Structured networks: search

Márk Jelasity

Outline

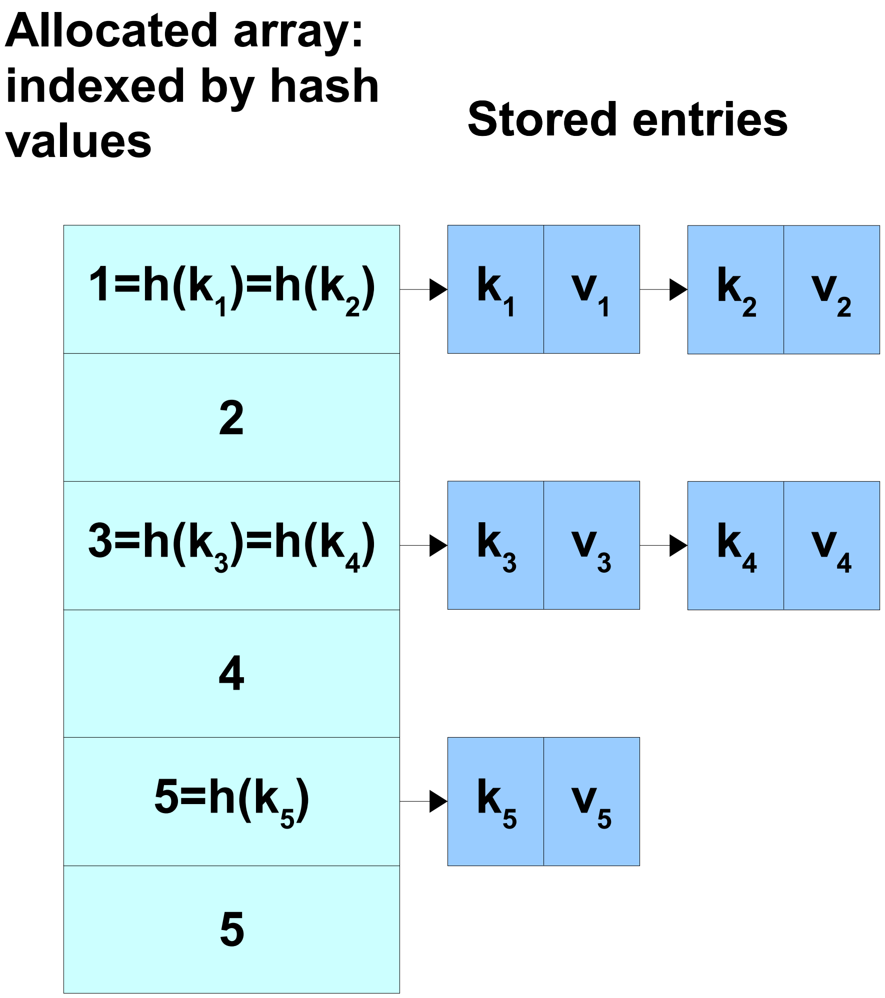
- Hash tables and distributed hash tables (DHT): the abstraction
- An example implementation: Chord
- Implementing keyword search on a DHT
- Some other other DHTs: Pastry and CAN
- Summary of DHT complexity results
- Hybrid (structured/unstructured) approaches to search

Motivation

- We have seen search does well in unstructured networks except when items are rare
- Can we come up with a technique that provides efficient search (lookup) for rare items?
  - Yes: distributed hash tables (DHT)
- What is the ultimate solution that is robust, cheap and works for popular and rare items too?
  - Hybrid solutions?
  - Something not yet invented?
- DHTs are good for other things too

Hash tables

- Store arbitrary keys and satellite data (value)
  - **put(key,value)**
  - **value = get(key)**
- Lookup must be fast
  - **Calculate hash function h() on key that returns a storage cell**
  - **Chained hash table: Store key (and optional value) there**



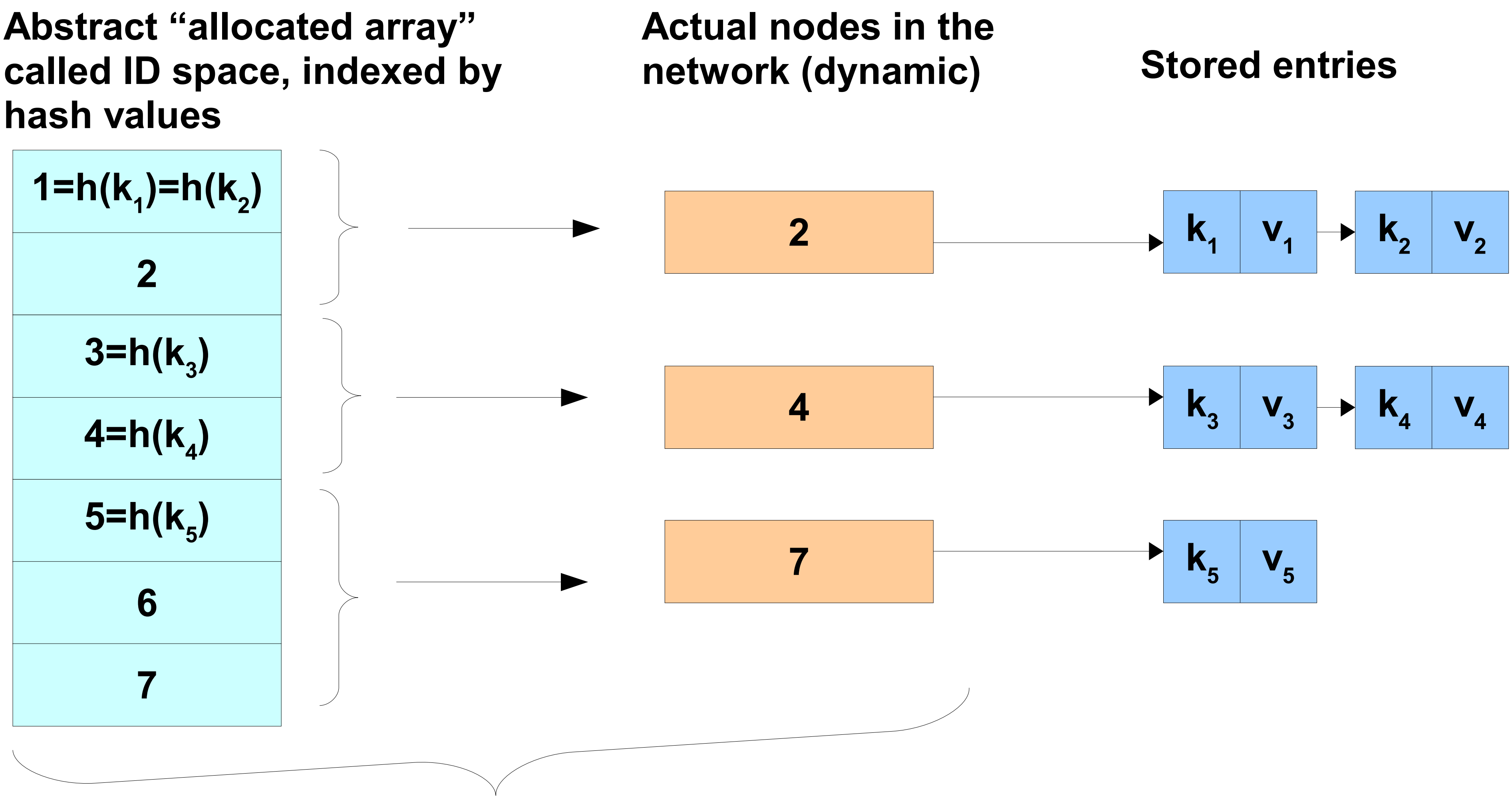
Why a hash table?

- Most often the point of a hash table is fast and cheap lookup of data indexed by a key
- When used for search, the issue of query richness comes up
  - In random walk/flooding, a query can be arbitrarily complex (even full text search with regular expressions).
  - If we use only key based lookup, we must be creative and work more to allow for non-trivial queries
    - **Inverse indexing, etc**
- The idea is trading some flexibility and simplicity off for efficiency and effectivity

Distributed hash table

- We want hash table functionality in a p2p network: lookup of data indexed by keys
- Assume the storage space is a distributed set of nodes (not an array)
  - Note that in all cases we will have an overlay network that connects these nodes in tricky ways
  - The exact set of nodes is not known locally and can change all the time
  - We work with an idealized storage space,
    - **Hash function maps to this ideal space**
    - **We assign parts of the space to nodes in a distributed way dynamically: extra complications**

Distributed hash tables



consistent hasing of keys to nodes
typically two step, as shown above

Distributed has tables: main functions

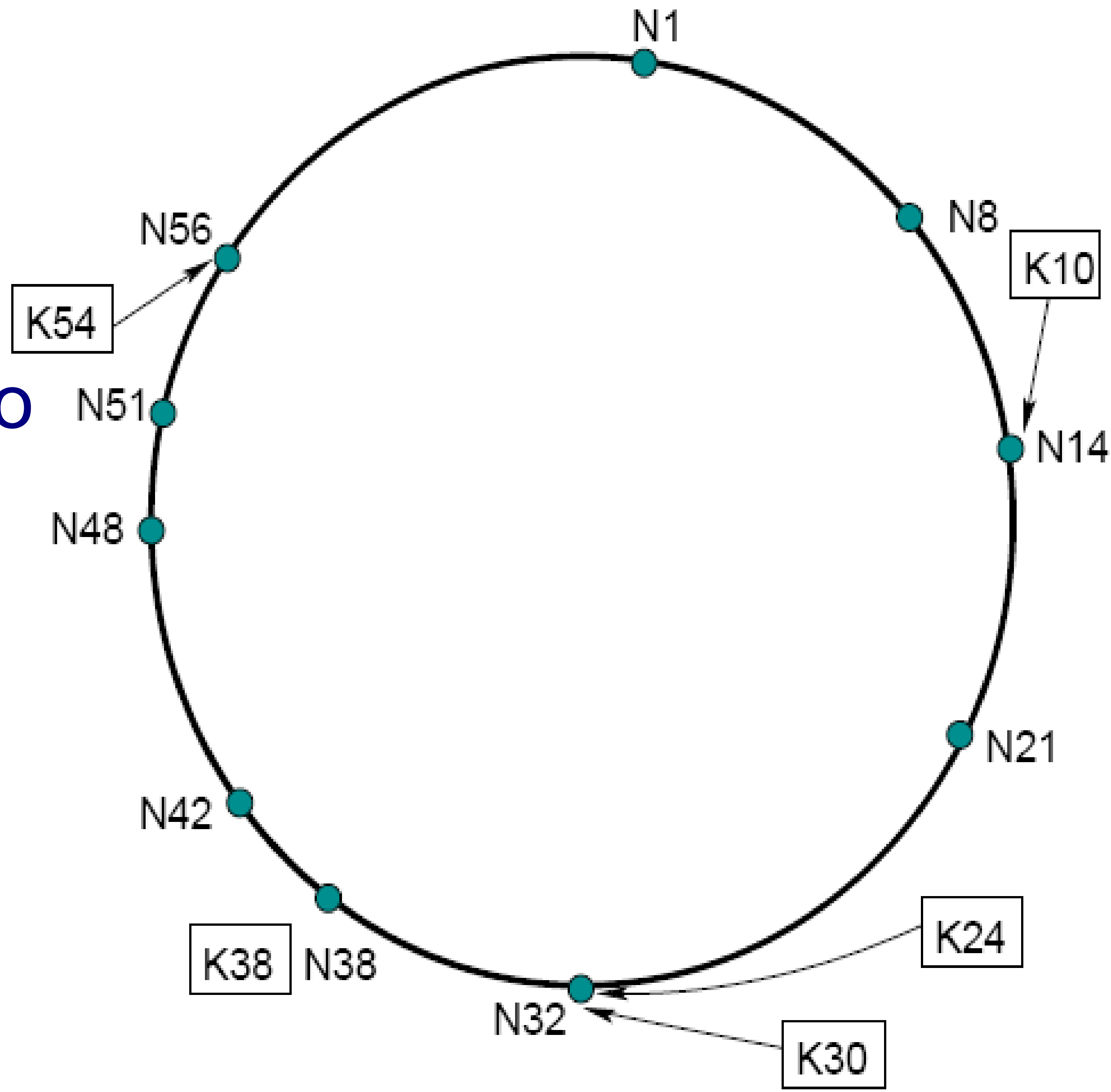
- Key-hash ↔ node mapping
  - Assign a unique live node to a key
  - Find this node in the overlay network quickly and cheaply (routing)
- Maintenance, optimizations
  - Implement DHT API on top of routing
  - Load balancing: maybe even change the key-hash ↔node mapping on the fly
  - Replicate entries on more nodes to increase robustness
  - etc

Chord

- Most cited DHT implementation (3000+ citations to date!!!)
- Advantages
  - Simple
  - Good storage and message complexity
- Consistent hashing based on an ordered ring overlay
  - This is why it is “structured”

Hashing in the Chord ring

- Identifier circle
  - 10 nodes
  - 5 keys
- Both keys and nodes are hashed to 160 bit IDs (SHA-1)
- Then keys are assigned to nodes using consistent hashing
  - Successor in ID space

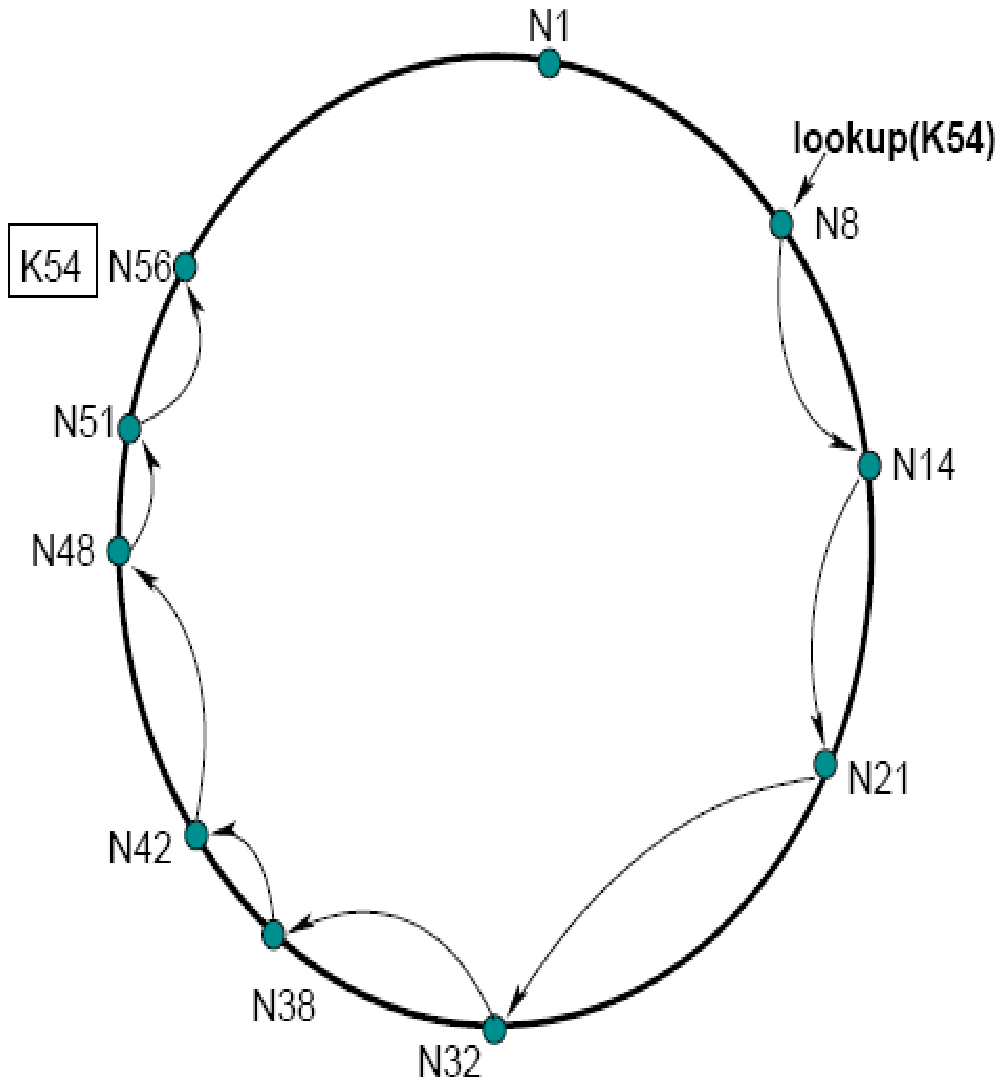


Chord hashing properties

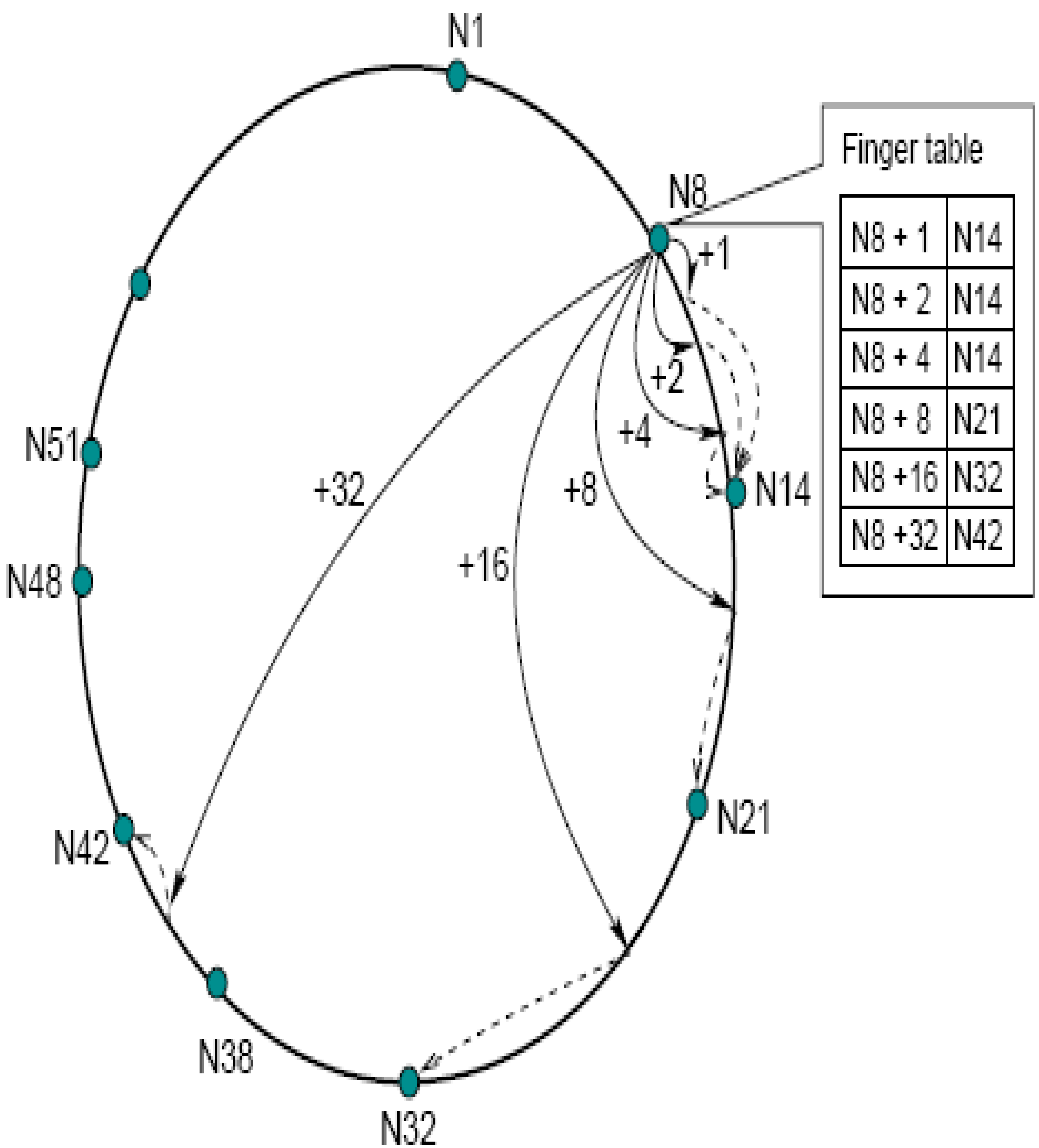
- Consistent hashing
  - randomized
    - **All nodes receive roughly equal share of load**
  - Local
    - **Adding or removing a node involves an O(1/N) fraction of the keys getting new locations**
- Actual lookup
  - Chord needs to know only O(log N) nodes in addition to successor and predecessor to achive O(log N) message complexity for lookup

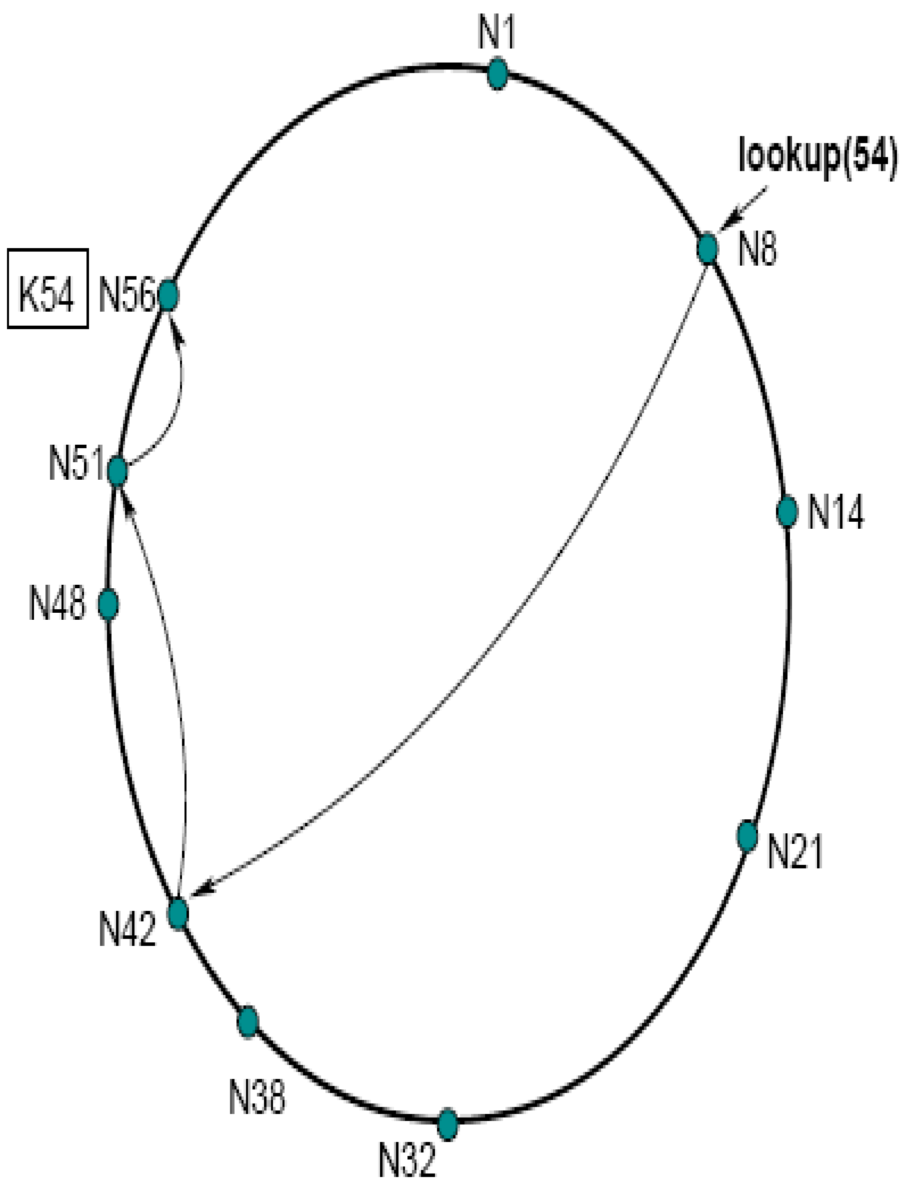
A primitive lookup algorithm

// ask node n *to find the successor of* id
n.find_successor(id)
  if (id $\in$ (n, *successor*])
    return *successor*;
  else
    // forward the query
    // around the circle
    return *successor.find_successor*(id);



A scalable lookup algorithm





A scalable lookup algorithm

```
// ask node n to find the successor of id
n.find_successor(id)
  n' = find_predecessor(id);
  return n'.successor;
```

```
// ask node n to find the predecessor of id
n.find_predecessor(id)
  n' = n;
  while (id ∉ (n', n'.successor])
    n' = n'.closest_preceeding_finger(id);
  return n'
```

- Jump to the closest preceeding finger
- O(logN) jumps
- O(logN) neighbors stored at each node
- This formulation assumes one node coordinates the lookup (not recursive) but could be

Join: an expensive approach

- A new node has to
  - Fill its own successor, predecessor and fingers
  - Notify other nodes for which it can be a successor, predecessor of finger
- With several optimizations this can be done on O(logN) time
- But the resulting protocol is complex
- Can be done simpler, using a relaxed and simple stabilization protocol, used also for error correction

Join: a relaxed approach

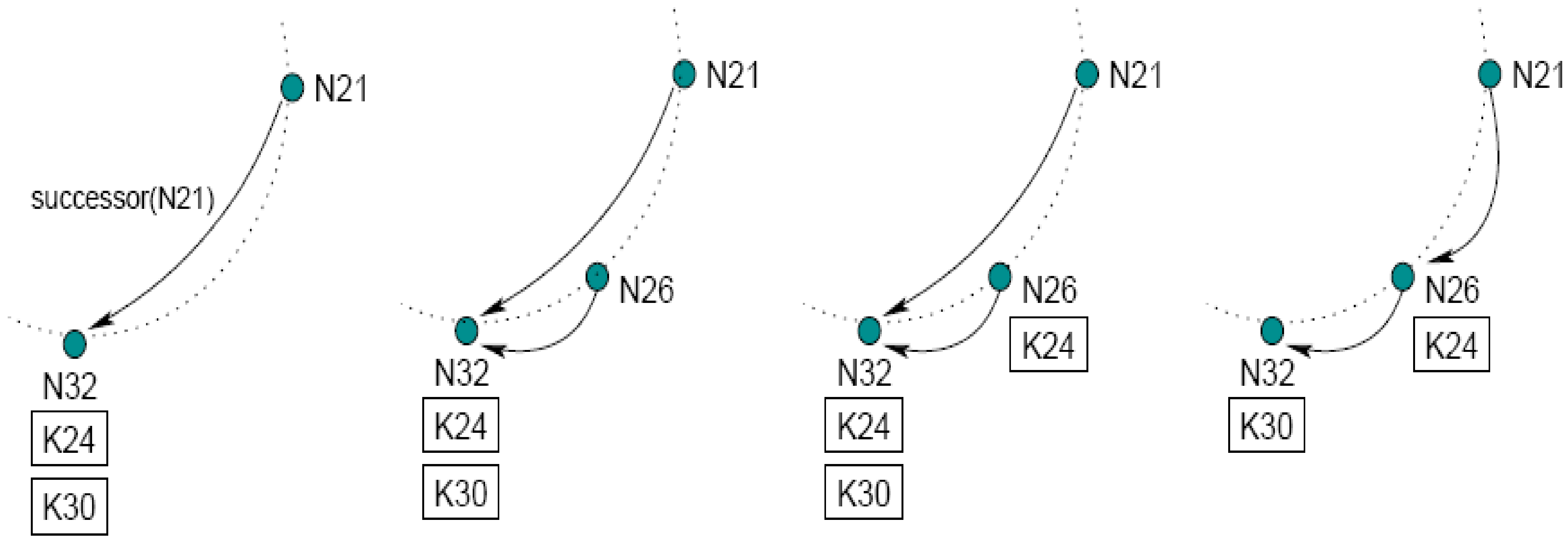
- If the ring is correct, then routing is correct, fingers are needed for the speed only
- Stabilization
  - Each node periodically runs the stabilization rutine
  - Each node refreshes all fingers by periodically calling find_successor($n+2^{i-1}$) for a random i
  - Periodic cost is O(logN) per node due to finger refresh

```
n.stabilize()
  x = sucessor.predecessor;
  if (x ∈ (n, successor) )
     successor = x;
  successor.notify(n);
```

```
n.join(n')
  predecessor = nil;
  sucessor =
        n'.find_successor(n);
```

Join: a relaxed approach

- Node join: find successor and then stabilize
  - Ring is immediately joined: routing works
  - Routing also fast enough if not too many nodes join concurrently, but eventually fingers will be ok too

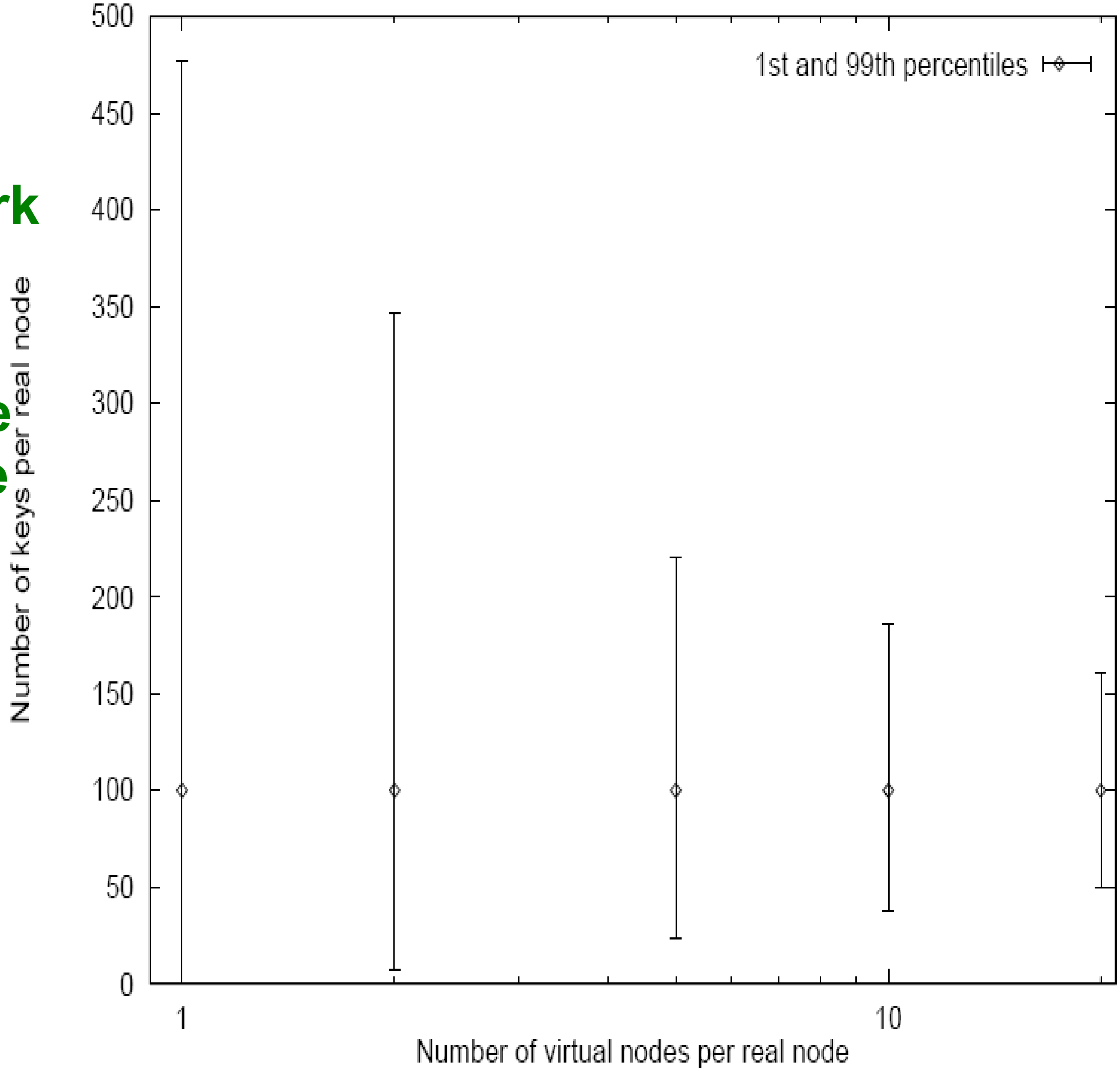


Failure and replication

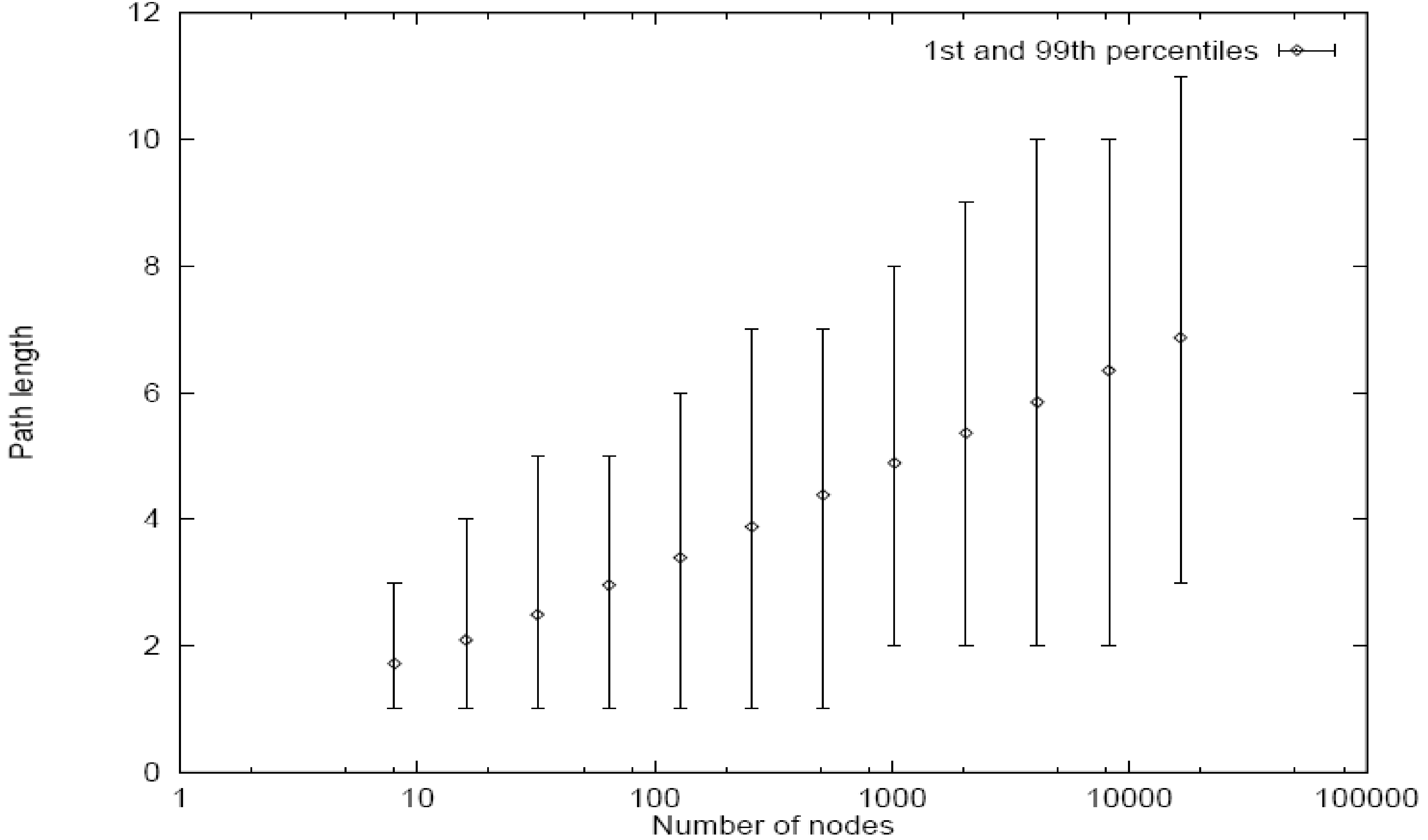
- Failed nodes are handled by
  - Replication: instead of one successor, we keep r successors
    - **More robust to node failure (we can find our new successor if the old one failed)**
  - Alternate paths while routing
    - **If a finger does not respond, take the previous finger, or the replicas, if close enough**
- At the DHT level, we can replicate keys on the r successor nodes
  - The stored data becomes equally more robust

Virtual nodes

- A physical node acts as if it was many nodes
  - **The Chord network appears to be larger**
  - **One phisical node gets a much more balanced number of keys**
  - **Maintenance cost grows**
  - **Path length does not grow significantly**



Path length in simulations



Conclusions

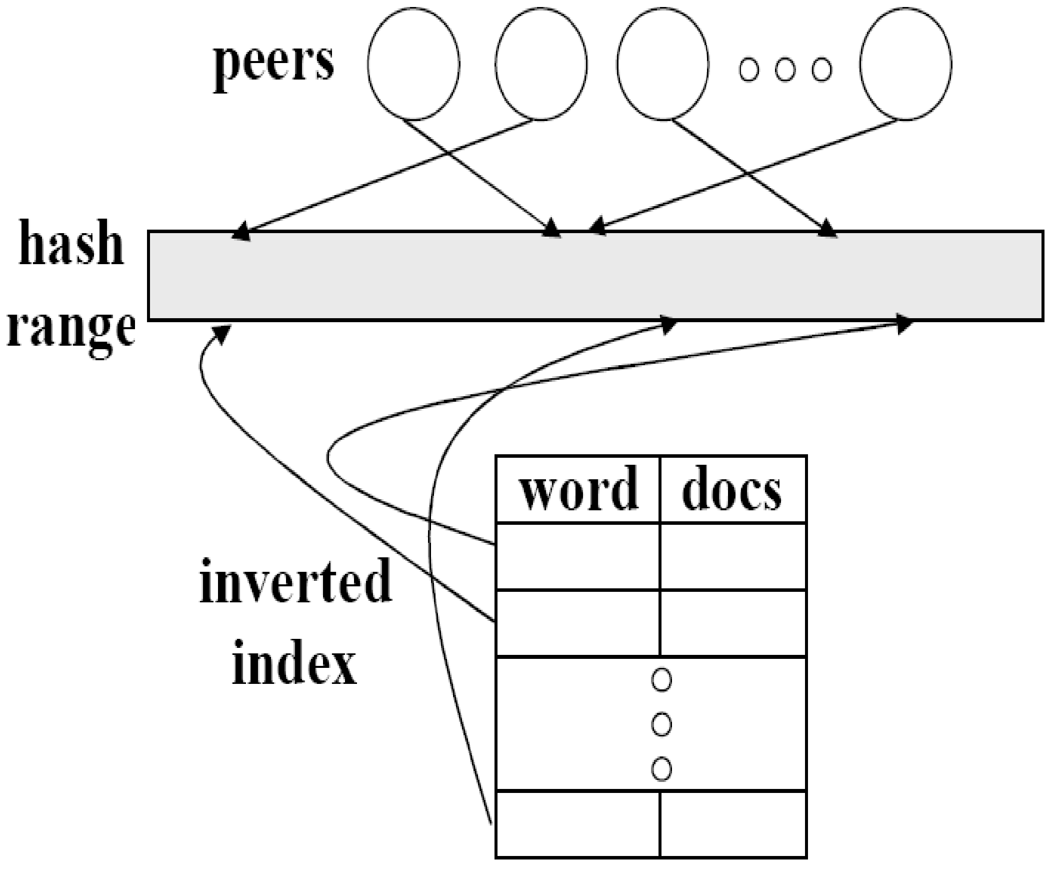
- The DHT abstraction can be implemented in a fairly simple and efficient way
- All implementations are based on a distributed datastructure, a so called “structured overlay”
  - Chord used an ordered ring, with fingers (shortcuts)
- Some remaining issues to consider
  - Can more complex and more flexible applications be implemented such as keyword search (yes)
  - Can the storage or message complexity improved (yes)
  - So, what is the best way to implement a file sharing system?

Keyword search in DHTs

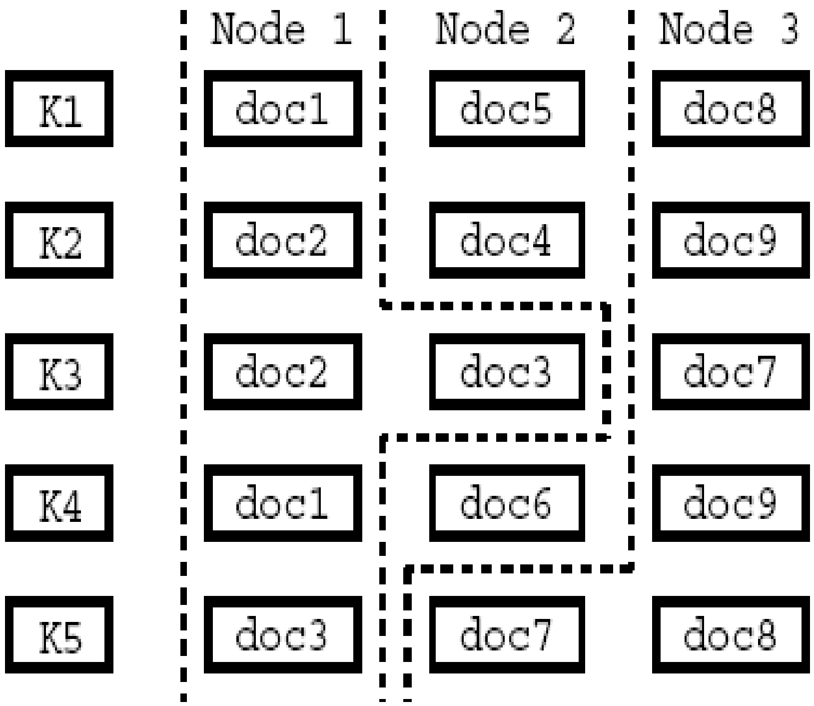
- DHTs support only key lookup by default
- We need to perform complex queries as in unstructured networks
- We need to be creative: here we discuss an inverted index-based approach
  - Document identifiers are stored in a DHT with all contained keywords as keys
  - All keywords are looked up and the intersection of matches is calculated
  - A few techniques to optimize the cost of all this

Inverted index approach

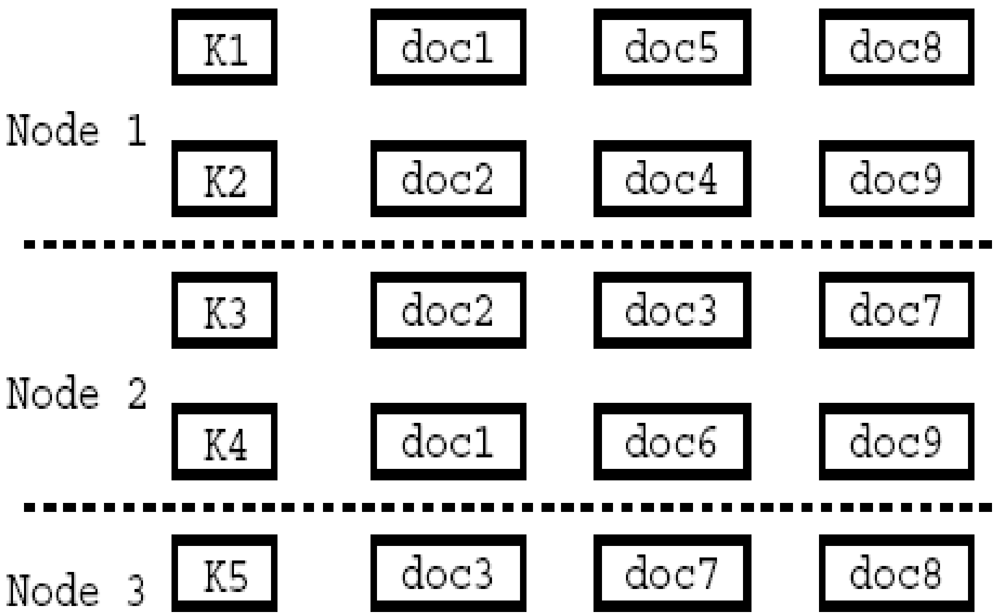
- Inverted index usual in search engines
  - For all keywords collect the documents that contain that keyword
  - Create intersection, union, etc, base on keyword based query
- Do that P2P style



Distributing the inverted indices



Horizontal partitioning



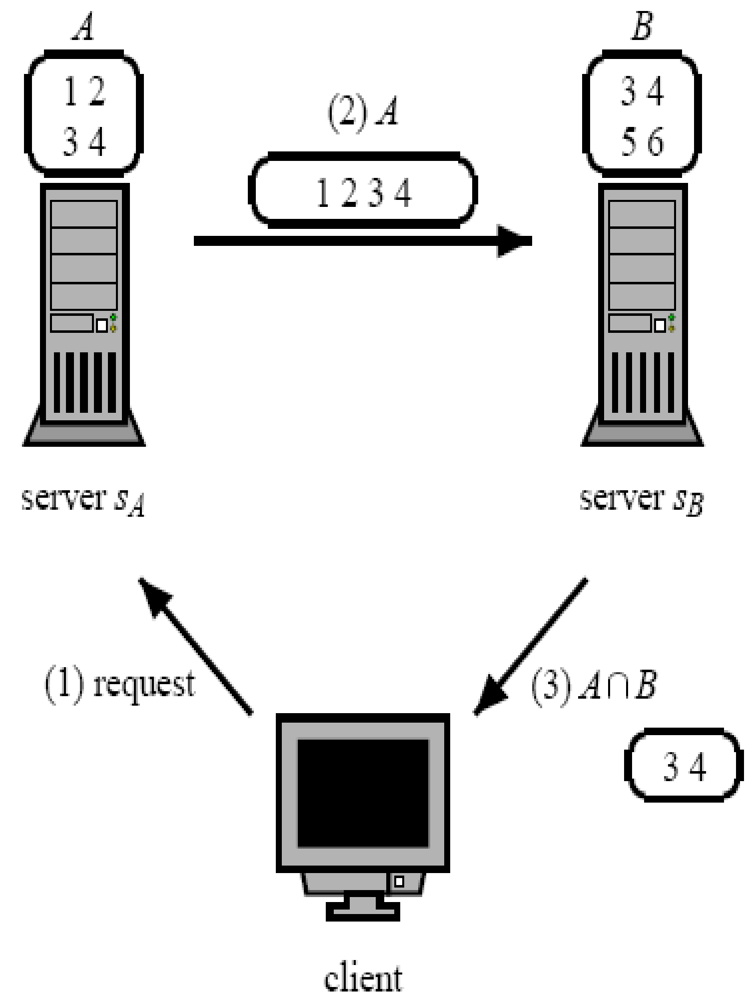
Vertical partitioning

Mainly centralized services
cheap update, expensive lookup

Better if update is rare but
communication is expensive

DHT for storing documents sets

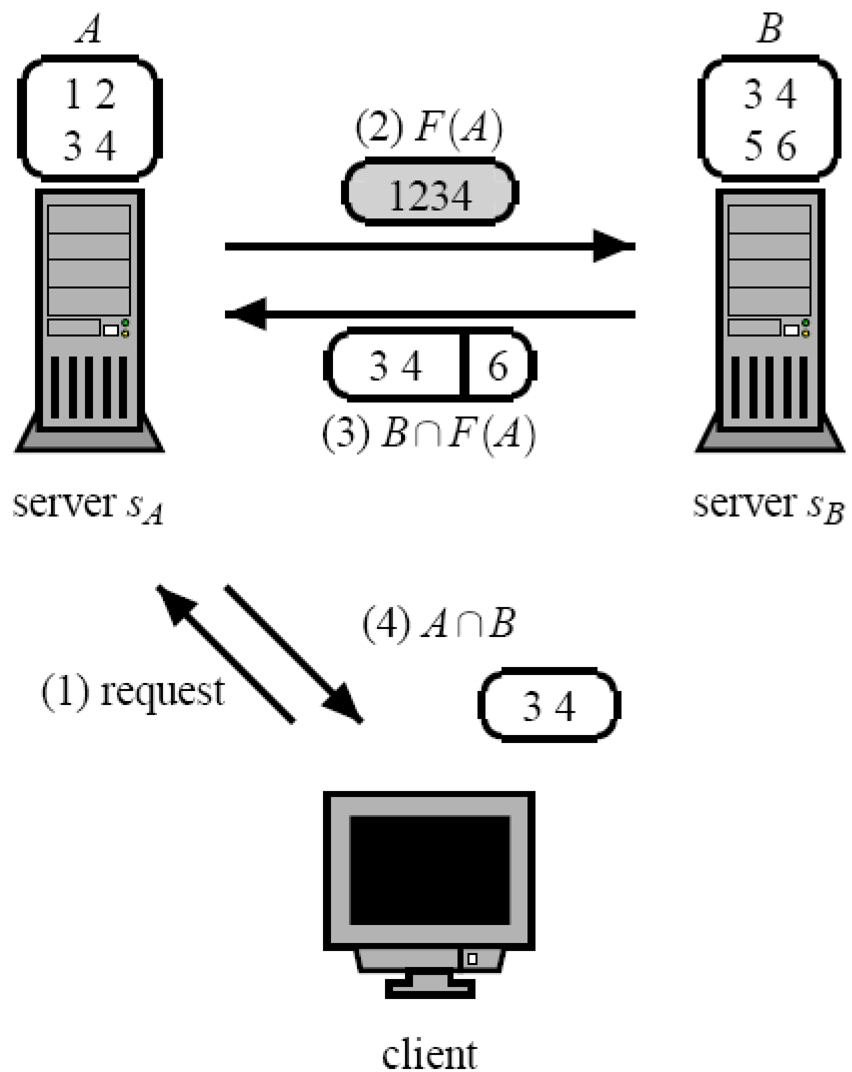
- A DHT is used to map keywords to nodes
  - A node is assigned a set of keywords, and stores sets of pointers to documents that contain the given keyword
- The retreival procedure needs to AND sets
  - Naive procedure shown
    - **Set A on server s_A contains documents that have keyword k_A**



Request is "k_A & k_B"

Optimizations: Bloom filters

- Bloom filter of A is sent to s_B (2)
- s_A removes false positives ("6" in this example)
- It saves bandwidth if set is large enough
  - We use filters for more than 300 elements only
- Smaller set should be visited first (natural thing)
- Works for more keywords too
  - All servers need to see the final result to remove false positives



Optimizations: Caches

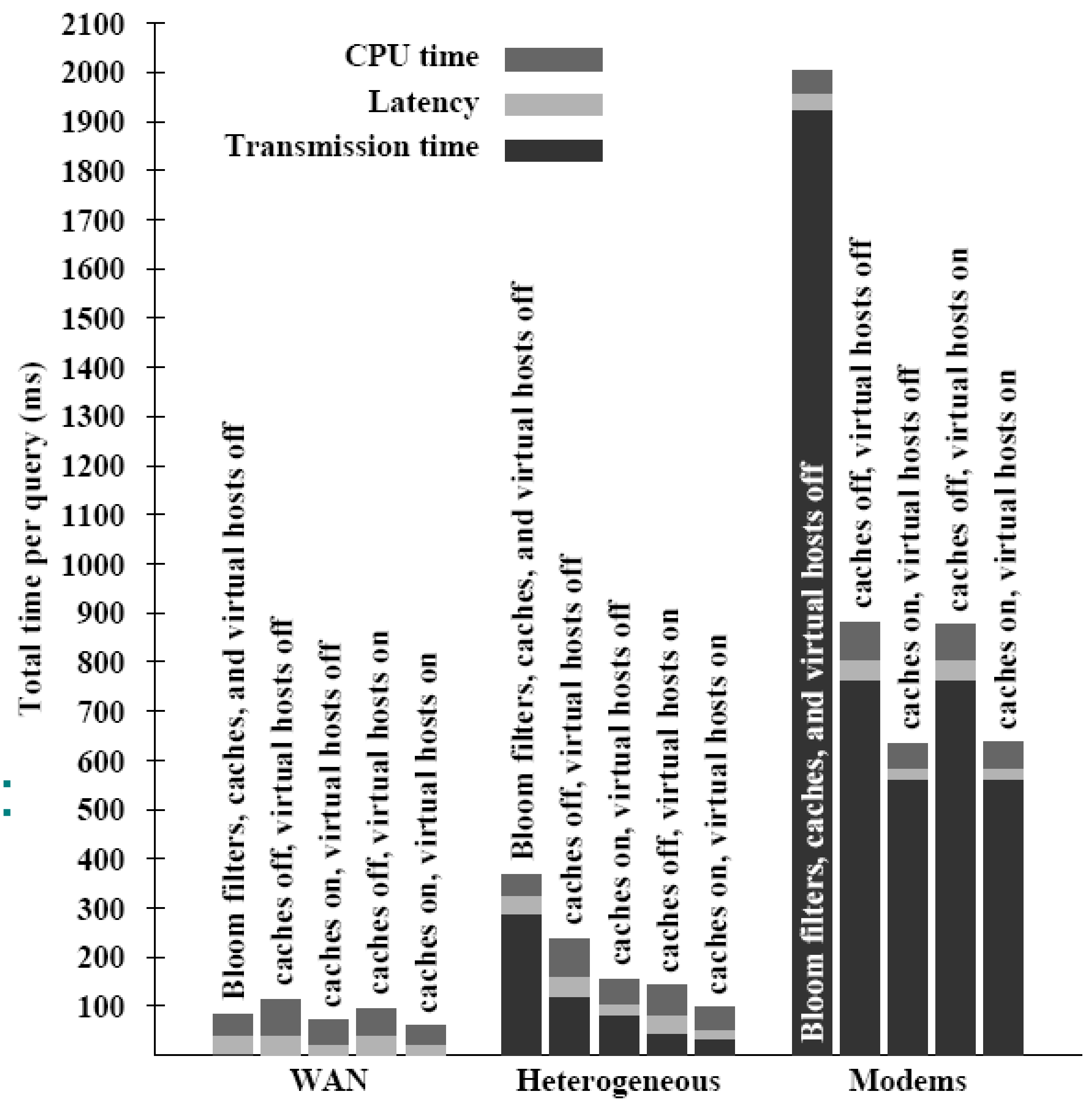
- Bloom filters or unencoded keyword match sets can be cached
  - Some measurements indicate there are very popular keywords (power law distr) so hit rate can be good
- Utilization of caches
  - A server checks if it has cached info on a next keyword to be intersected
  - If yes, performs intersection locally, skips the corresponing server

Optimizations: virtual nodes

- Same idea as in Chord
- Assign virtual nodes proportional to capacity
  - Number of keywords proportional to capacity
  - Variance due to random hashing is reduced (as in Chord)
- Load balancing still a problem
  - Keyword popularity is not equal
    - **Number of keywords is not a good measure, popularity needs to be considered too**

Experiments

- Network types
  - All backbone, all modem, and gnutella trace
- Search trace: IRCache log file
- Parameters
  - Bloom filter threshold 300, Bloom filter size: 18/24 with cache on/off



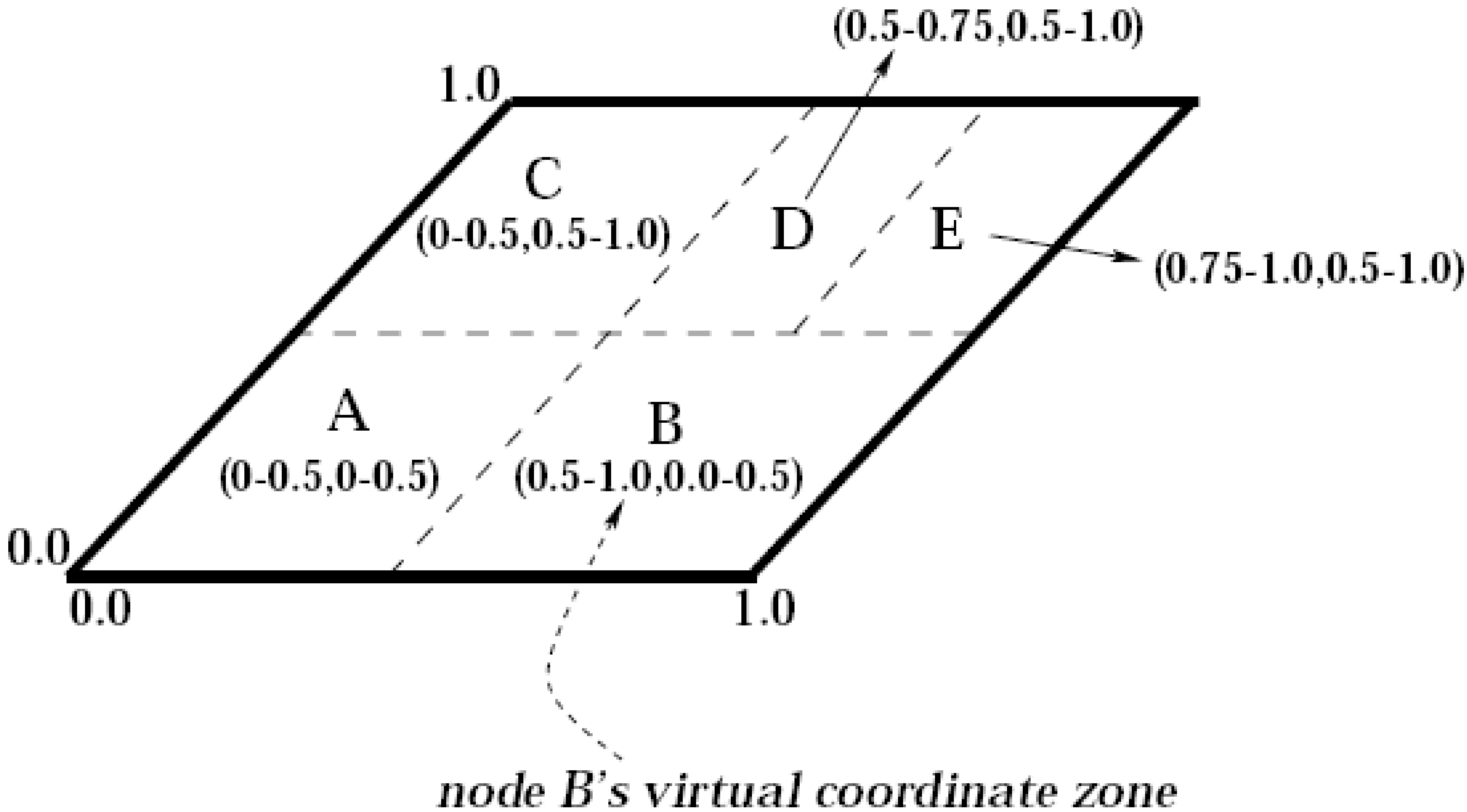
Other DHT designs

- A DHT is an abstraction
  - Eg previous keyword search technique used a generic DHT
- A DHT has many popular implementations, we review two briefly: CAN and Pastry
- Different implementations have different tradeoffs and complexity properties, we review these

Content addressable network (CAN)

- CAN became the name of a specific algorithm, although it is in fact a synonim to DHT
- Logical space to which keys are mapped by a hash function
  - D-dimensional real space $[0,1]^d$
- All nodes are assigned a partition of this space
  - At any point in time the set of current nodes cover the space
- Compare with Chord!
  - Logical space is different; partitioning of this space is implicit (but nevertheless well defined)

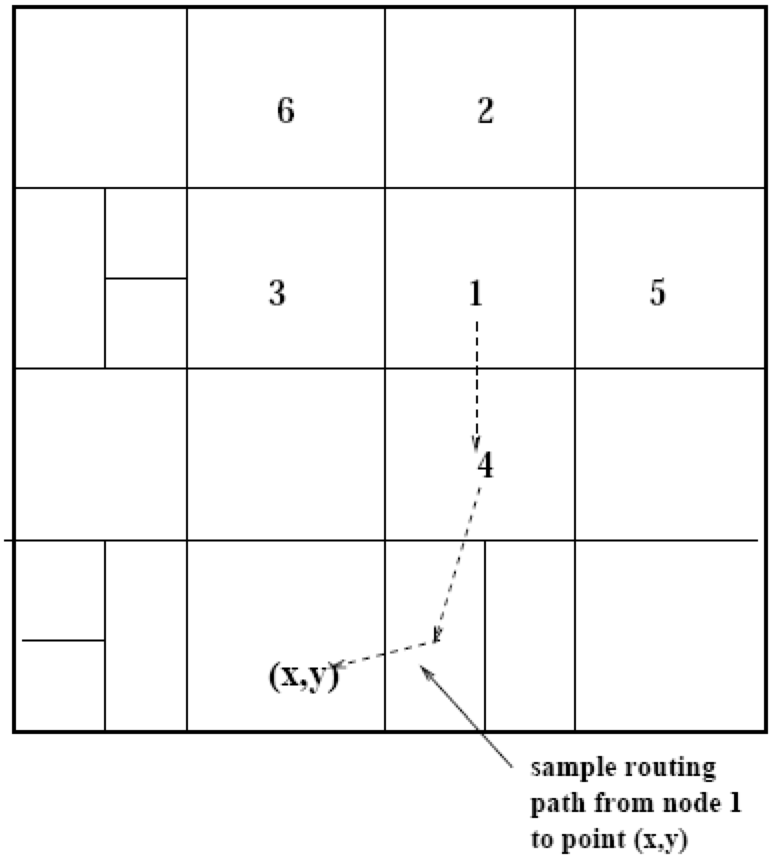
CAN logical space



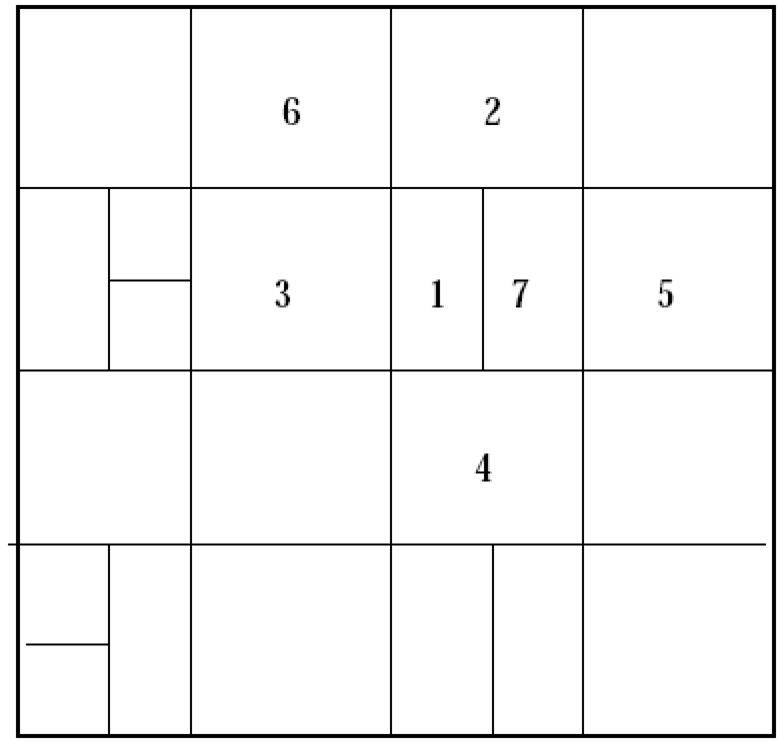
Routing and node join

- Greedy routing to neighbor that is closest to destination
  - Hop count is $O(dN^{1/d})$
  - Number of neighbors is $O(d)$
  - If $d=O(\log N)$, then roughly same as Chord
- Join
  - Create random point in virtual space
  - Find the node that is responsible for that point
  - Split the block of that node and update neighbors appropriately

Node join in CAN



1's coordinate neighbor set = {2,3,4,5}
7's coordinate neighbor set = { }



1's coordinate neighbor set = {2,3,4,7}
7's coordinate neighbor set = {1,2,4,5}

Node departure and recovery

- Failure detection through missing heartbeat
- Neighbors of failed node independently try to take over the zone of the failed node
- The winning node merges the failed zone if possible, or simply holds it if not possible
- Background repair mechanism reassigns zones to prevent fractioning
- Perhaps this is the weakest point of CAN
  - Possibility for incosistency, complex repair and failure handling procedure

Optimizations

- Increasing d
  - Shorter path length, more fault tolerance (more paths) but more neighbors
- More realities
  - Maintain many virtual spaces (CANs) in parallel
  - Replicate stored data on all realities
  - Improves path lengths (jumps inside a node) and fault tolerance (replication, more paths)
- Uniform partitioning: more balanced zone sizes
  - When joining, the selected random node replaces itself with the neighbor with the largest zone

Optimizations

- Improved routing taking proximity into account
  - When selecting a neighbor, use network latency also
- Overloading zones: more nodes in the same zone
  - When joining, zones are not split, only if enough nodes are in the zone
  - Reduces path length (fewer zones)
  - Reduces latency (possibility to select neighbor that has smallest latency)
  - Improved fault tolerance due to redundancy

Pastry: another DHT

- Applies a sorted ring in ID space like Chord
- Virtual space: same as Chord
  - We interpret IDs as sequeces of digits with base 2^b
- Applies Finger-like shortcuts to speed up routing
- The node that is reponsible for a key is the numerically closest (not the successor)
  - Pastry is bidirectional and uses numeric distance

Pastry routing

- If destination is among the leafs, stop
- Otherwise Pastry either forwards the message to a node which
  - has a longer common prefix with the destination or
  - has an equally long prefix but is numerically closer
- Routing is succesful if no L/2 consequtive nodes fail (ring is intact)

NodeId 10233102

Leaf set

SMALLER		LARGER	
10233033	10233021	10233120	10233122
10233001	10233000	10233230	10233232

Routing table

-0-2212102	1	-2-2301203	-3-1203203
0	1-1-301233	1-2-230203	1-3-021022
10-0-31203	10-1-32102	2	10-3-23302
102-0-0230	102-1-1302	102-2-2302	3
1023-0-322	1023-1-000	1023-2-121	3
10233-0-01	1	10233-2-32	
0		102331-2-0	
		2	

Pastry maintenance

- Join
  - Use routing to find numerically closest node already in network
  - Ask state from all nodes on the route and initialize own state
- Error correction
  - Failed leaf node: contact a leaf node on the side of the failed node and add appropriate new neighbor
  - Failed table entry: contact a live entry with same prefix as failed entry until new live entry found, if none found, keep trying with longer prefix table entries

Proximity in Pastry

- All routing table entries are drawn from rather large sets (unlike with Chord)
  - Pastry puts emphasis on optimizing the actual entry based on proximity
  - Entries can be selected based on other criteria as well (semantic proximity, capacity, etc)
- The shorter the common prefix, the larger the set of potential entries (exponentially)
- Original Pastry approach for actually implementing the proximity bias can be improved (not discussed here)

Are Pastry and Chord a different protocol?

- Chord and Pastry are variations of the same idea and can be tranformed into each other smoothly
- What is not different
  - Basic idea: ring + shortcuts to exponentially increasing distance
  - Leaf set/successor list: Chord also uses r successors/predecessors
  - Chord can also use more fingers to achieve the same hop count and model a b letter alphabet ID space
  - Same lazy repair protocol for leafs/successors

Are Pastry and Chord a different protocol?

- What is different?
  - A Chord finger is a unique node, whereas with Pastry a routing table entry can come from a large set
    - **Chord could define fingers more loosely, but that needs a different update protocol for fingers**
  - Chord routing is unidirectional, Pastry is direction independent
    - **Chord could easily be bidirectional too with fingers into two directions**

A final note on complexity

- Chord and Pastry have O(logN) storage and hop count complexity
- CAN have $O(dN^{1/d})$ hop count complexity and O(d) storage
- It is possible to have O(1) storage complexity with O(logN) hop count (Viceroy) or with $O(\log^2 N)$ hop count (Symphony)
  - Sounds good but more complex protocols, less reliability and logN is small enough: is it worth it?

So, how to implement filesharing?

- Get the best of both worlds: hybrid approaches
- Use DHT for rare items, random walk for popular items
- What about the topology of the overlay network?
  - Unstructured networks are easy to build and maintain, and robust to churn
  - Are DHT-s realy more complicated or expensive or less robust? Not necessarily
- We overview two hybrid approaches along the lines above

Gnutella: observing the long tail

- Gnutella (latest version with ultrapeers and dynamic query) is excellent for locating popular items (reliable, fast)
- Gnutella is not so good at locating rare items
  - 41% of queries receive <10 results, 18% none at all
  - Queries that return a single result take 73s on average, and for <10 results, first is 50s on average
  - Very often results are not found that actually exist (eg the 18% failure can be reduced to 6%)
- Lots of room (we knew that) and need (this is new info) for improvement for rare items

Hybrid approach

- Inverted index for popular keywords is
  - expensive to compute (many messages to the responsible node)
  - Expensive to use (the distributed join (ie intersection of matches for keywords in query) is expensive)
- For rare keywords all that is cheap
  - We need to identify rare files and rare keywords and publish those to the DHT
  - When a query has no result for some tome (~30s), we ask the DHT
  - Rarity can be determined by seeing a file in a small result set, and by other heuristics

Another kind of hybrid

- Common wisdom
  - Structured overlays are more expensive and less robust to churn and failures
- Is this true?
  - Comparison is very difficult: too many factors, not clear how to be fair
  - But there are indications it is NOT necessarily true
- If it is indeed not true, they are actually (much) better to support “unstructured” search algorithms, such as flooding and random walks

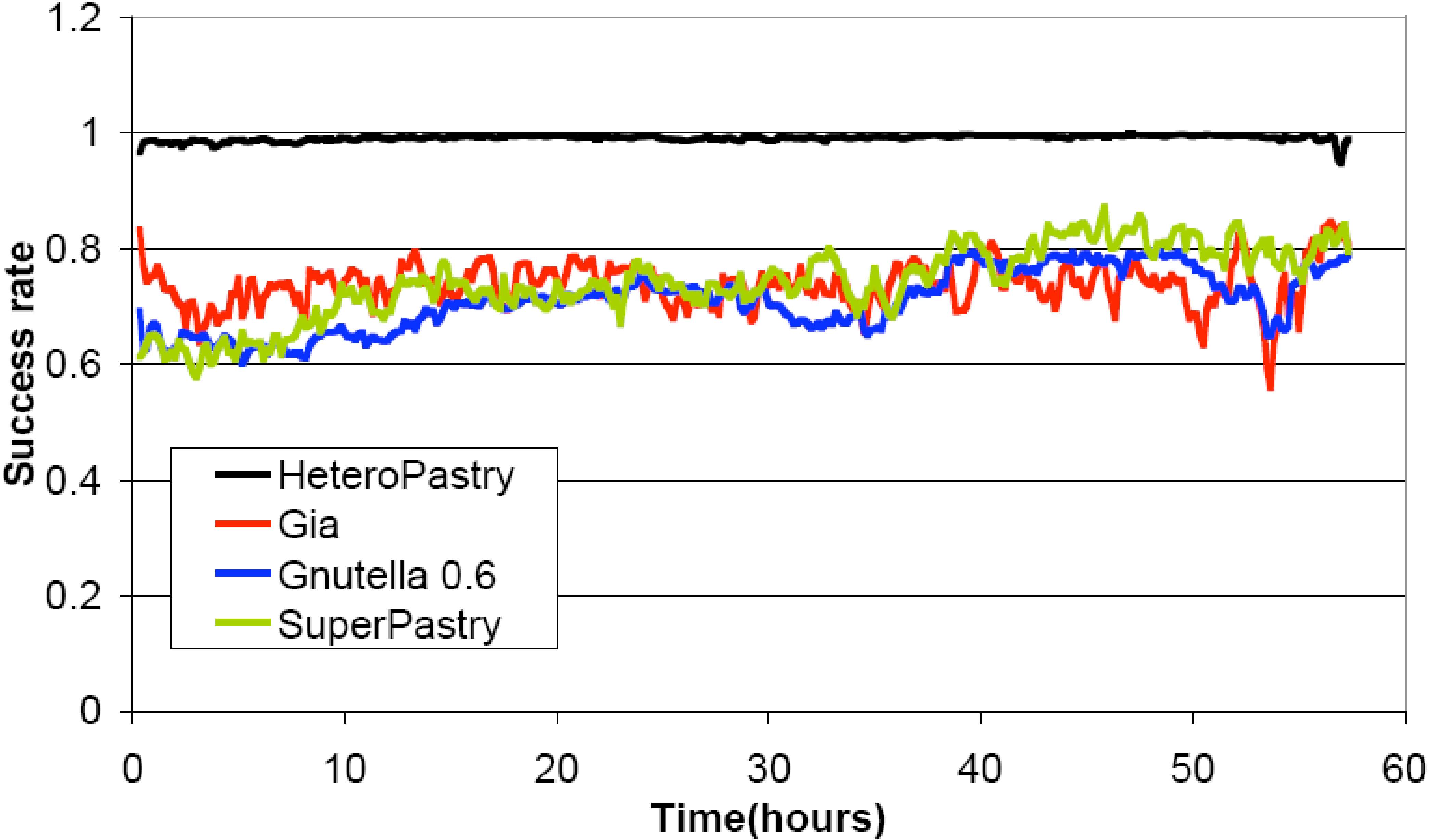
Busting a myth?

- On some real traces maintenance cost of MS Pastry appears to be better than that of Gnutella
  - Heartbeat messages only to one node: the left neighbor in ring (as opposed to gnutella)
- Heterogeneity can also be captured
  - Super Pastry: similar to Gnutella, but ultrapeers form a Pastry network
  - Hetero Pastry: similar to GIA: routing table entries are optimized to prefer high capacity nodes, and a bound on the in-degree can also be set
  - Maintenance overhead is still fine here

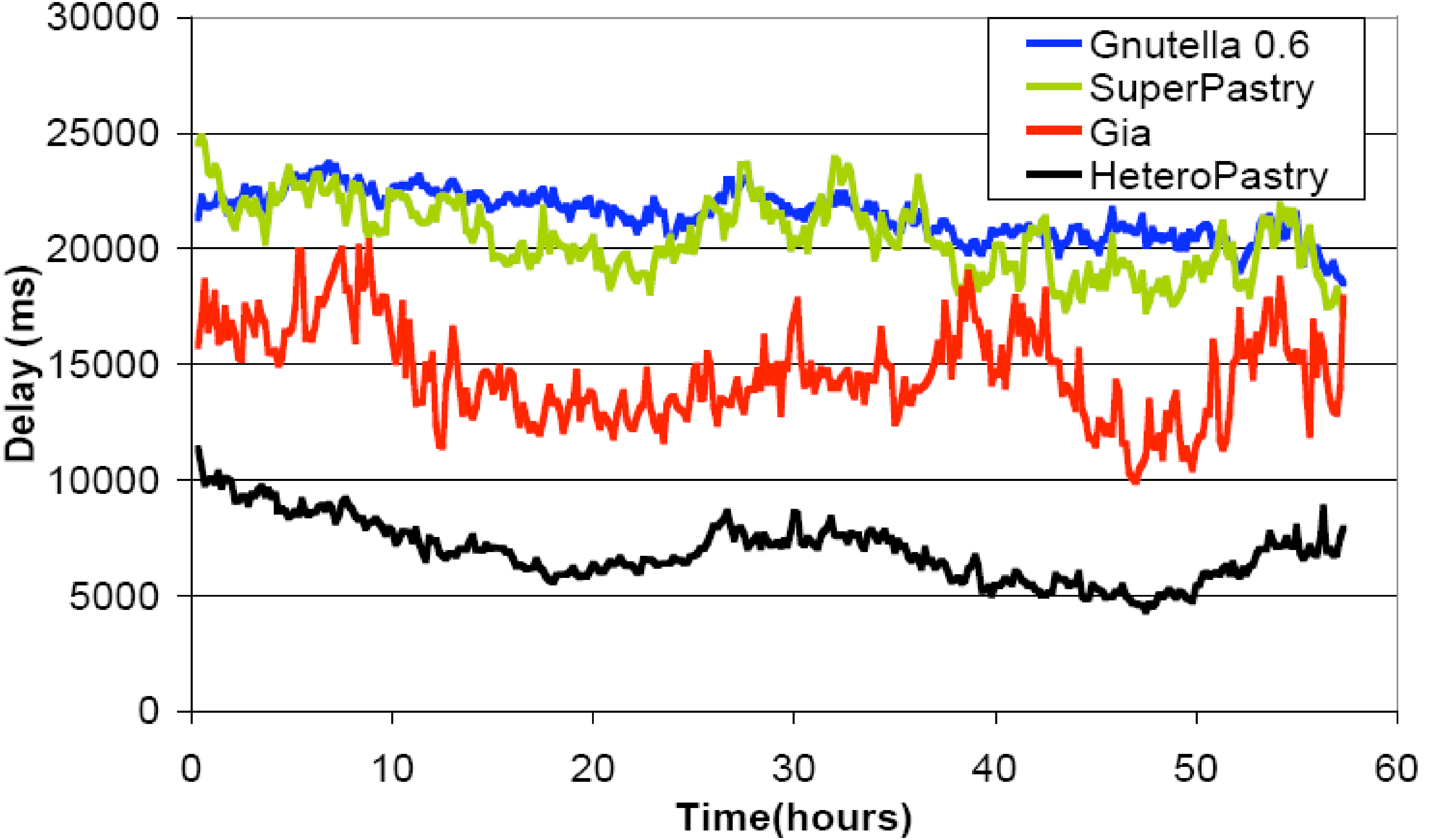
Flooding and random walk in structured networks

- Exploiting the structure of the overlay, broadcast can be optimized to have almost no wasted traffic
- Restricted flooding: a given number of nodes can be visited effectively in parallel
  - Same mechanism for random walk: sequential instead of parallel traversial
- Compare some algorithms
  - using an eDonkey trace
  - max 128 node random walk, one hop replication in all cases (in Pastry, on routing table entries)

Experimental results



Experimental results



Conclusions

- DHTs are an alternative to support search
  - They are very efficient
  - They support key based lookup but
  - They can be adapted to support more complex queries as well
- Restricted flooding and random walk is still better for not-so-rare items
- Hybrid approcahes
  - Use DHT for rare items only
  - Use structured network to support flooding-style queries instead of random network

Some refs

- Papers this presentation used material from

  - Miguel Castro, Manuel Costa, and Antony Rowstron. Peer-to-peer overlays: structured, unstructured, or both?. Technical Report MSR-TR-2004-73, Microsoft Research, Cambridge, UK, 2004.
  - Boon Thau Loo, Ryan Huebsch, Ion Stoica, and Joseph M. Hellerstein. The case for a hybrid P2P search infrastructure. In Proceedings of the 3rd International Workshop on Peer-to-Peer Systems (IPTPS'04), San Diego, CA, USA, 2004.
  - Patrick Reynolds and Amin Vahdat. Efficient peer-to-peer keyword searching. In Middleware 2003, volume 2672 of Lecture Notes in Computer Science, pages 21–40. Springer-Verlag, 2003.
  - Sylvia Ratnasamy, Paul Francis, Mark Handley, Richard Karp, and Scott Schenker. A scalable content-addressable network. In Proceedings of the 2001 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications (SIGCOMM), pages 161–172, San Diego, CA, 2001. ACM, ACM Press.
  - Antony Rowstron and Peter Druschel. Pastry: Scalable, decentralized object location and routing for large-scale peer-to-peer systems. In Rachid Guerraoui, editor, Middleware 2001, volume 2218 of Lecture Notes in Computer Science, pages 329–350. Springer-Verlag, 2001.
  - Ion Stoica, Robert Morris, David Karger, M. Frans Kaashoek, and Hari Balakrishnan. Chord: A scalable peer-to-peer lookup service for internet applications. In Proceedings of the 2001 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications (SIGCOMM), pages 149–160, San Diego, CA, 2001. ACM, ACM Press.

- http://www.inf.u-szeged.hu/~jelasity/p2p/