Attack-Resistant Peer-To-Peer Networks

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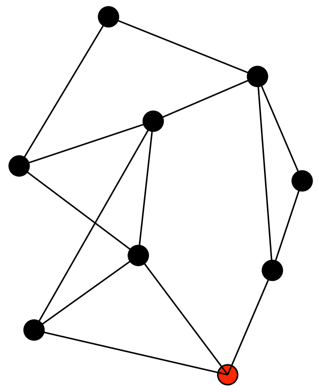
What is Peer-to-Peer(P2P)?

Distributed network for sharing content (music, video, software, etc.) where each machine acts as both a server and a client

- Napster, Gnutella, Morpheus, Kazaa, Audiogalaxy, iMesh, Madster, FreeNet, Publius, Freehaven, SETI@Home, NetBatch, MBone, Groove, NextPage, Reptile, Yaga, etc., etc.
- Why the Excitement?
  - Pool Vast Resources
  - Dynamic Search
  - Anonymity

Gnutella: A Typical P2P System

Overlay network: Link from peer x to peer y in overlay network means x knows the IP-address of y



Gnutella Protocol:

- A new peer decides on its own which other peers to link to in the overlay network and what content to store
- Search requests are broadcast to all peers within some fixed number of hops in the overlay network

P2P Design

Focus on providing efficient access to content across network so:

- Topology of overlay matters
- Where content is stored matters
- Search protocol matters

Gnutella's design decisions give

- Poor Performance - due to search broadcasts
- Poor Reliability - due to ad hoc topology and content storage

Design decisions have big implications for performance *and* reliability.

Our Research

Current P2P

- Many deployed systems have poor performance (efficiency and scalability)
- No systems have both good performance and attack-resistance

Our Research: P2P systems which have

- Attack-Resistance
- Good Performance

Why Attack-Resistance?

Content is vulnerable to

- Attack by malicious agents
- Censorship by states and corporations
- Loss due to system faults

Key Point:

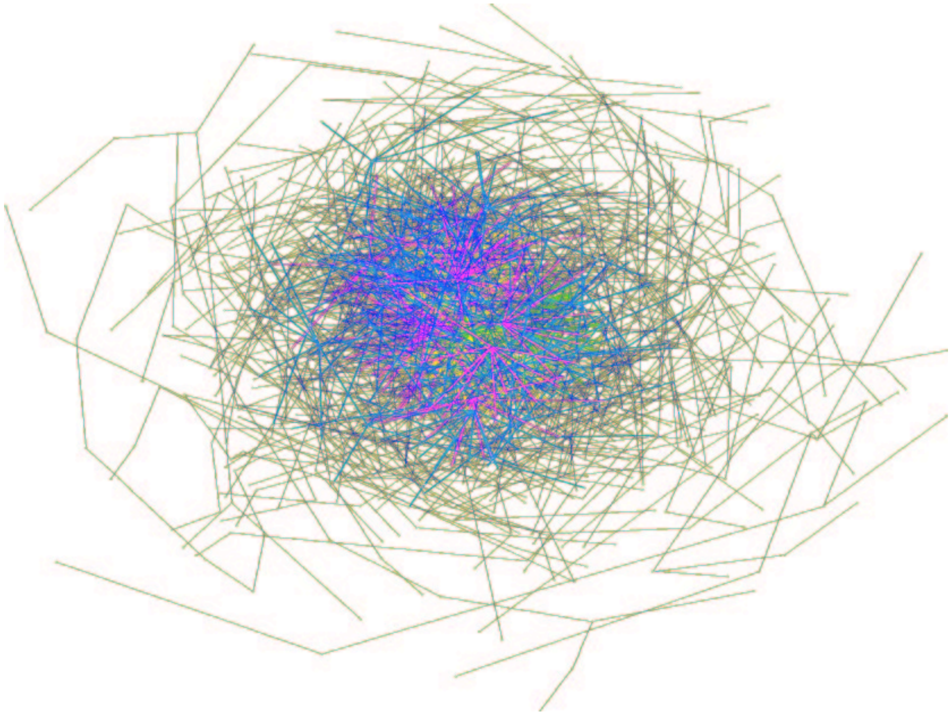
- Single peer has limited technical and legal resources

Current P2P is not Attack-Resistant

Examples:

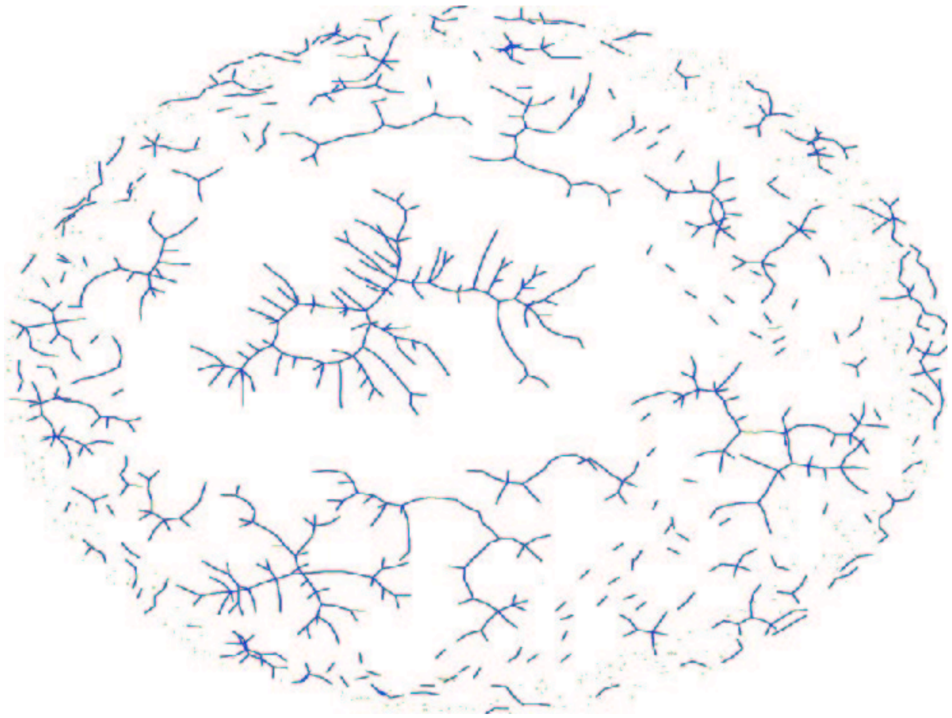
- Napster shut down by attacks on central server
- Flatplanet has launched successful spam attack on Gnutella
- Removal of a few peers will shatter Gnutella[SGG, 2002]

Gnutella is Vulnerable



Snapshot of Gnutella February, 2001 (1800 peers)[SGG]

Gnutella is Vulnerable



Same Network (1800 peers) after deleting 63 peers[SGG]

Can we do better?

Reasons for hope:

- P2p networks have many, many peers
- Lots of flexibility in design of network

Our Contributions

- First P2P networks provably robust to massive targetted attack by
  - *Fail-stop faults* - Deletion Resistant Network (DRN)
  - *Byzantine faults* - Control Resistant Network (CRN)
- Both networks are scalable and efficient in terms of time and space

Attack-Resistant Property (DRN)

After deletion of *any* 2/3 fraction of the peers,
99% of the remaining peers can access 99% of the data items.

Performance

This would be simple if we didn't care about performance!

Naive System:

- Topology is fully connected
- Data Items are stored everywhere
- Insertion by broadcast to all nodes

Performance

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Naive System:

- Topology is fully connected
- Data Items are stored everywhere
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Our System:

- Pick a robust topology with small maximum degree
- Pick a data replication strategy that balances availability with storage overhead
- Pick a routing protocol that is efficient but redundant enough

Example Result (DRN)

After deletion of *any* 2/3 fraction of the peers,
99% of the remaining peers can access 99% of the data items.

Resource Bounds (n peers, $O(n)$ data items):

- $O(\log n)$ storage per peer
- Search takes $O(\log n)$ time
- Search takes $O(\log^2 n)$ messages

Related Work

Network	Storage Per Peer	Search Time	Search Messages	Deletion Resistant?	Control Resistant?
CRN[FS]	$O(\log n)$	$O(\log n)$	$O(\log^2 n)$	Yes	Yes
DRN[FS]	$O(\log n)$	$O(\log n)$	$O(\log^2 n)$	Yes	No
Chord[SMK+]	$O(\log n)$	$O(\log n)$	$O(\log n)$	No	No
CAN[RFH+]	$O(\log n)$	$O(\log n)$	$O(\log n)$	No	No
Tapestry[KBC+]	$O(\log n)$	$O(\log n)$	$O(\log n)$	No	No

Deletion Resistant? = Resistant to Deletion Attacks?
Control Resistant? = Resistant to Control Attacks?

Outline

- Description of DRN
- Theorems for DRN and CRN and overview of proofs
- Dynamic Attack-Resistance Results
- Conclusion and Future Work

DRN Description

Best Resource Bounds:

- $O(\log n)$ search time
- $O(\log^2 n)$ messages per search
- $O(\log n)$ storage per peer

This Talk:

- $O(\log n)$ search time
- $O(\log^3 n)$ messages per search
- $O(\log^2 n)$ storage per peer

Designing a P2P System

Must Specify:

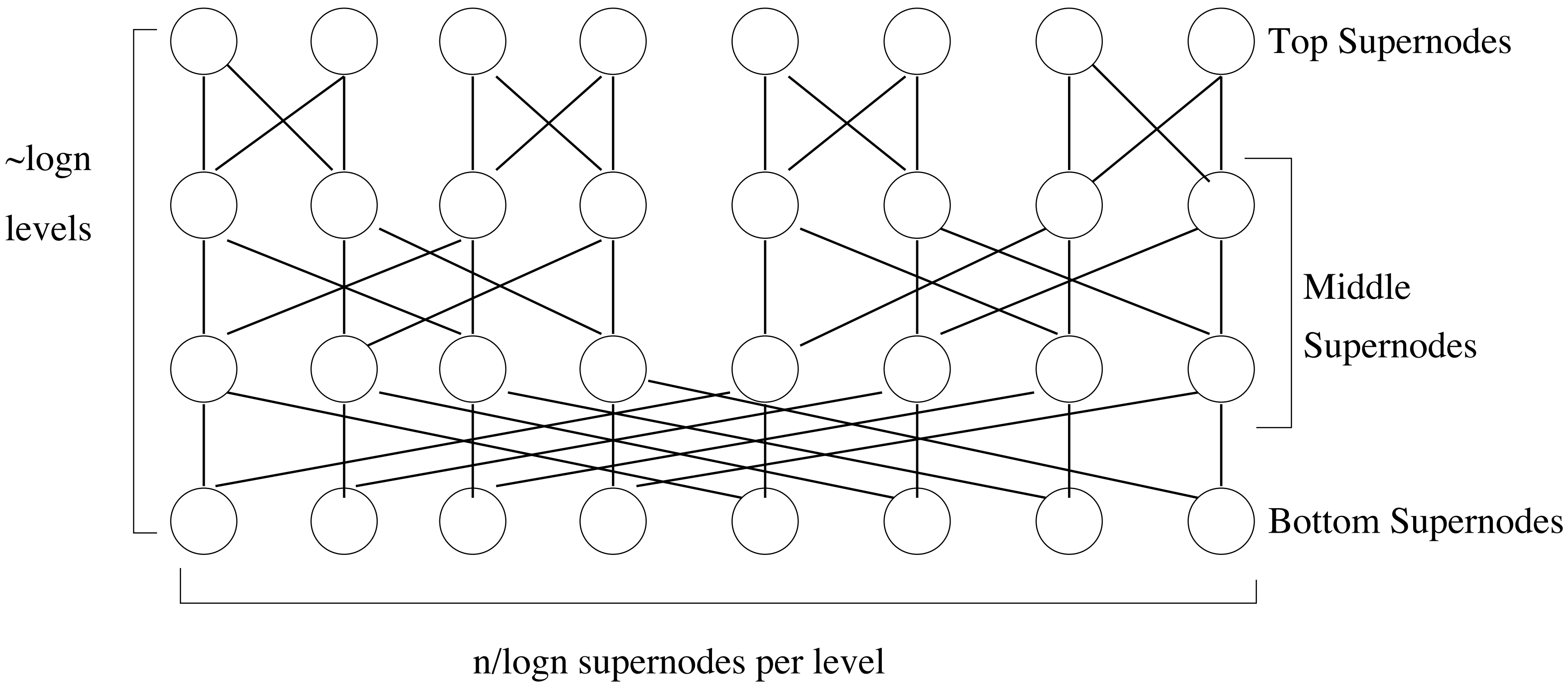
- Overlay topology
- Where to store content
- Protocol for accessing content

DRN Topology

Topology based on the butterfly network (constant degree version of hypercube)

- Each vertex of butterfly is called a *supernode*
- Each supernode represents a set of peers
- Each peer is in multiple supernodes

DRN Topology

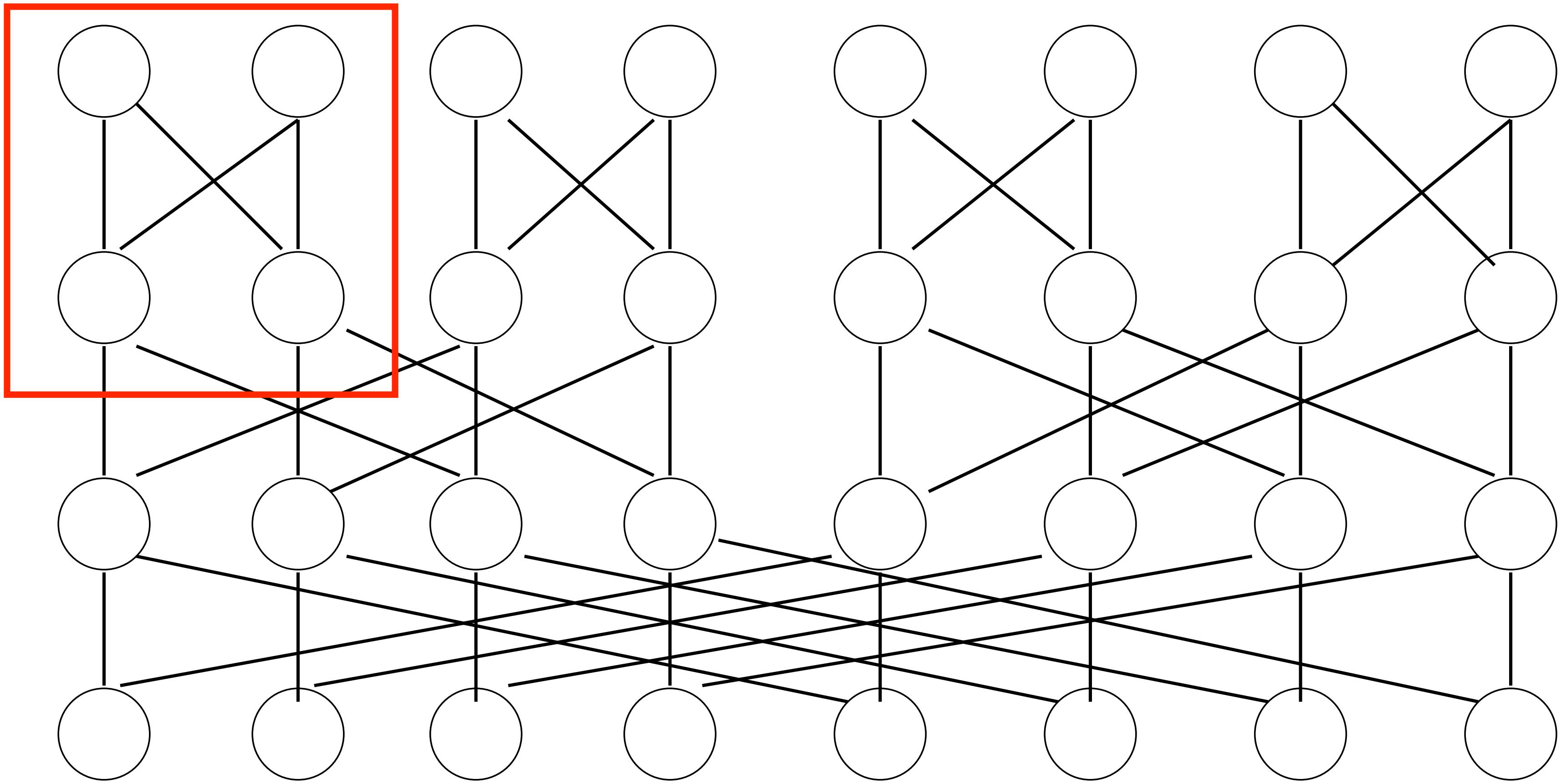


Unique path from every top supernode to every bottom supernode.

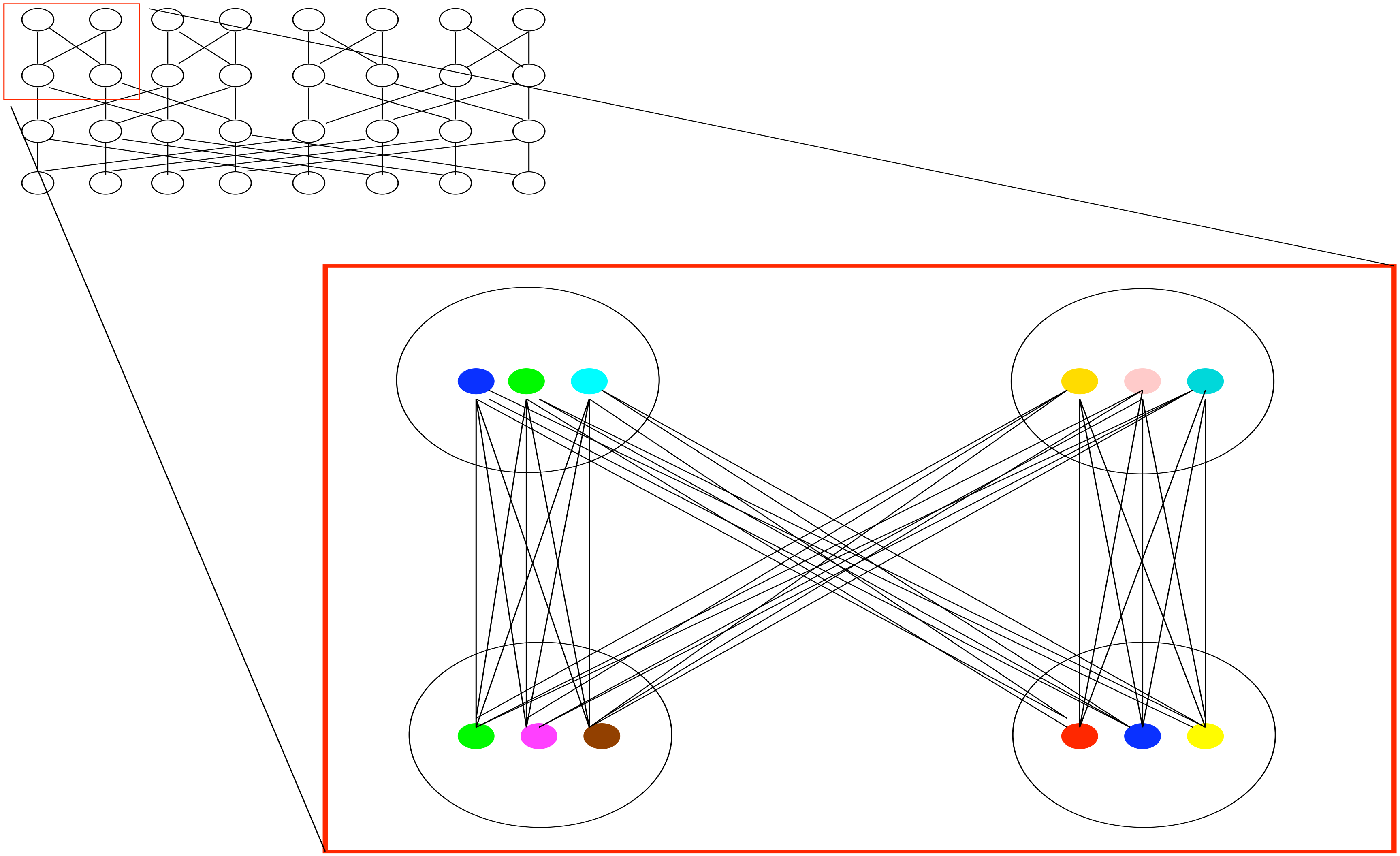
DRN Topology

- n peers, n supernodes
- Each peer participates in $C \log n$ supernodes chosen randomly from set of all supernodes
- Supernode X connected to supernode Y in butterfly means all peers in X connected to all peers in Y.

DRN Topology



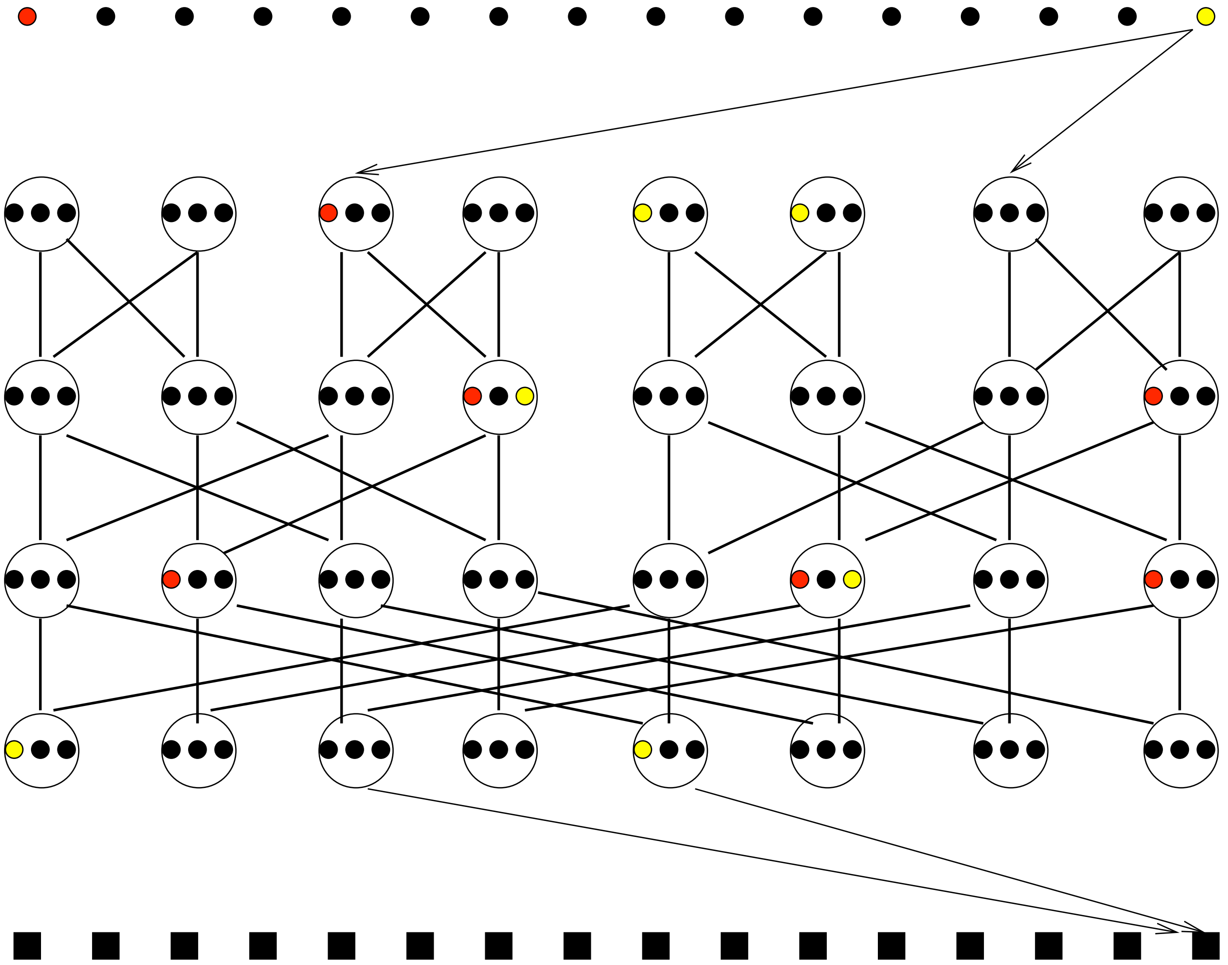
DRN Topology



DRN Topology

- Each peer connected to all peers of T random top supernodes
- Each data item is stored on all peers in B random bottom supernodes
- Each peer participates in $C \log n$ supernodes chosen randomly from set of all supernodes
- T,B and C depend on fault tolerant parameters

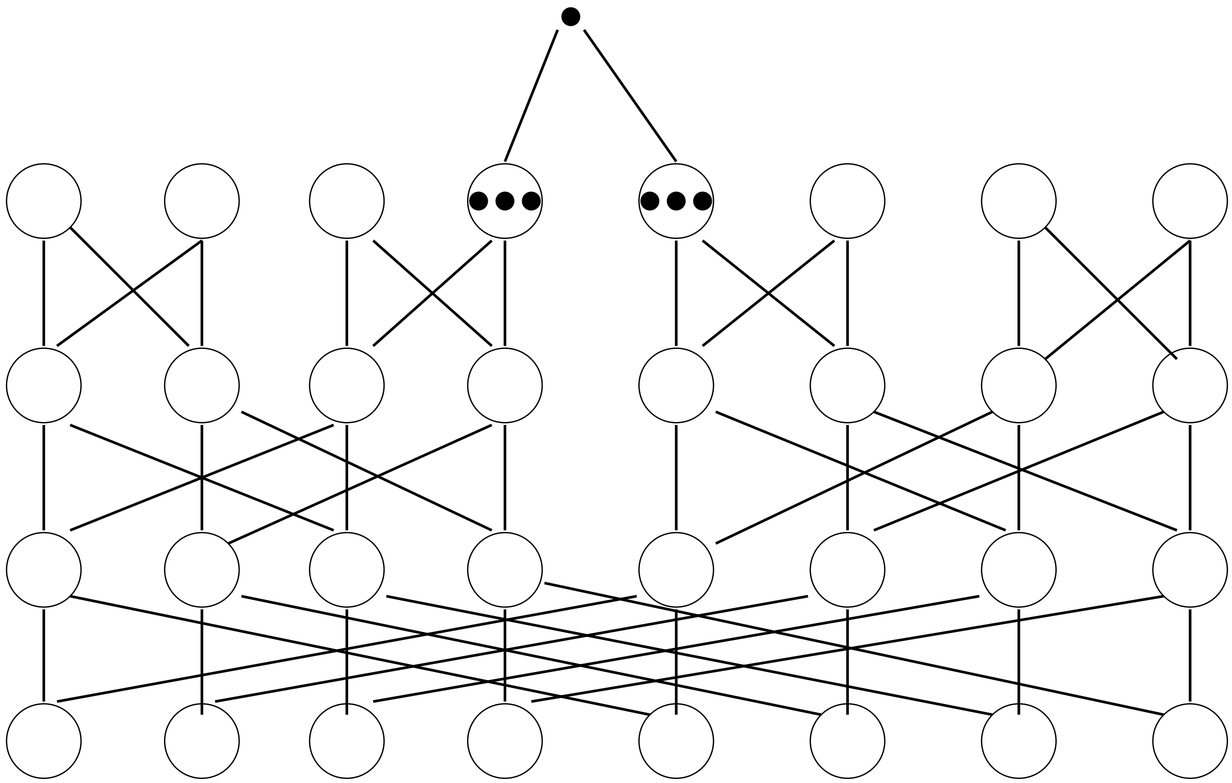
DRN Topology



n peers

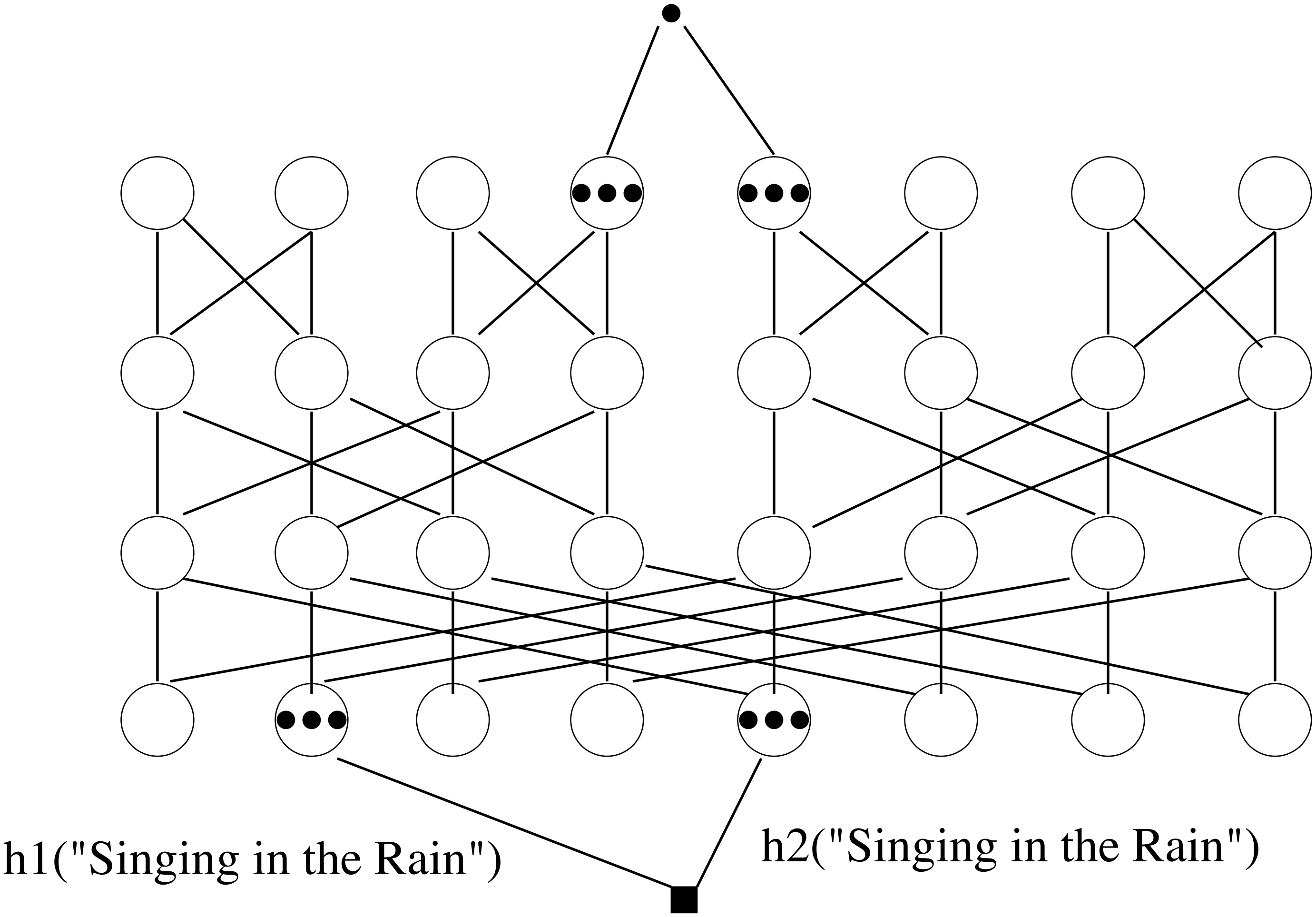
n data items

DRN Searches

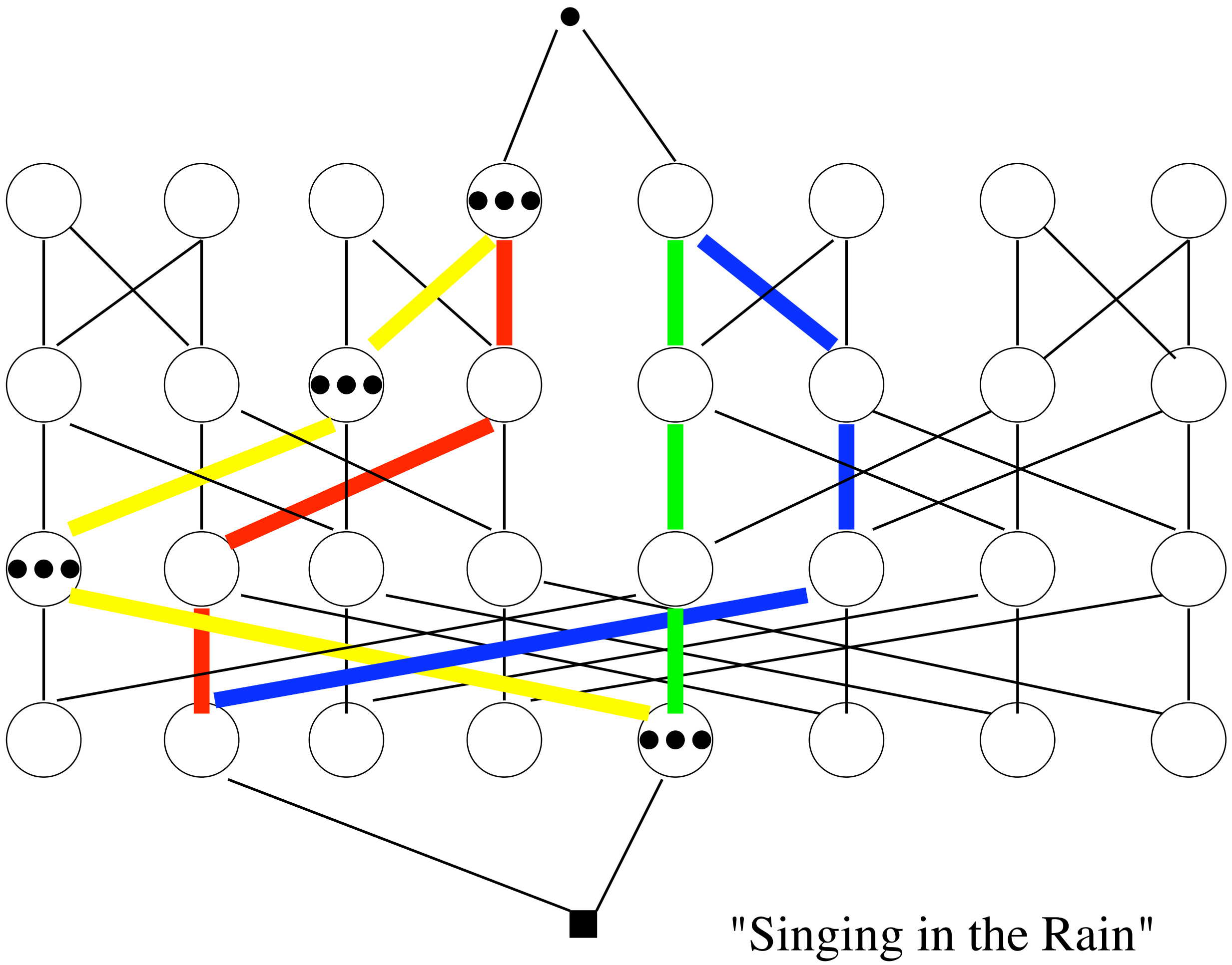


■ "Singing in the Rain"

DRN Searches



DRN Searches



"Singing in the Rain"

DRN Searches from v for d

- Hash “title” to get B target bottom supernodes
- Send request to peers in all top supernodes v connects to
- In parallel, for each path between a top supernode t which v connects to and a bottom supernode b where d is stored do:
  - Send request from t to b in the butterfly:
    - ∗ Each peer sends request down to all peers in the supernode below it
  - return d from b to t along same path
    - ∗ Each peer passes up content to all peers in the supernode above it

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Deletion Resistant Network (DRN)

Theorem 1 *For any fixed* $\alpha < 1$, $\epsilon > 0$, *there is a DRN over* n *peers accessing* $O(n)$ *data items with the property that:*

After deletion of any set of αn *peers, a* $(1 - \epsilon)$ *fraction of the remaining peers can access a* $(1 - \epsilon)$ *fraction of the original data items.*

Example: After deletion of *any* 2/3 fraction of the peers, 99% of the remaining peers can access 99% of the data items.

Proof Sketch

Theorem 1 *For any fixed* $\alpha < 1$, $\epsilon > 0$, *there is a DRN network for* n *peers, accessing* $O(n)$ *data items such that:*

After deletion of any set of αn *peers, a* $(1 - \epsilon)$ *fraction of the remaining peers can access a* $(1 - \epsilon)$ *fraction of the original data items.*

- Critically rely on random assignment of:
  - peers to supernodes
  - peers to top supernodes
  - data items to bottom supernodes
- Use the Probabilistic Method

Proof Sketch

Definitions:

- A supernode is *good* if it has one live peer.
- A path is *good* if it contains all good supernodes

Lemma 1: A good path enables secure communication

Proof Sketch

Definitions:

- A supernode is *good* if less than half its peers are controlled by adversary.
- A path is *good* if it contains all good supernodes

Lemma 1: A good path enables secure communication

Lemma 2: After adversarial attack, all but $\epsilon n / \log n$ supernodes are good

Proof Sketch

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Lemma 3: All but an ϵ fraction of the paths are good

Proof Sketch

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Lemma 1: A good path enables secure communication

Lemma 2: After adversarial attack, all but $\epsilon n / \log n$ supernodes are good

Lemma 3: All but an ϵ fraction of the paths are good

These Lemmas Imply:

$(1 - \epsilon)$ fraction of remaining peers can access $(1 - \epsilon)$ fraction of the data items

Control Resistant Network (CRN)

Theorem 2 *For any fixed* $\alpha < 1/2$, $\epsilon > 0$, *there is a CRN network for* n *peers, accessing* $O(n)$ *data items such that:*

Even if adversary controls any set of αn *peers,* $(1-\epsilon)$ *fraction of the remaining peers can access* $(1-\epsilon)$ *fraction of the* true *data items.*

Even if adversary *controls* 1/3 of the peers, 99% of the peers can access 99% of the *true* data items.

Adversary has *complete* knowledge of the system. Knows topology of network and where all data items are stored.

CRN is “Spam Resistant”

Assume:

- All true data items are stored in the network
- Adversary takes over 1/3 of the peers
- Adversary uses these peers to send “fake” messages instead of what was requested

Then it’s still the case that

- 99% of the remaining peers can access 99% of the true data items

Overview of CRN

Key change for searches:

- Each peer only passes along a message if it received that message from a majority of its neighboring peers.

Key ideas for proof:

- Call a supernode *good* if a majority of its peers are not faulty
- Call a path good if all its supernodes are good

- *Lemma 1*: A good path enables secure communication
- *Lemma 2*: After adversarial attack, all but $\epsilon n / \log n$ supernodes are good

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Dynamic Attack-Resistance

The Problem

- DRN is robust only to a static attack
- If all the original peers are attacked, the networks fails, even if many new peers have joined

What do we want?

- Adversary can delete all the original peers, if enough new peers join
- Must have as many new peers join as are deleted

Dynamic Attack-Resistance

The Result [Saia, Fiat, Gribble, Karlin and Saroiu]

Assume:

- Always storing $O(n)$ data items
- Each joining peer knows one random peer in network
- In any fixed time interval, more peers join the network than are deleted

What do we get?

- At any time, 99% of the live peers in the network can access 99% of the content

Contributions

- First P2P networks provably robust to targetted attack by
  - Fail-stop faults
  - Byzantine faults
- Time and space resource bounds for both networks are competitive with other networks which are not provably attack-resistant

Future Work (1/2)

- Empirical Evaluation of DRN and CRN
- Restraining “Free Riders”
  - Given: a rule for peer behavior such as, “For every 10 search requests issued by a peer, the peer must service 1 search request”
  - Problem: Enforce that rule for most peers in the network in the face of massive Byzantine faults

Future Work (2/2)

Robustness in Networks of Embedded Systems

- Embedded networks are inherently peer-to-peer
- Severely constrained resources
- Focused tasks
- Fault tolerance is crucial

Data Insertion

Data Insertion

- Peer performs search and sends data with the search
- Store data at the bottom supernodes in the search
- This insertion fails with small constant probability

Peer Insertion

Peer Insertion

- Peer copies links to top supernodes of some other peer
- Takes $O(\log n)$ time
- Peer does searches from these top supernodes
- This insertion does not increase resiliancy of CAN

Distributed Creation of CRN

Creation requires n broadcasts or transmission of n^2 messages.

- Each peer hashes its IP-address to get a set of $C \log n$ supernodes to which it belongs
- Each peer broadcasts a message containing identifiers of these supernodes
- Each peer receives messages from other peers giving supernodes to which they belong
- If some other peer belongs to a neighboring supernode, a link is formed to that peer

Dynamically Fault-Tolerant CAN

Assumptions:

- Start with a network on n peers
- Number of items indexed is fixed
- Each joining peer knows one random "good" peer

Definitions:

- An *adversary is limited* if for some $\gamma > 0, \delta > \gamma$, at least δn peers join the network in any time interval when adversary deletes γn peers.
- A CAN is ϵ-*robust* at some particular time if all but an ϵ fraction of the peers can access all but an ϵ fraction of the content.
- A CAN is ϵ-*dynamically fault tolerant* if, WHP, the CAN is always ϵ-robust during period when a limited adversary deletes number of peers polynomial in n.

Dynamically Fault-Tolerant CAN

Result: For any $\epsilon > 0$, $\gamma < 1$ and $\delta > \gamma + \epsilon$, we give a ϵ-dynamically fault-tolerant CAN:

- CAN is ϵ-robust assuming δn peers added whenever γn peers deleted.
- Search takes $O(\log n)$ time and $O(\log^3 n)$ messages
- Every peer maintains pointers to $O(\log^3 n)$ other peers
- Every peer stores $O(\log n)$ data items
- Peer insertion takes $O(\log n)$ time

Related Work - Robustness

- Robust File Systems: Publius[WRC], Alon et al.[AKKMS]
- Quorum systems[MRW,MRWW]. A robust way to read and write to a shared variable.
- For strongly robust versions of these systems, search takes $\Omega(n)$ time.

The Constants

- Search takes $\log n$ hops
- Tradeoffs for other constants (e.g. choosing higher constant for storage gives lower constant for messages sent)
- "Typical" values for these constants (i.e. number of messages and storage) are currently in the 100's.

Reducing the constants (for number of messages sent and storage)

- Proof of Concept
- Currently Have Large Constants to Make Proof Easier
- Decrease in Constants for Expander Graphs Will Decrease Our Constants
- In Practice, May Still Get Very Strong Robustness Even With Smaller Constants than Are Required By Our Proofs.

Improving the Bounds

For Theoreticians Only

- $O(\log n)$ pointers per peer
- $O(\log n)$ time per search
- $O(\log^2 n)$ messages per search

To get these bounds, connect supernodes with expander graphs rather than complete graphs.