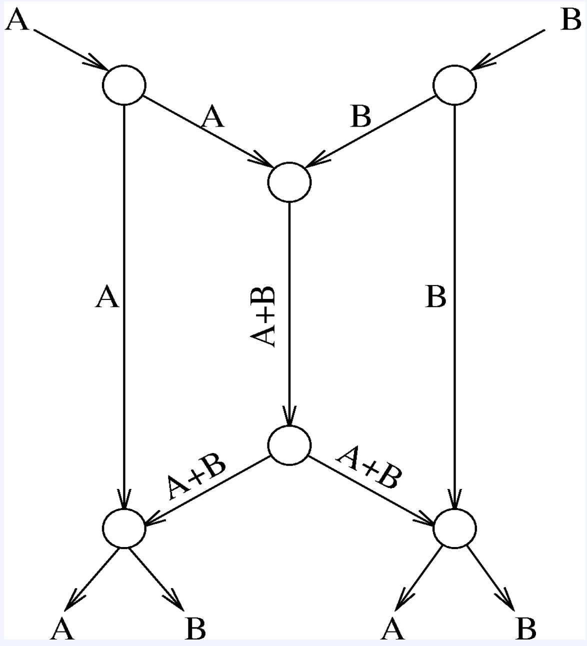
Redundancy

- No need to always replicate full objects
  - What if parts of objects are distributed?
  - We can go beyond simple splitting…
- Erasure codes
  - Split each object into N fragments
  - Compute K redundant fragments
  - Disseminate these N+K blocks
  - Any N out of these N+K blocks suffice for reconstructing the object
- Most efficient and common method: network coding
  - Based on linear combinations of orthogonal vectors in finite fields
  - But easier to explain with XOR :-)
  - Network coding applied for numerous things nowadays (e.g. mobile nets)

Network coding

R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung, "Network Information Flow", *(IEEE Transactions on Information Theory*, IT-46, pp. 1204-1216, 2000)

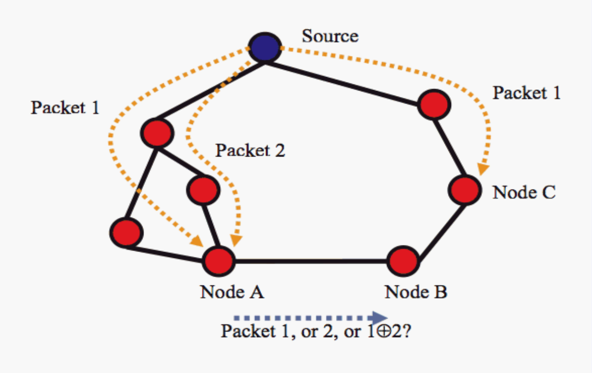


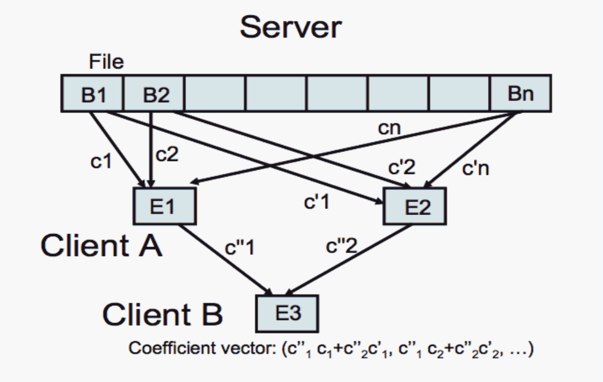
Example:

- Bits A and B should be transmitted
- Only one bit can be sent on each link
  - Simply send the bits: left side gets A, right side gets B, one of them can get the other in addition via middle link
  - By sending A XOR B, both sides can get A and B in one step

Practical Network Coding

- Avalanche (Gkantsidis, Rodriguez, 2005)
- Goal
  - Avoid Coupon-Collector-Problem when getting blocks of an object
    - Calculation of how often to buy in order to get all 10 different coupons
    - Problem does not need to arise with network coding: an object consisting of m parts can be reconstructed from <u>any</u> m parts
    - This is closer to most coupons in real life…
  - Optimal dissemination of data regarding available bandwidth
- Method
  - Disseminate linear combinations of object parts
  - Receiver collects everything, then reconstructs original object





Pro‘s and con‘s of network coding

- Major performance and reliability gains claimed for a multitude of things
- But: significant overhead
- Storage overhead
  - E.g. 4 GB file with 100 KB block must contain variable vector of 4 GB/100 KB = 40 KB = 40% overhead per block
  - Better: 4 GByte and 1 MByte-Block; resulting overhead per block 4 KB = 0,4%
- Decoding: memory and CPU
  - Inverting a m x m-matrix (m = size of variable vector)
  - this needs time O(m^3) and memory O(m^2)
- Read-/write-access to files
  - Encoding / decoding: for m blocks, must traverse whole file m times
  - Disk cache cannot be exploited because no data locality

Conclusion

- Security and reliability are major issues in P2P systems
  - They are related
- Reliability is also related to performance
  - Avoid long paths: more reliable, shorter lookup latency
  - Network coding: can improve reliability and performance
- A lot of unresolved issues and open questions
  - How to efficiently cope with Sybil attacks
    - E.g. reputation management systems
  - How to ideally replicate (depending on distribution of popularity items)
  - Trade-off between redundancy and replication
    - Will network coding prevail?

References / acknowledgments

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