KIRA – Scalable ID-based Routing Architecture for Control Planes

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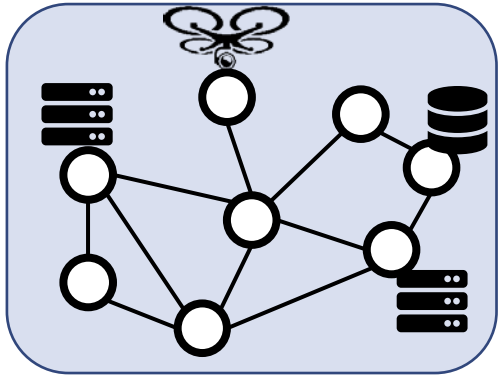
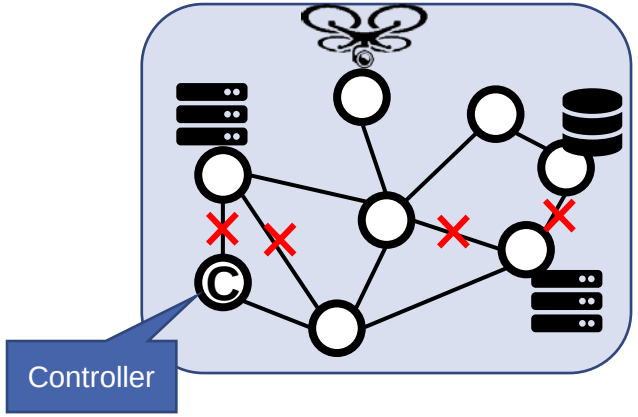
What KIRA aims at…

Interconnects a Large Pool of Networked Resources

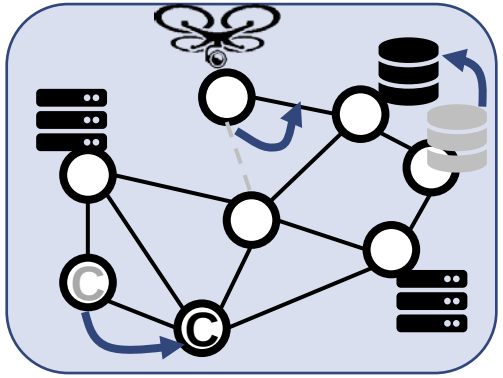


Compute, Storage, Network

Resilient Connectivity for Control Plane

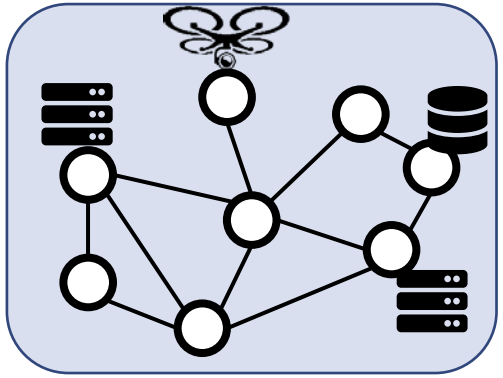


Stable Addresses for Moving Resources



What KIRA achieves…

Interconnects a Large Pool of Networked Resources



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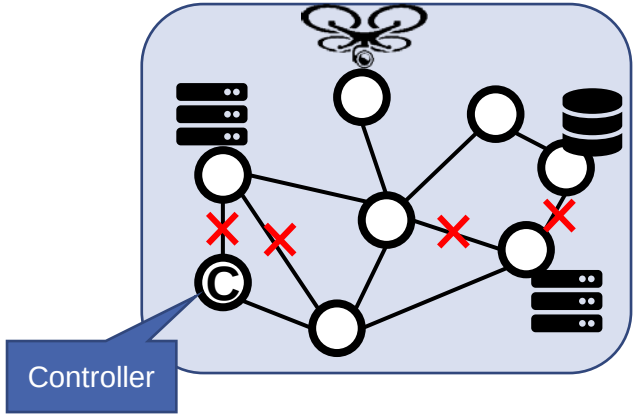
Resilient Connectivity for Control Plane



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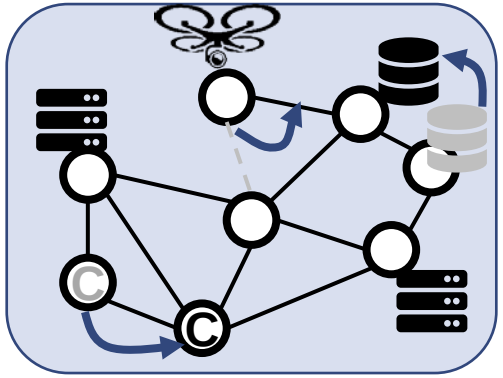

- KIRA provides (all-in-one)
  - Massive scalability (100,000s of nodes)
  - Zero-touch (no configuration)
  - Dynamics: fast convergence, loop free
  - Topological versatility
  - Efficient routes
- Related Works (examples)
  - UIP: lacks dynamics, efficient routes
  - DISCO: lacks dynamics
  - RIFT, Data Center BGP/OSPF/IS-IS: specific topologies only, not ID-based
  - RPL: traffic concentration near root, zero-touch?

KIRA – Main Components

- Routing Tier → connectivity

R²/Kad

- **ID-based addresses**
- **Source routing**
- **On top of link layer**

- Forwarding Tier → optimization

PathID-based Forwarding

- **Eliminates source routing**
- **Label switching approach**
- **Reduces overhead**

KIRA – Main Components

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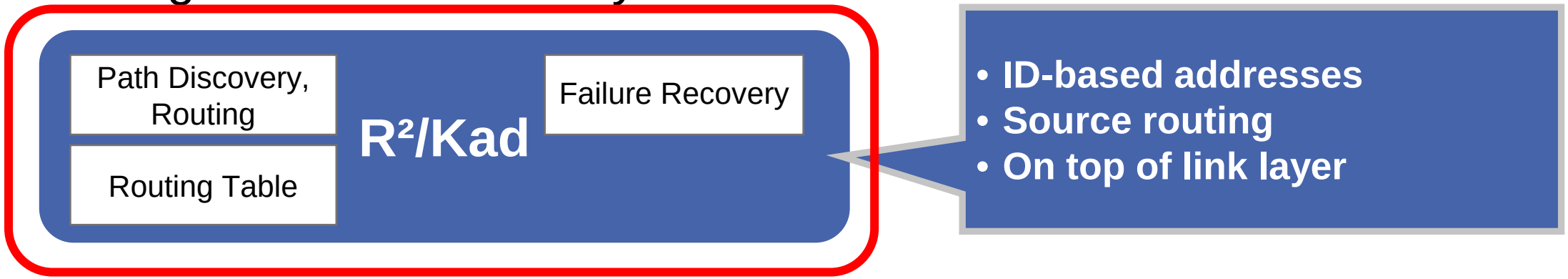
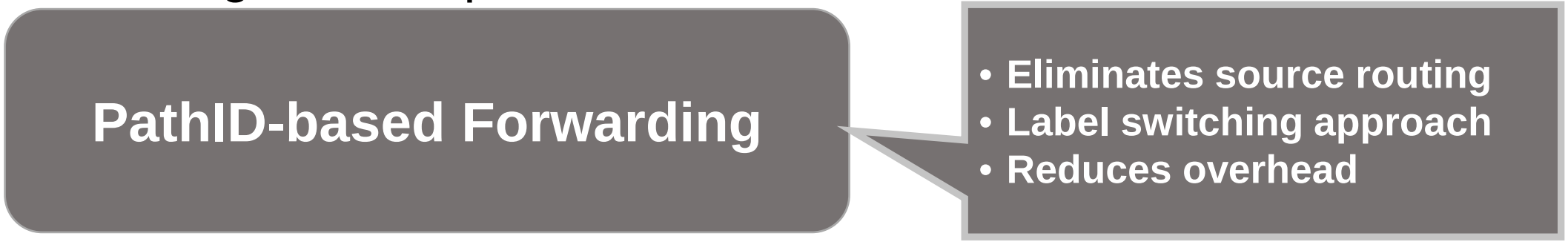
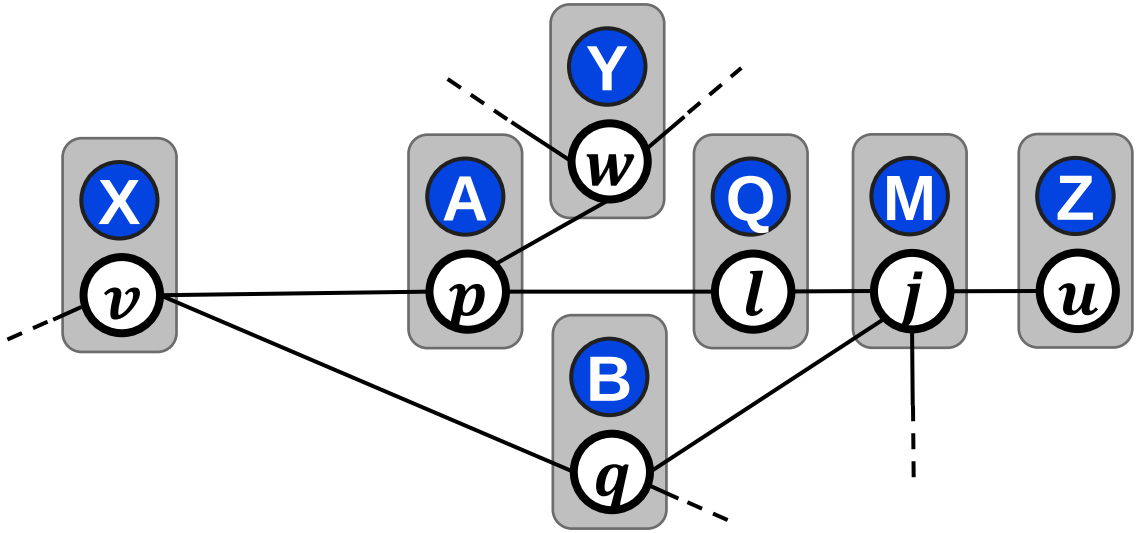


- Forwarding Tier → optimization



R²/Kad – Path Discovery

- Each node
  - randomly chooses its NodeID (Overlay)
  - learns its 2-hop vicinity (Underlay)
    - X learns contacts A, Y, B, M, …

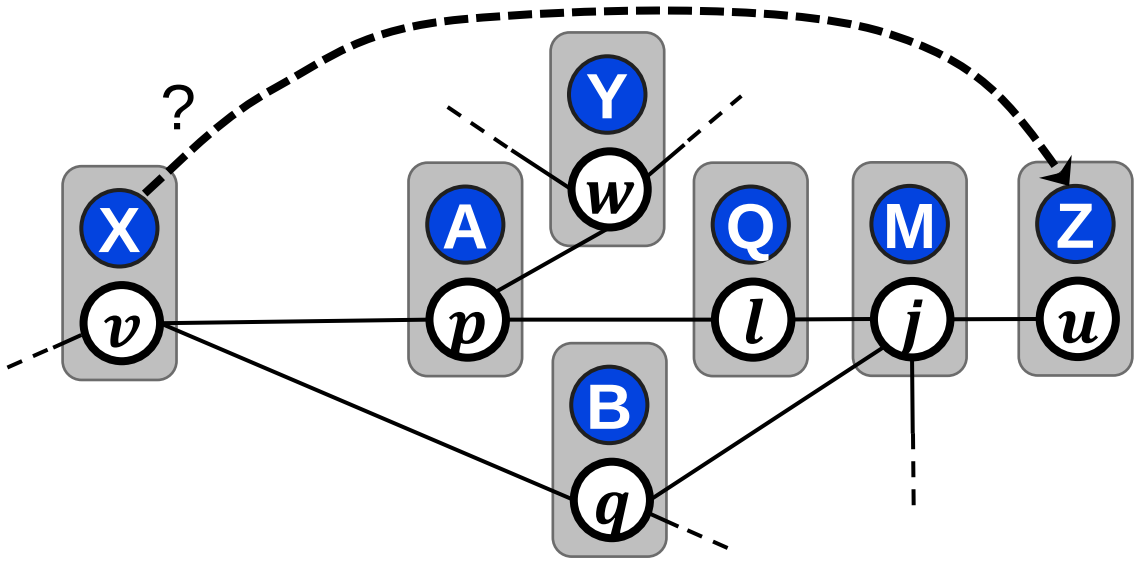


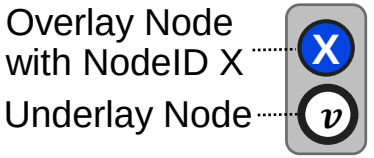
Overlay Node with NodeID X

Underlay Node

R²/Kad – Path Discovery

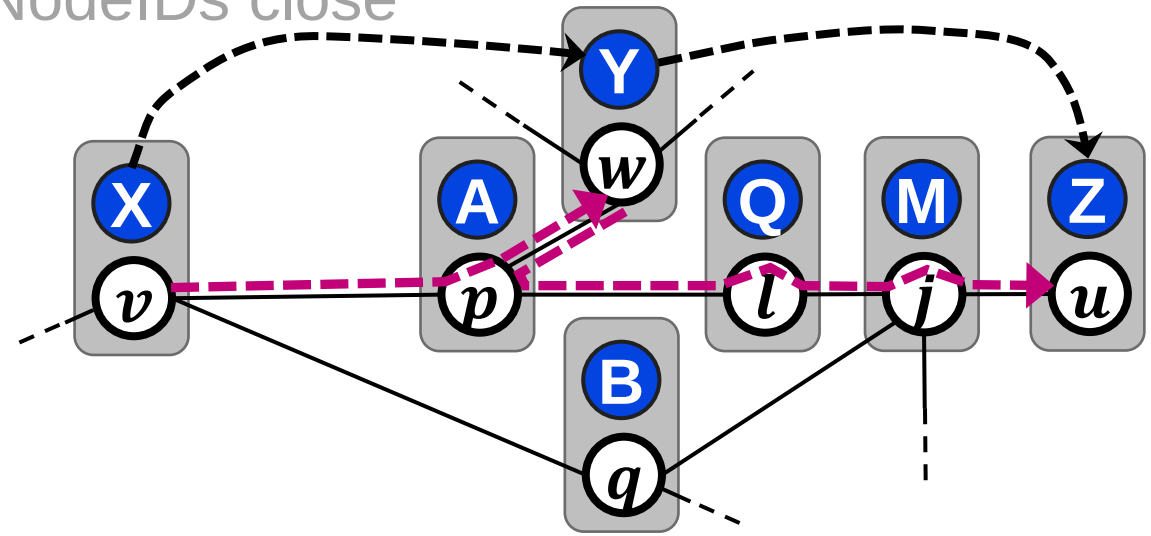
- Each node
  - randomly chooses its NodeID (Overlay)
  - learns its 2-hop vicinity (Underlay)
    - X learns contacts A, Y, B, M, …
- X: path to Z?
- Approach:
  construct underlay routes
  by using the NodeID-based overlay
  - Source route to contact that is closest to destination NodeID
  - Distance of NodeIDs: XOR metric $d(X,Y) = X \oplus Y$
    - Longer shared prefix → closer

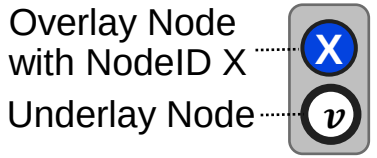




R²/Kad – Path Discovery Example

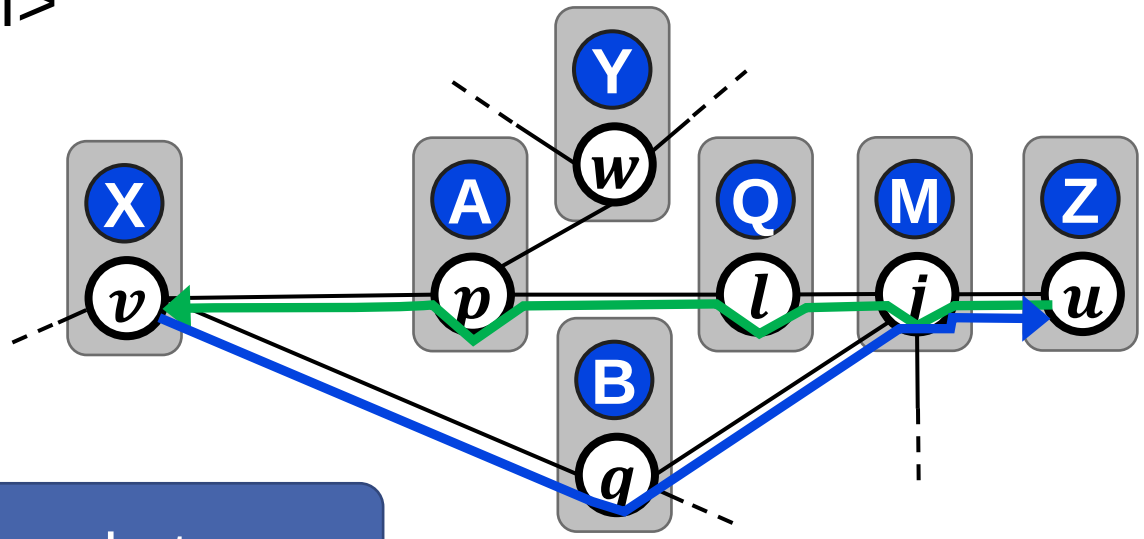
- X sends FindNodeReq to contact closest to NodeID Z
  - Example: letters close in alphabet ↔ NodeIDs close
  - Next (overlay) hop: Y
- X → Y via source route <A>
- Assume Y knows Z already
- Y → Z via source route <A,Q,M>
- FindNodeReq records complete route <X,A,Y,A,Q,M>
  - incurs path stretch: $\frac{|\text{selected path}|}{|\text{shortest path}|}$





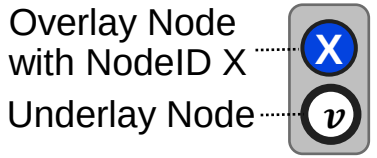
R²/Kad – Path Discovery Example

- Shortened recorded route <A,Q,M> is returned to X in FindNodeRsp
- Later packets use shorter route <B,M>
  - if X already knows M via <B>



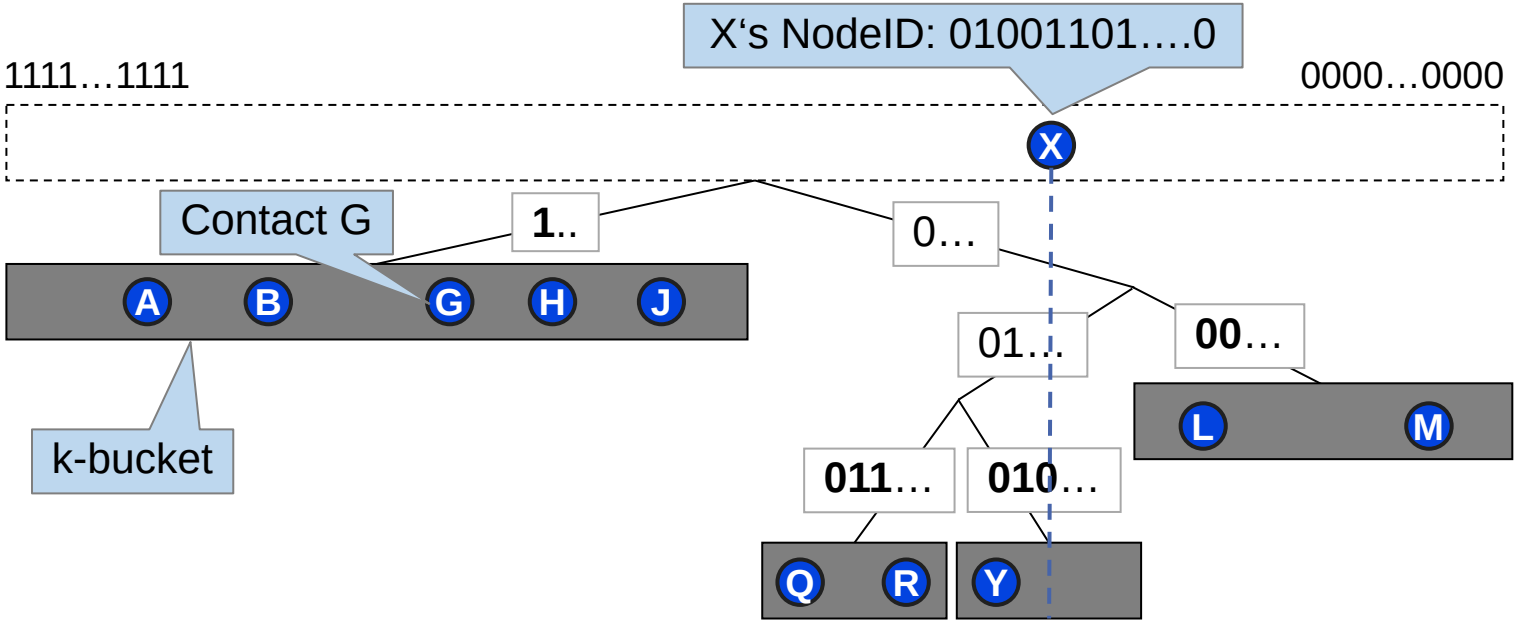
Initial stretch can be reduced for later packets

- R²/Kad offers flexible memory/stretch trade-off…



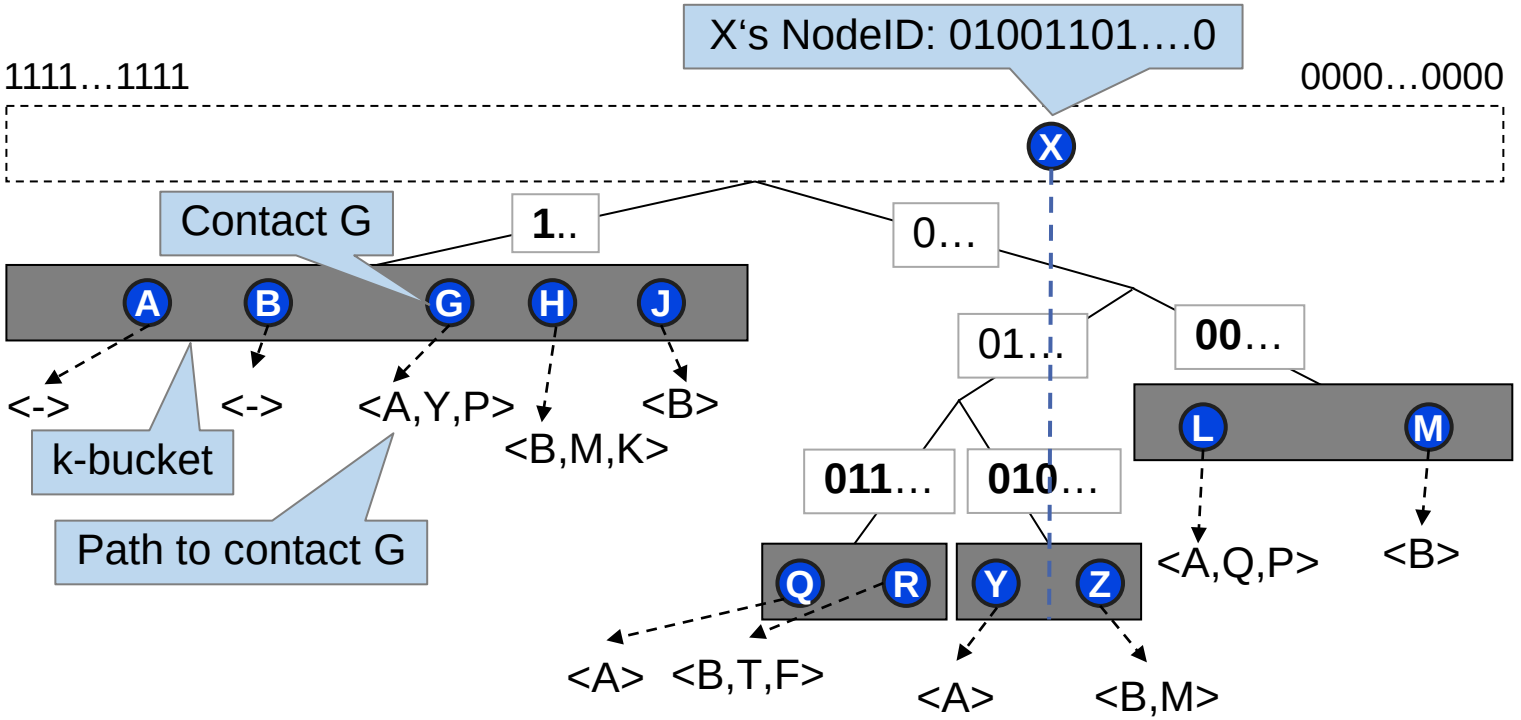
R²/Kad – Routing Table

- Tree of buckets holding up to k contacts (e.g., k=20)
  - Arranged by XOR distance
  - Bucket split if already full and contains own NodeID



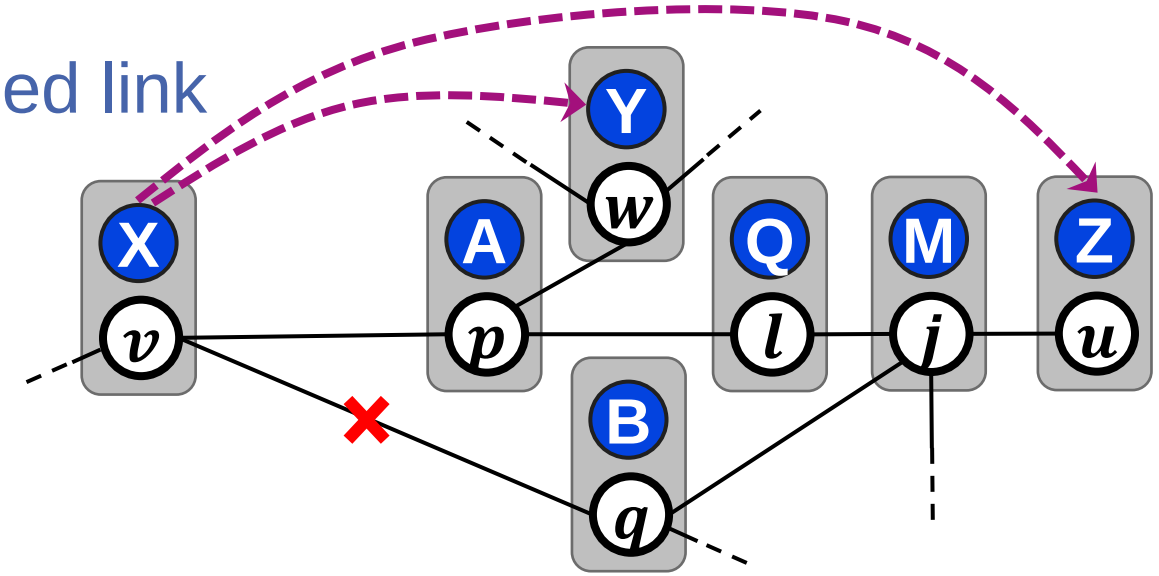
R²/Kad – Routing Table

- Tree of buckets holding up to k contacts (e.g., k=20)
  - Arranged by XOR distance
  - Bucket split if already full and contains own NodeID
- Path vectors are stored for each contact
- Efficient routes
  - Shorter routes preferred
- Size k of k-buckets can be set per node
  → flexible memory / stretch trade-off
- Routing table size: $O(l_G \log n)$, l_G average path length



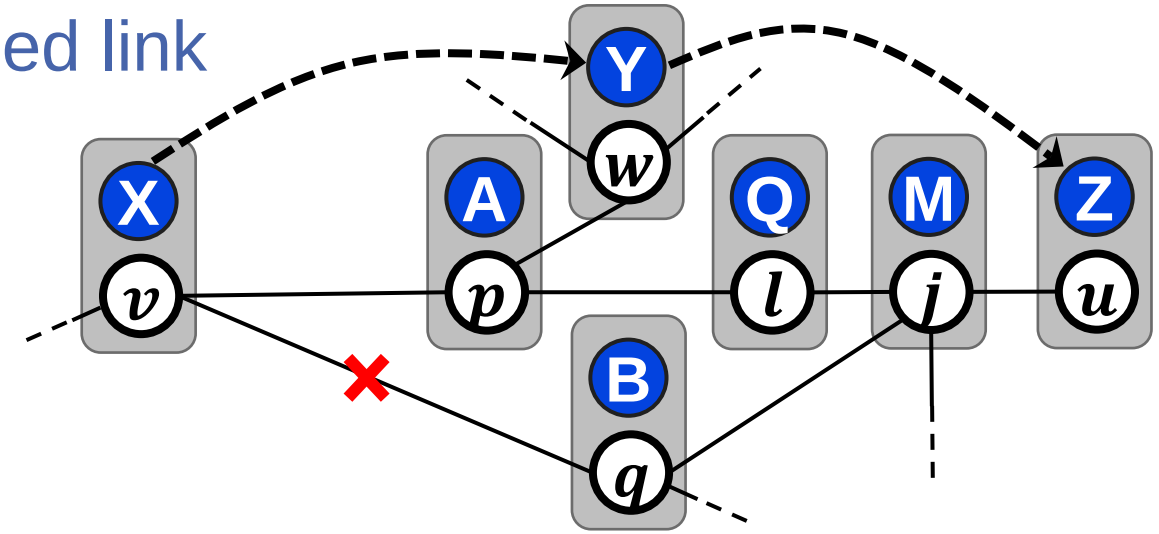
R²/Kad – Dynamics: Rediscovery Procedure

- Detection of node/link failure in the underlay
- Two step strategy
  1.) inform ID-wise neighbors about failed link
  2.) …



R²/Kad – Dynamics: Rediscovery Procedure

- Detection of node/link failure in the underlay
- Two step strategy
  1.) inform ID-wise neighbors about failed link
  2.) rediscover alternative paths via overlay routes (includes "Not Via" information)
- Periodically
  - probe contacts for broken paths
  - lookup own NodeID
- Validity
  - State sequence numbers
  - Path information age



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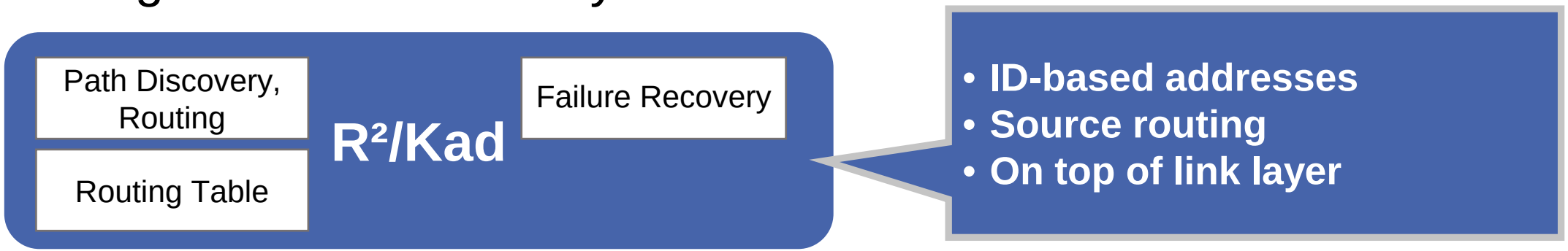
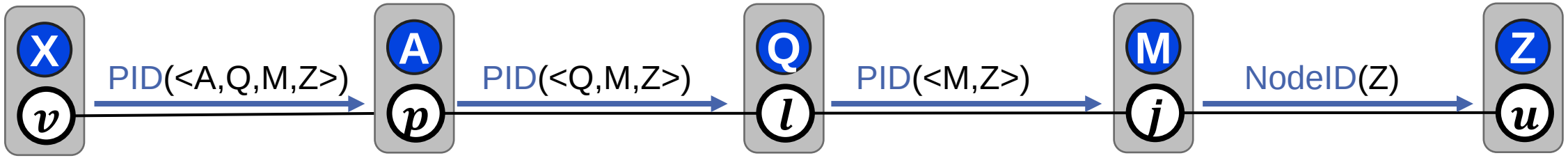


- Forwarding Tier → optimization

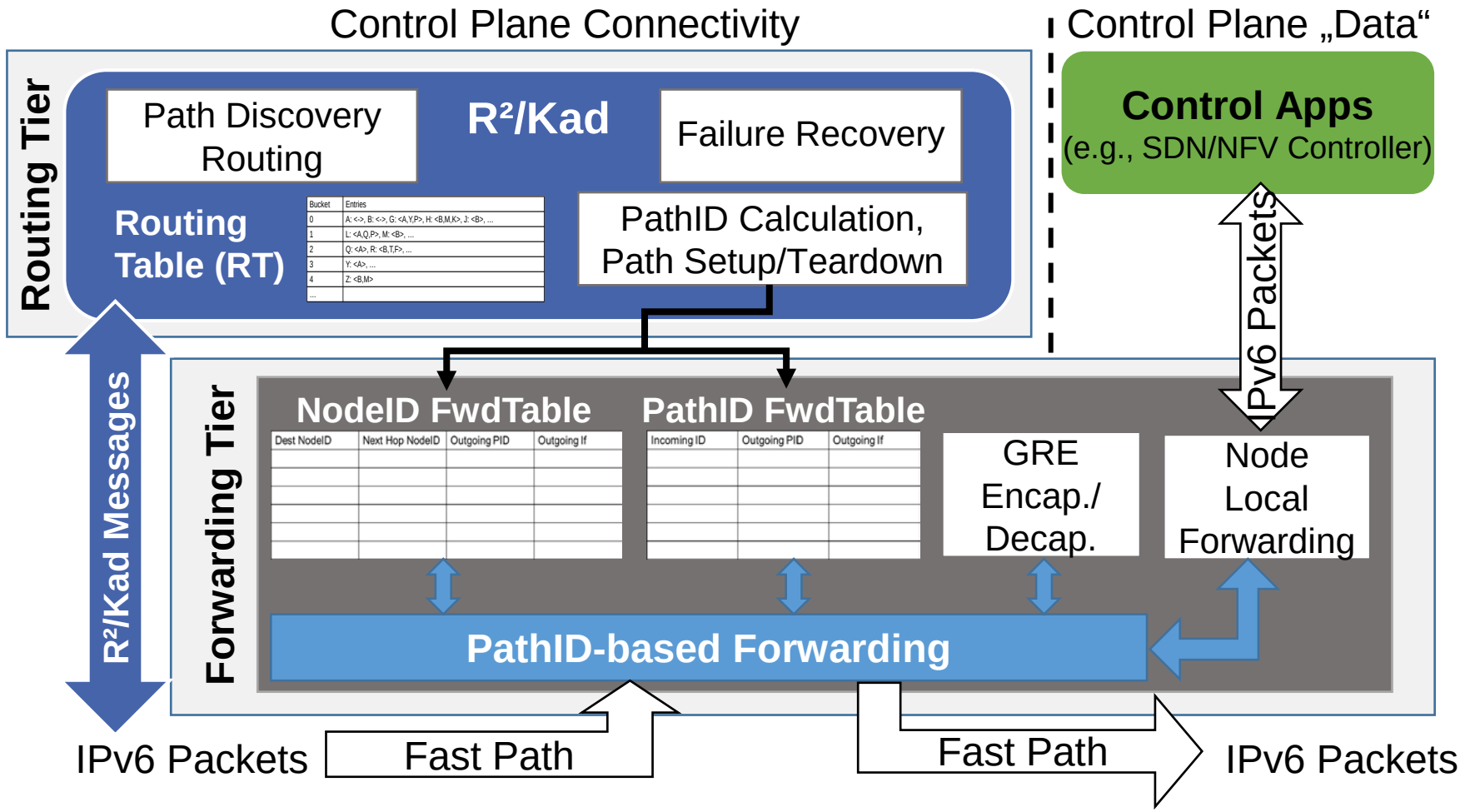
Forwarding Tier – Fast Forwarding

- Get rid of source routes for control plane packets
  - Reduce per packet overhead
- Approach: replace source routes with PathIDs
  - PathID(<A,Q,M,Z>)= Hash(A | Q | M | Z)
- Use PathID as label for source route → Label Switching



- Precalculate PathIDs for 2-hop (physical) vicinity
- Explicit path setup for paths ≥4 hops

KIRA – Routing Architecture

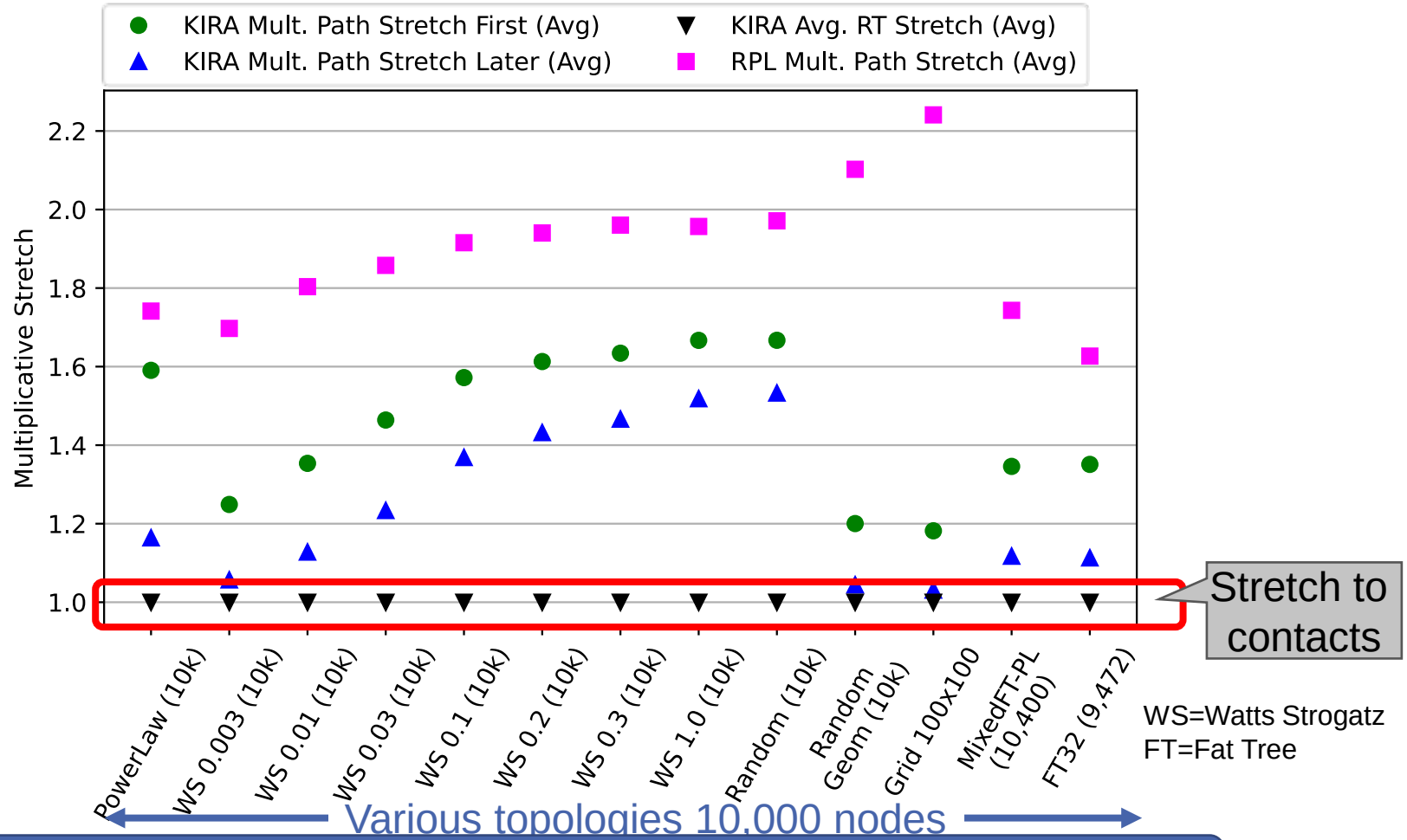


Evaluation – Simulation Setup

- Simulations using RoutingSim → Dynamics (node/link failures)
- OMNeT++ 5.7
- 10 repetitions with different seeds
- Random processing time per node uniformly drawn from [0…500]µs
- Various topologies of different sizes up to 200,000 nodes:
  - Small World: Power-Law, Watts Strogatz, Internet-AS level
  - Regular: Grid, Fat Tree, Mixed Fat Tree/Power Law
  - Random: Random, Random Geometric
  - Real: Topology Zoo

Evaluation – Topological Versatility

- Multiplicative Stretch
- Bucket size k=40
- RPL: Storing-mode, Single DODAG, Single DODAG version

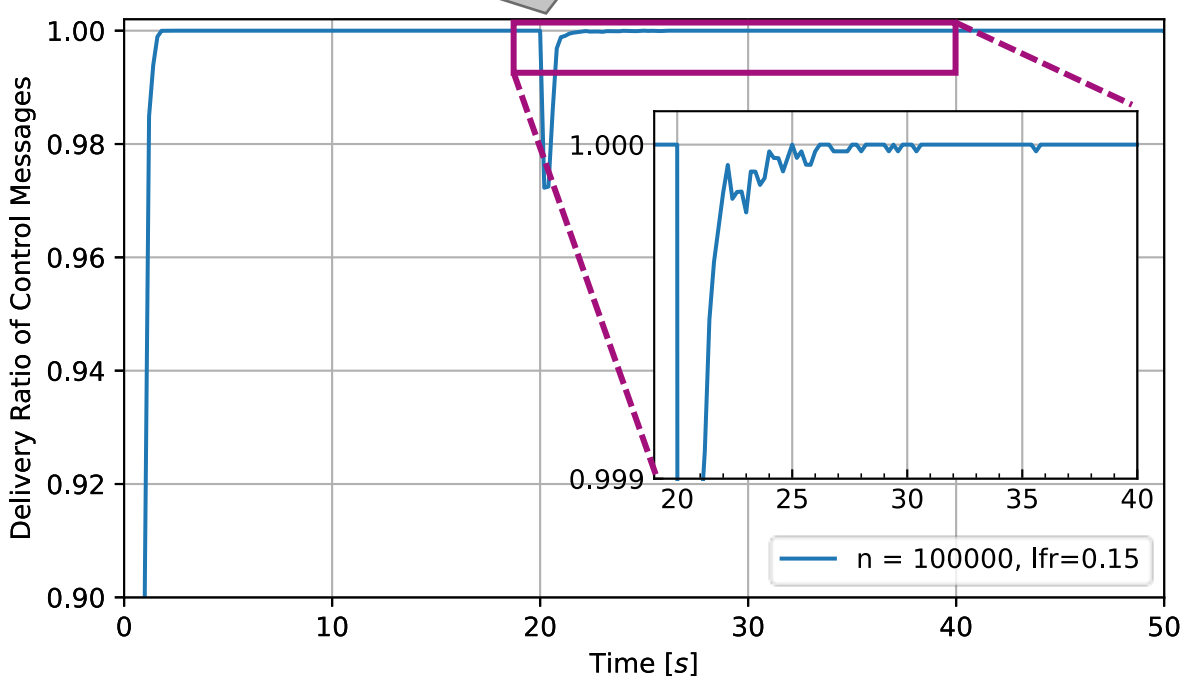


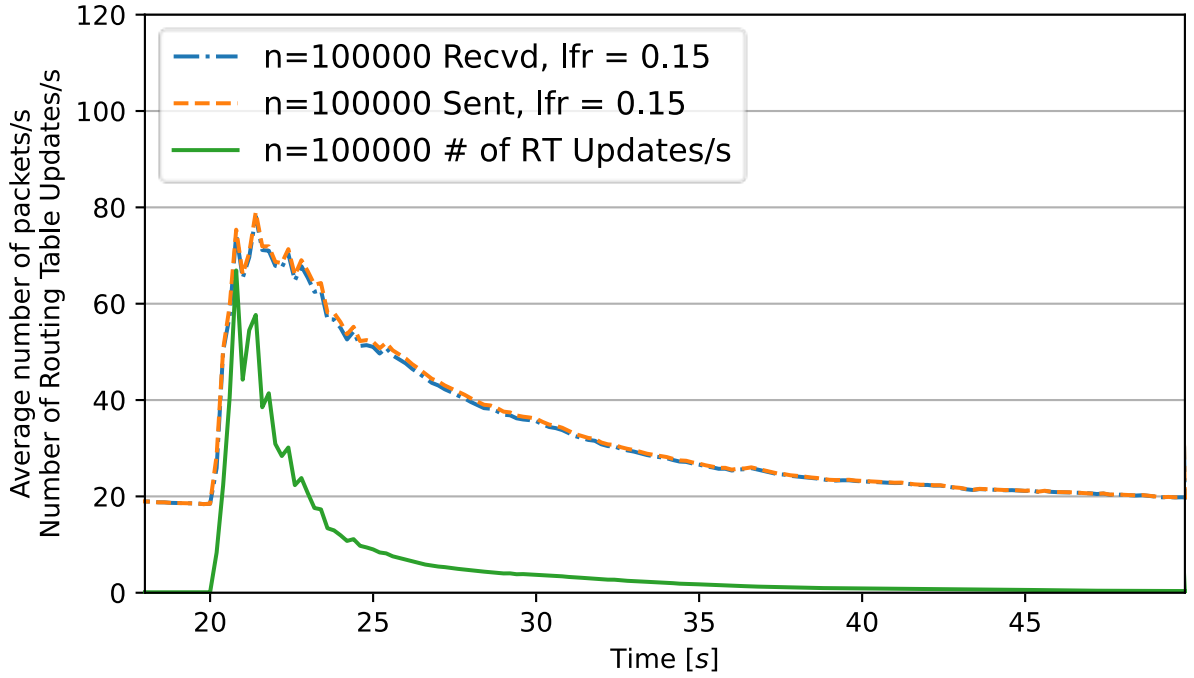
Low stretch across various topologies + Shortest paths to contacts

Evaluation – Dynamics

- 100.000 nodes Power-Law

15% links fail randomly and simultaneously





Fast Convergence + Scalable Overhead

Conclusions

Side meeting **today!**
Nov 10th, 19.00 Mezzanine 12

- KIRA= R²/Kad + PathID-based forwarding

  provides **self-organized robust** control plane connectivity

  - Designed for large provider domains (e.g., 5G, 6G) or even across multiple providers (Domain concept under development)
  - Could be a replacement for RPL in the ACP
    - Not specifically designed for IoT, but may be tweaked
  - Simply uses link-local IPv6 addresses for routing protocol messages
- KIRA offers an integrated DHT for simple name resolution/service discovery → more efficient and simplified discovery than with GRASP
- Supports multi-path routing and forwarding
- Supports scalable and efficient topology discovery

Backup Slides

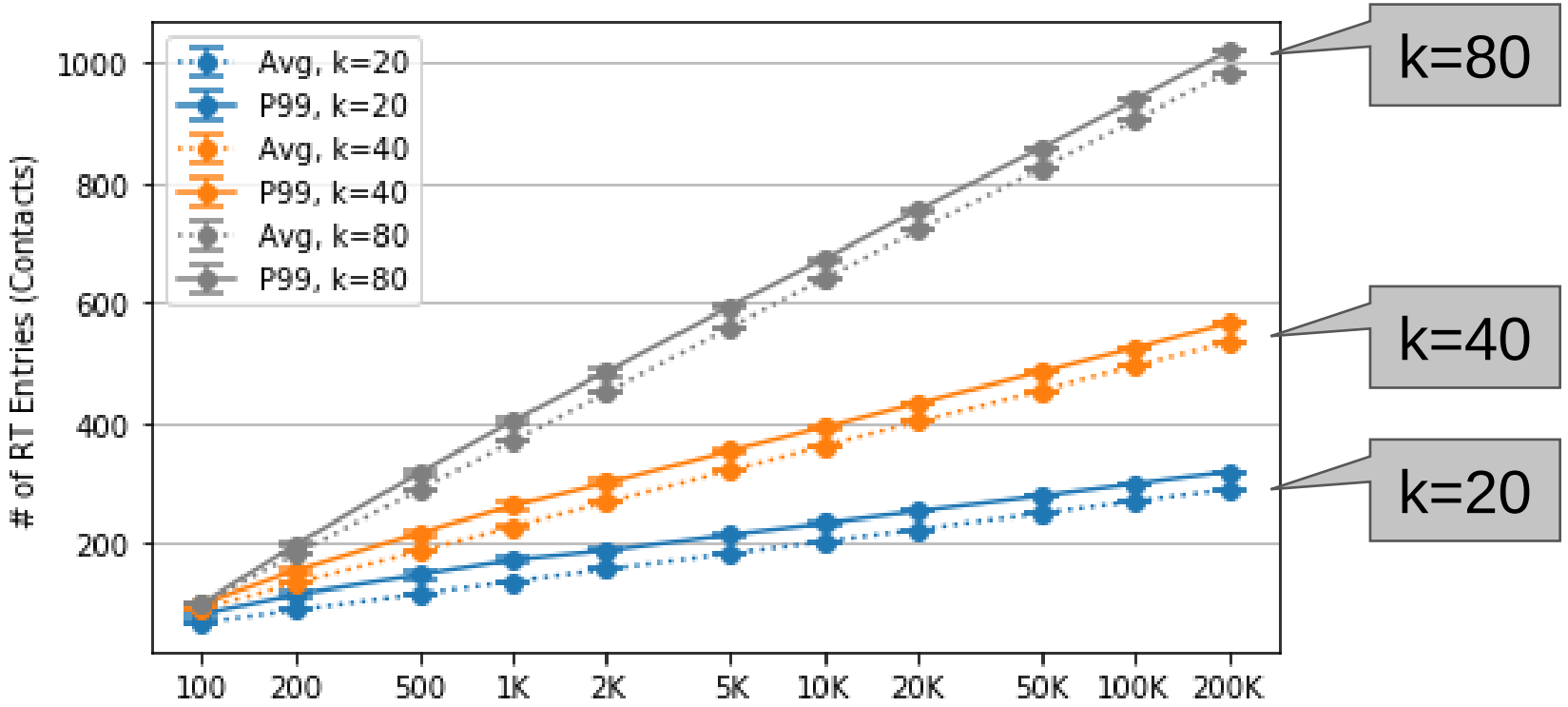
Further/Ongoing Work

- End-system mode variant
  - Saves a lot overhead
- Multi-path routing extension
- Efficient and lightweight topology discovery

- Multicast routing and forwarding
- Theoretical analysis
  - Guarantees and bounds
- Investigations w.r.t. mobility, ad-hoc/mesh networks
- Implementation in Rust

Evaluation – Scalability

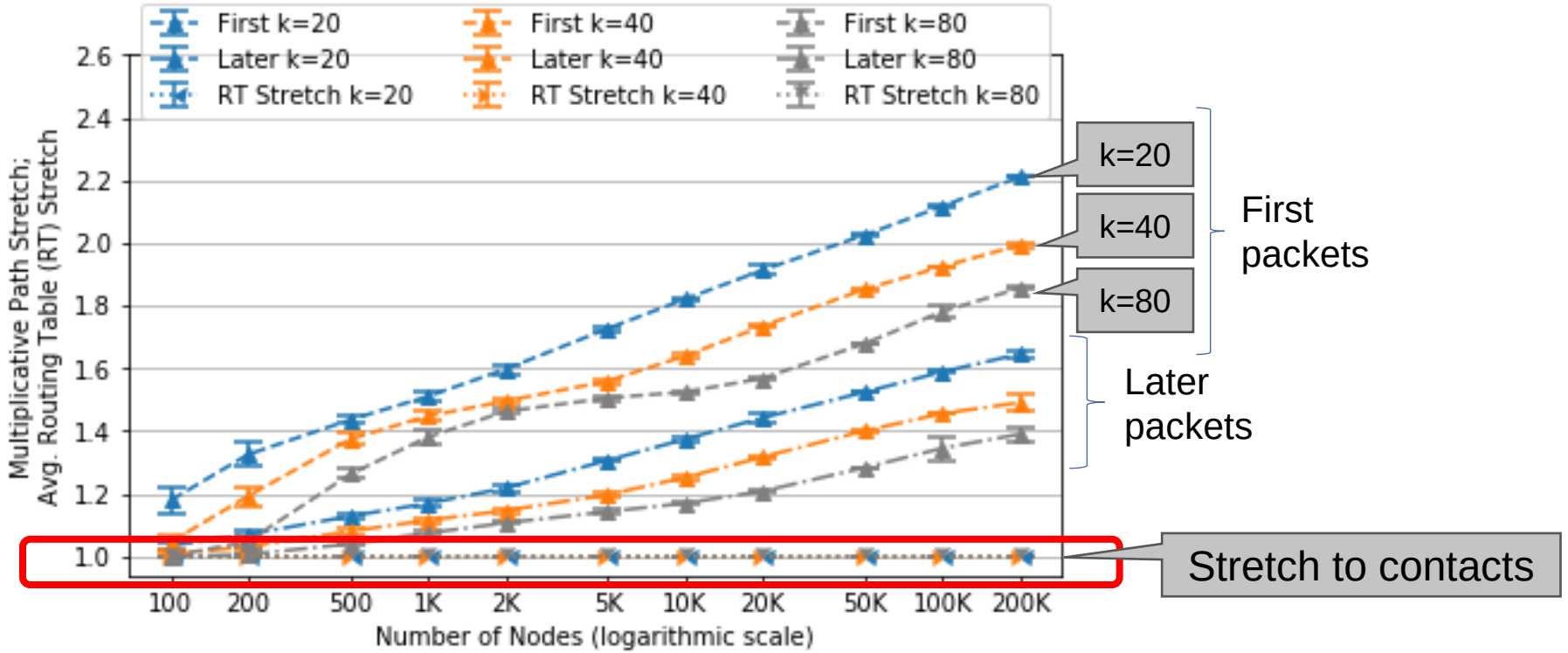
- Power-Law topologies



High Scalability: # of Routing Table Entries ~ $O(\log n)$

Evaluation – Stretch

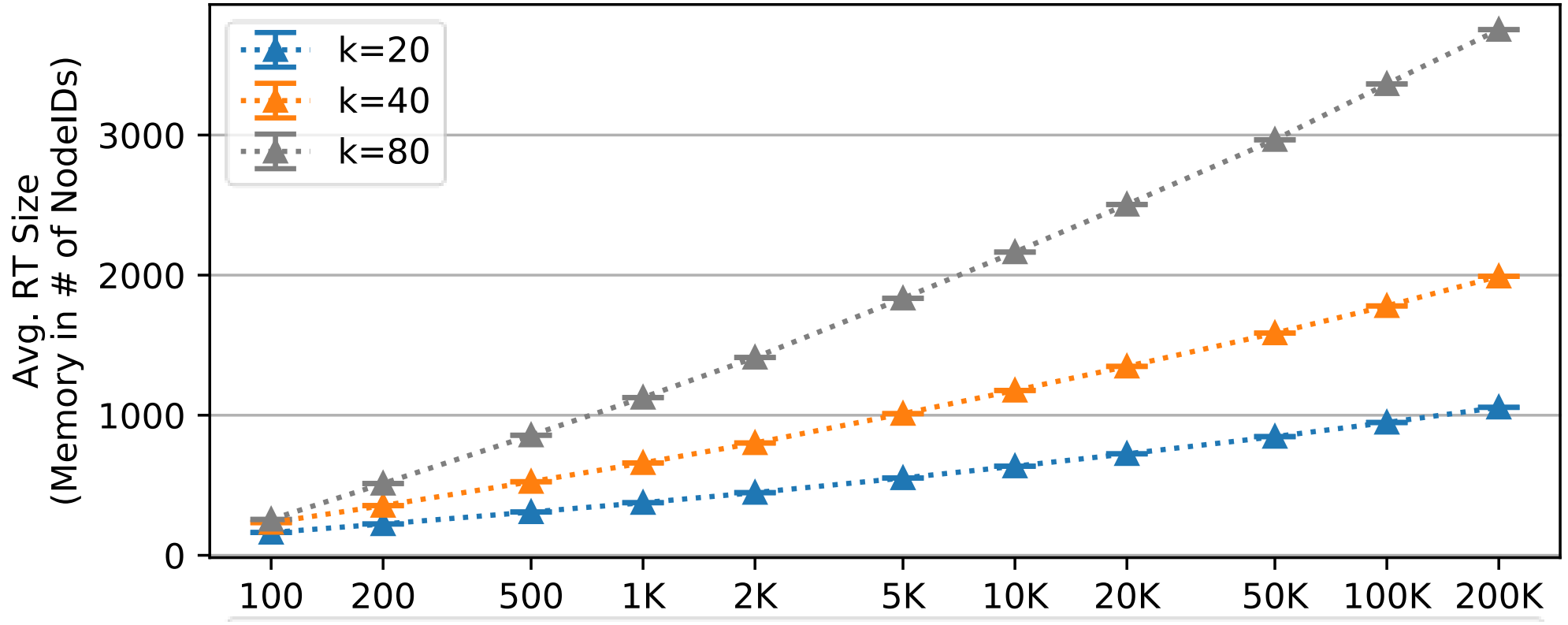
- Multiplicative path stretch
  $= \frac{|\text{selected path}|}{|\text{shortest path}|}$



Flexible memory / stretch trade-off + Shortest paths to contacts

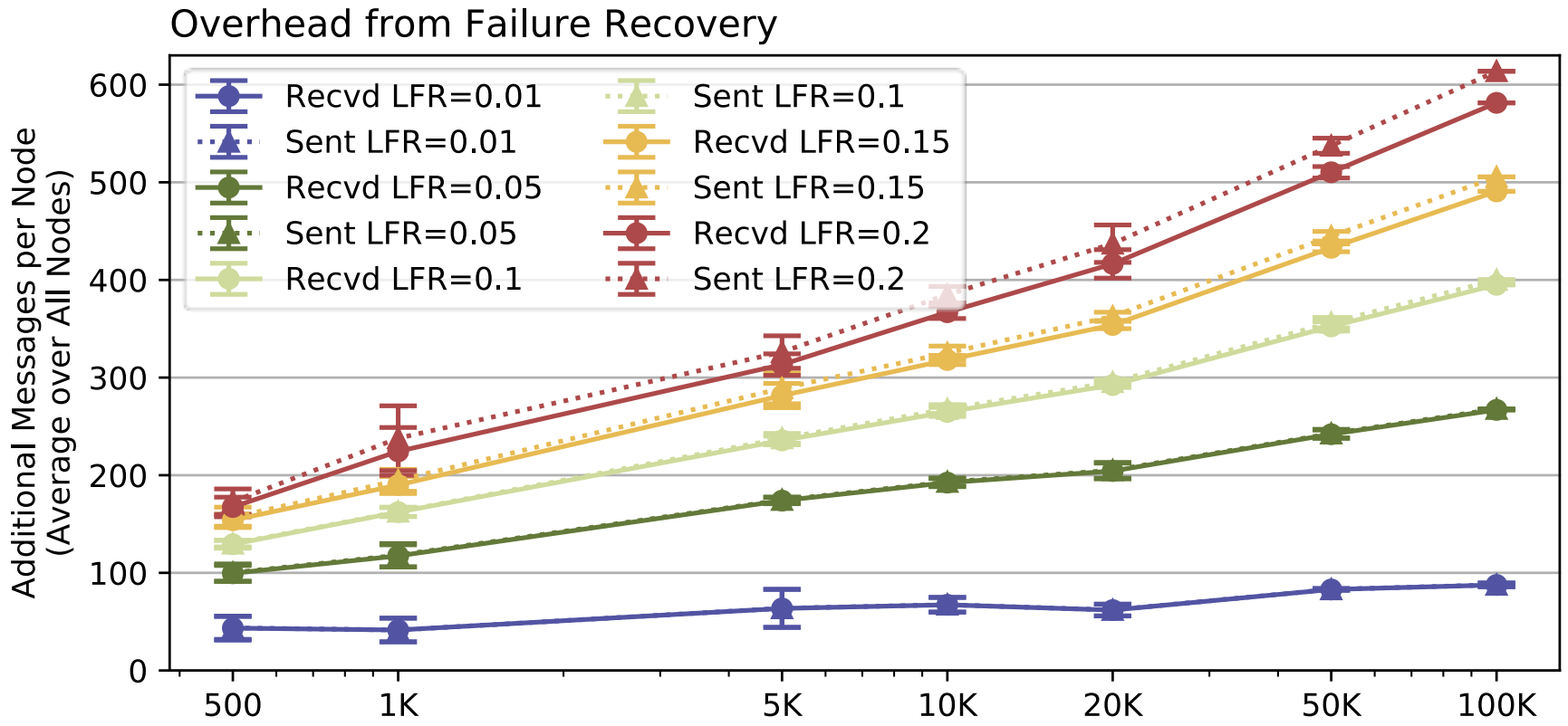
Memory Size in Number of IDs

- Contacts + Path Vectors



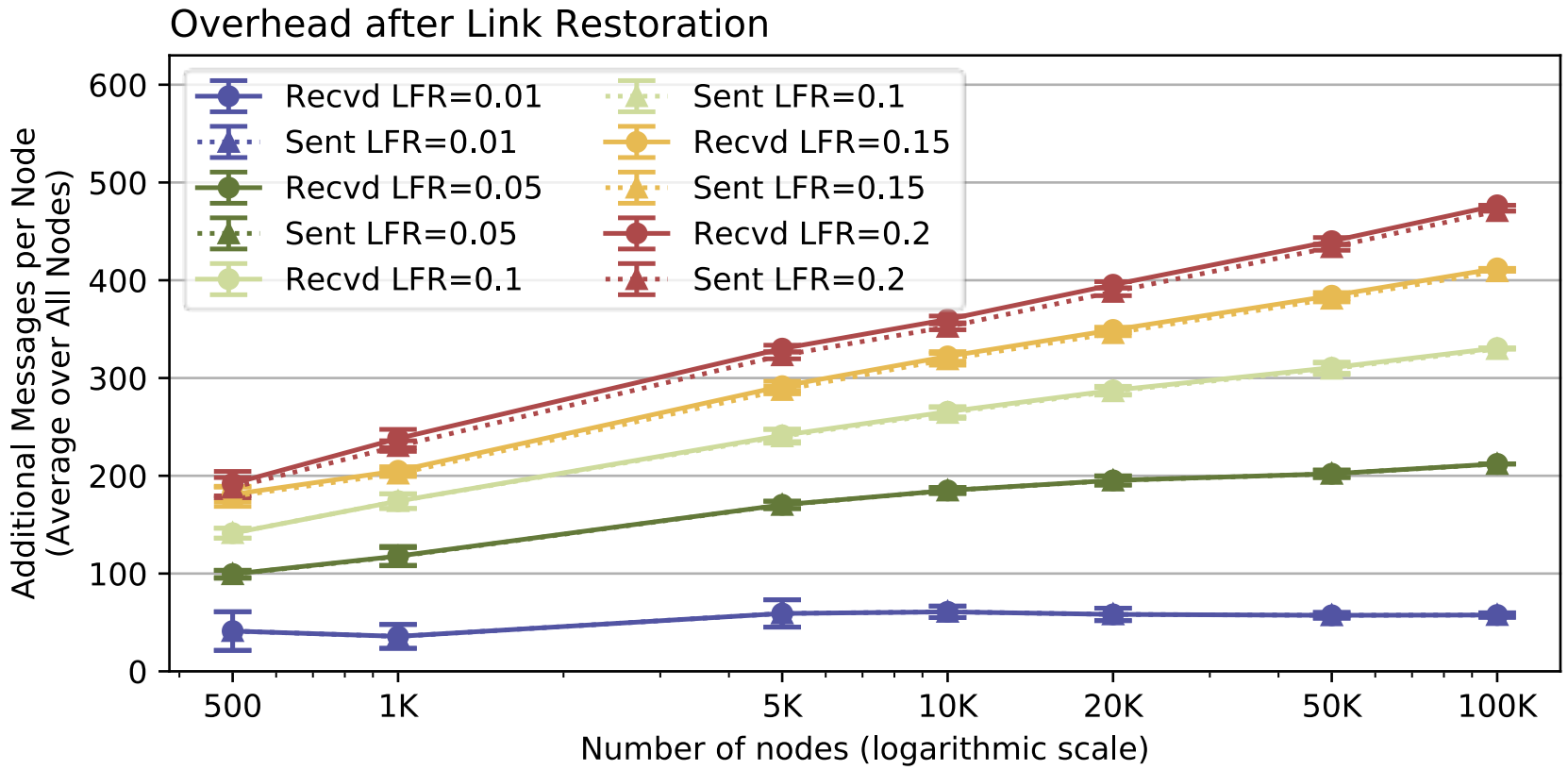
Dynamics – Control Message Overhead (1)

- Additional messages sent to recover from link failures

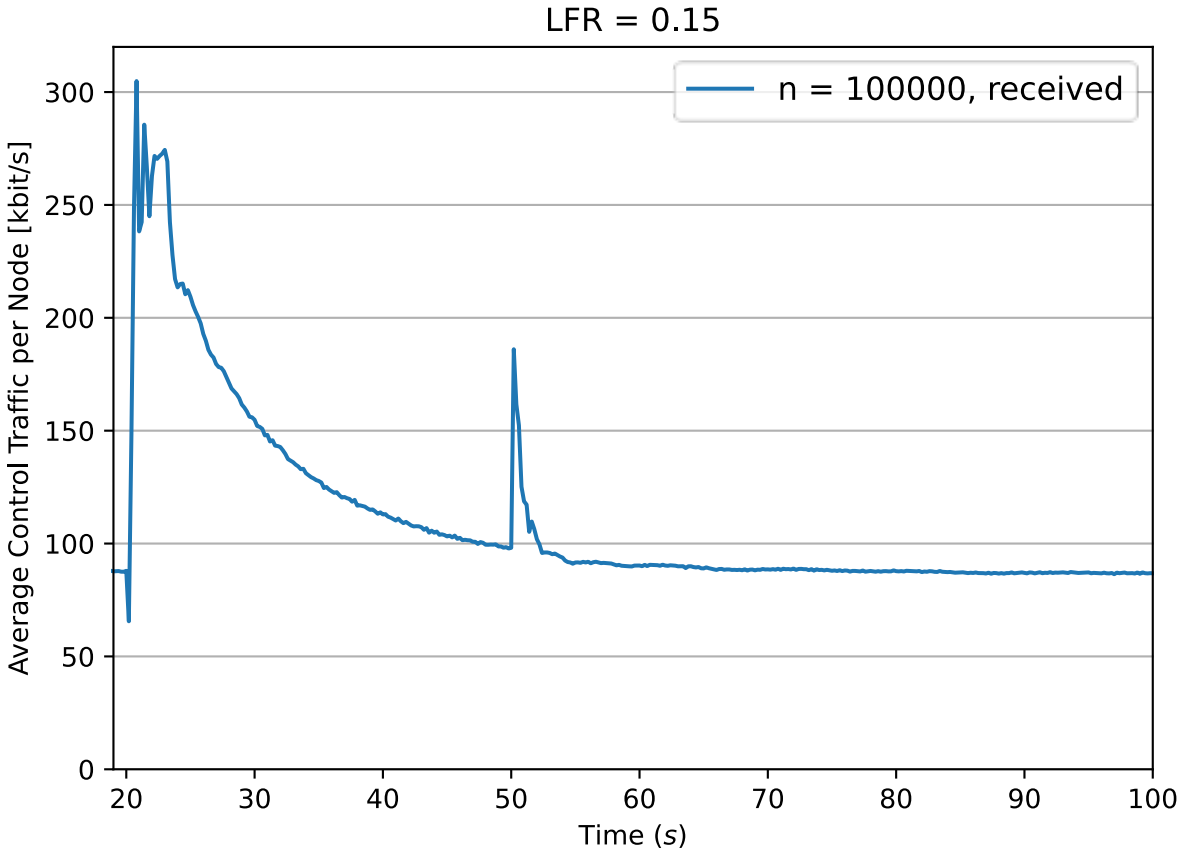


Dynamics – Control Message Overhead (2)

- Additional messages sent after failed links have been restored

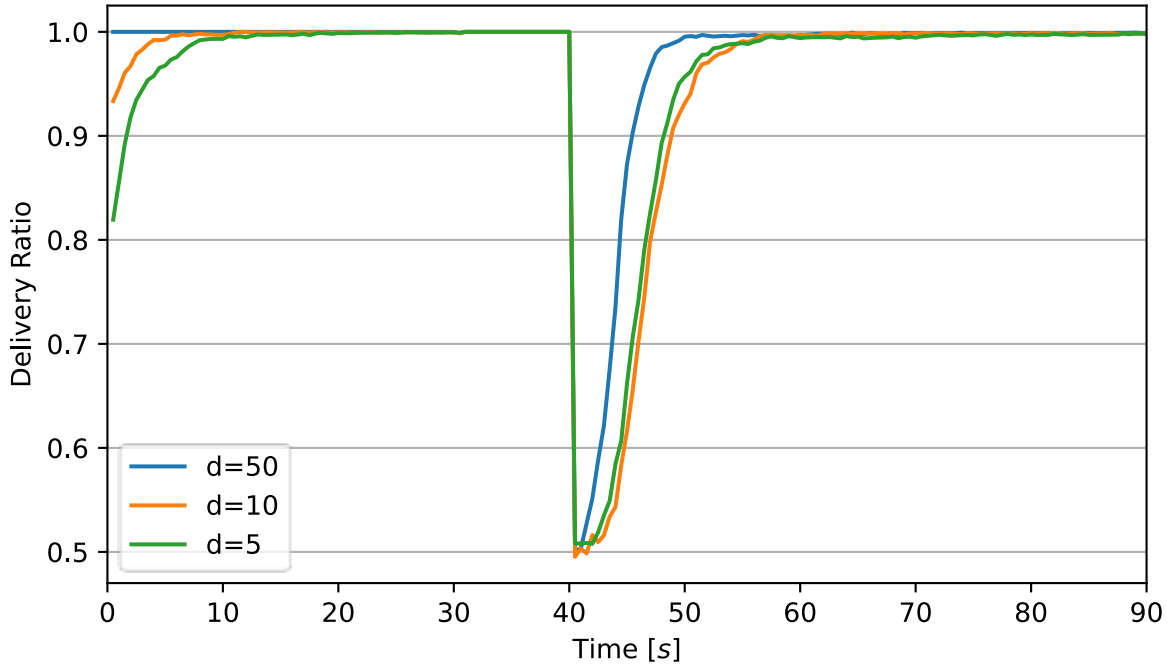


Control Traffic Data Rates



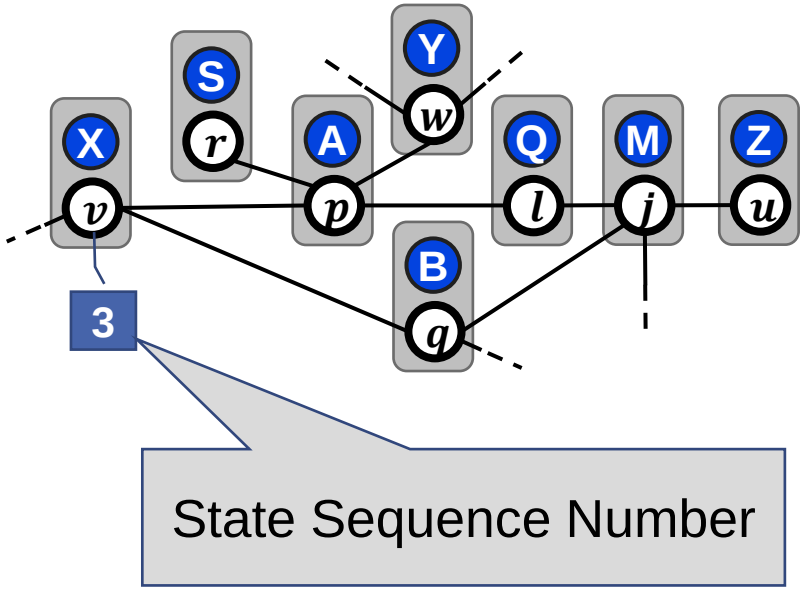
Network Partitioning

- Network partition 2 x 5000 nodes connected by d links
- $d \in \{5,10,50\}$
- D links break at 30s simultaneously, restored at 40s



State Sequence Numbers

- Per Node: State Sequence Number
  - reflects changes in node's physical neighbor set
  - Link down
  - Link up (also detecting a new node)
- 32-bit
  - Wrap around and special comparison:
    - $s < s' \bmod 2^{32}$ if $0 < (s' - s) \bmod 2^{32} < 2^{31}$
- Get periodically synchronized
- Node crashes
  - Node either uses new NodeID after restart
  - or, node stores NodeID and State Sequence Number across restart



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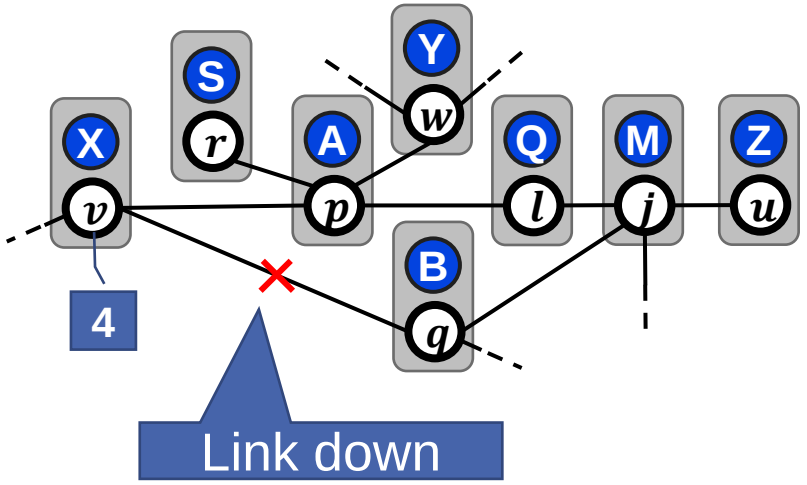

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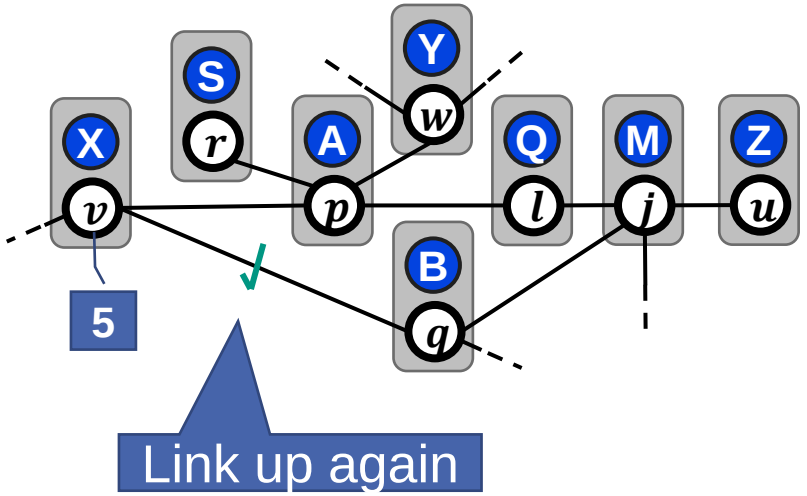

End-system Mode

- End-systems do not route, but may be multi-homed and mobile
- Reduce overhead by not transmitting routing updates to/from end-systems
- Routers are responsible to keep information on end-system reachability