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LEAD (LEArned DHT), with Learned Hash Function

New field for further research on integrating learned models with distributed systems.

Range Query

KV Cache Management

Content Delivery Network Storages

LLM Serving & RAG

Edge-AI & IoT Data Lakes

A Distributed Learned Hash Table

Vector Databases

Blockchain Indexing

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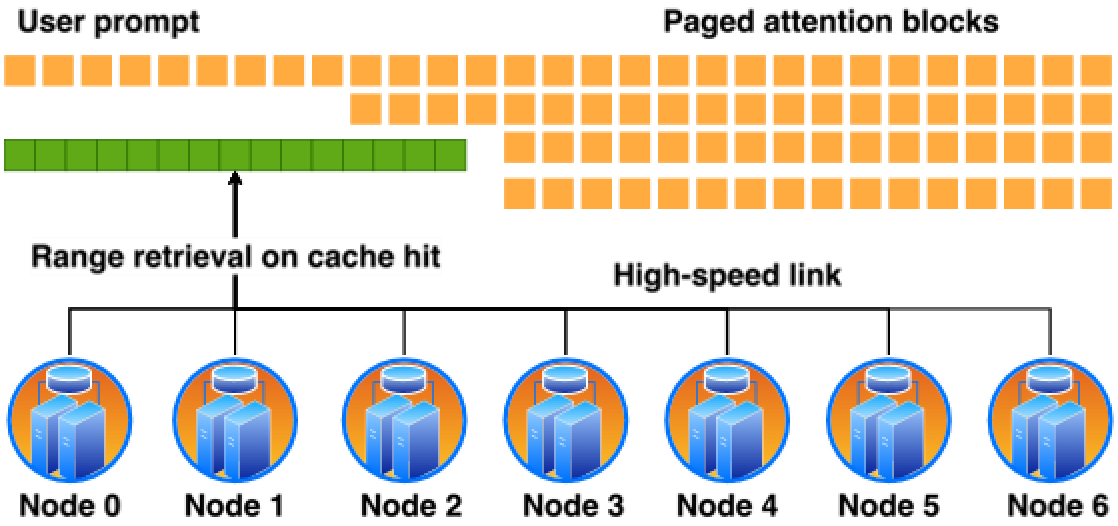
Fetching KV Cache you already computed.

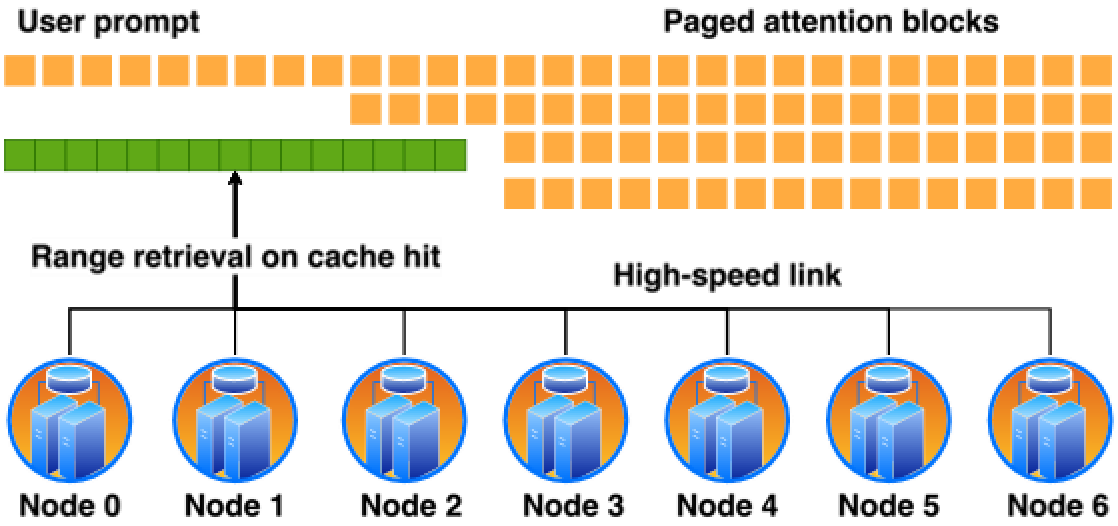
New Bottleneck in LLM serving



- Long contexts ⇒ massive KV; **Prefix sharing** across workers
- Need fast retrieval of **contiguous ranges**
- Avoid bottlenecks from **central KV router**

Fetching KV Cache you already computed.

New Bottleneck in LLM serving



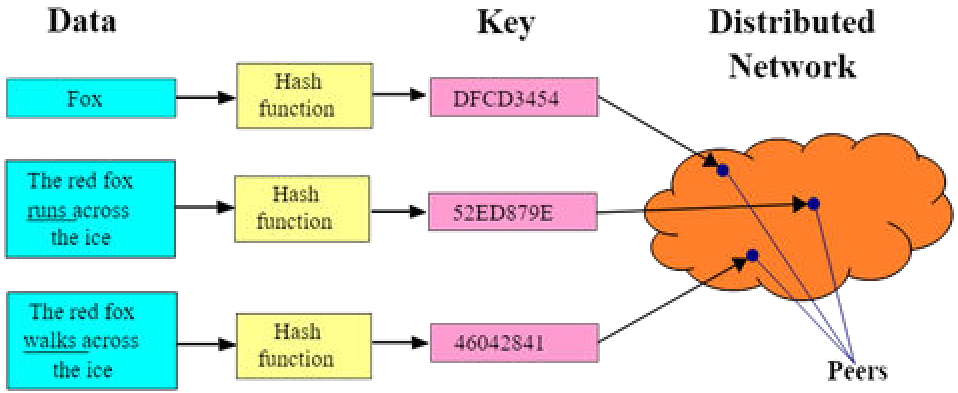
- **Fetch spans** (contiguous or semantic) , not only points
- **Few hops** per request; **Robust** to churn; Works at **scale**

Distributed Hash Table (DHT)

DHTs are pivotal in high-impact key-value applications

- **Consistent hashing** spreads key–value data across peers
- Map key → ID; place by ID; route via finger tables in **O(log N)**

Deployments: Storage (*IPFS*), DBs (*Cassandra*), Blockchains (*Ethereum*), Protocols (*BitTorrent*), CDNs, Edge/IoT, etc.



Classical DHTs fail for ranges.

Limitations of DHT for AI- and Data-driven workloads

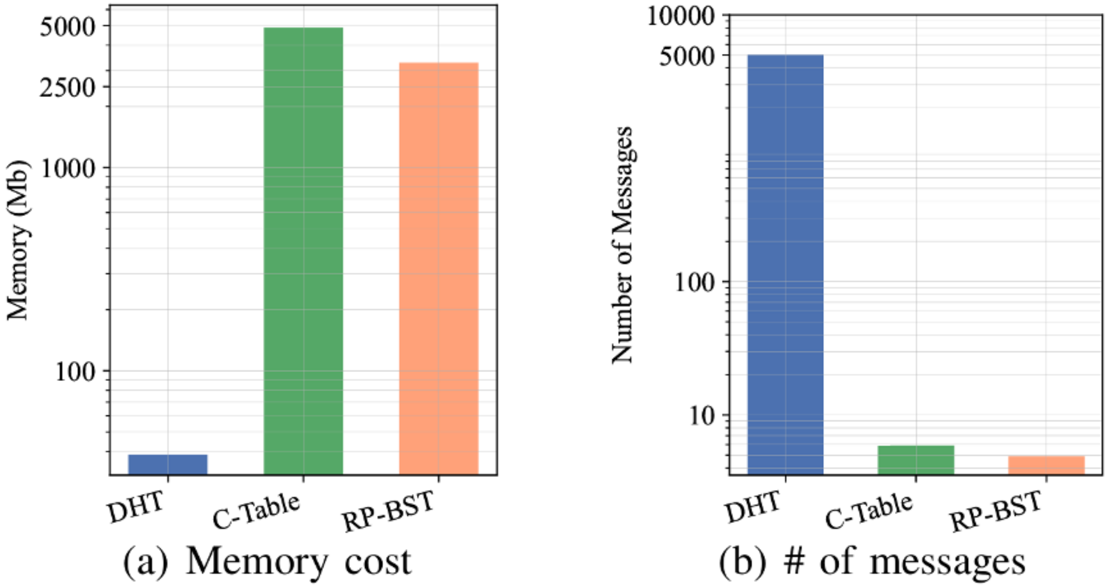


Fig. 1. Micro benchmark of Range Query Performance

- Hashing destroys **order**
- **Nearby** keys ⇒ **random** nodes
- **Range** ⇒ **massive** lookups

- Central tables/trees: **heavy** for maintenance, **brittle** for churns

LEAD = LEArned DHT.

Make DHTs even greater with efficient range query

- Learn the keys' **ECDF**
- Map to **ordered hash** IDs
- DHT routing & ownership
- **Ranges query ⇒ contiguous hash ranges**

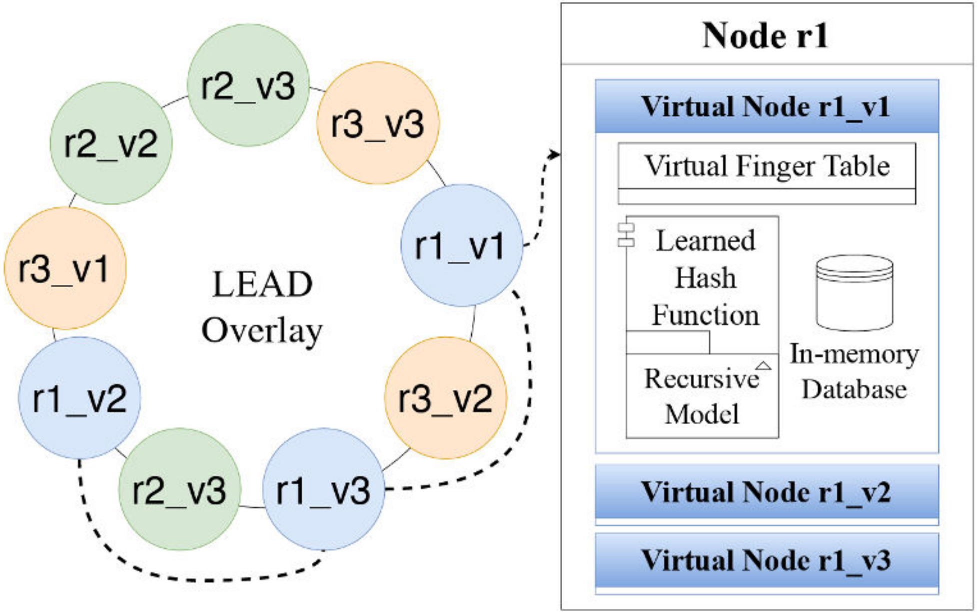
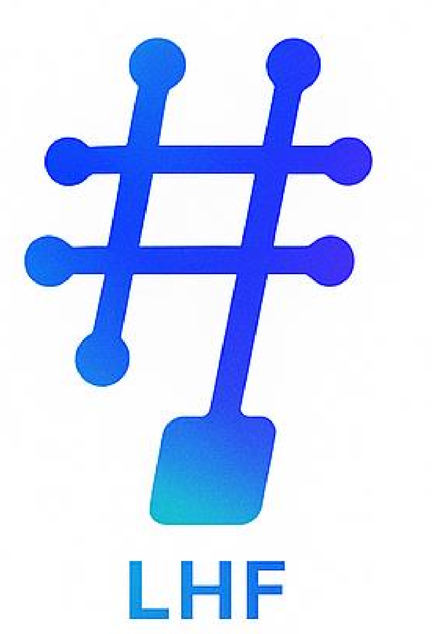


Fig. 2. LEAD System Design

Learned Hash Function (LHF).

Make DHTs even greater with efficient range query



- We argue that a **learned model** can **replace the hash function** to distribute keys in networked systems.
- LEAD **first** introduces the concept of the **Learned Hash Function** under the realm of distributed key-value systems.

Learned Hash Function (LHF).

Mapping keys into order-preserving hash

- Learning hash with **Recursive Model (RMI)** structure
- At each stage, the sub-model determines the appropriate child model to engage for a key.

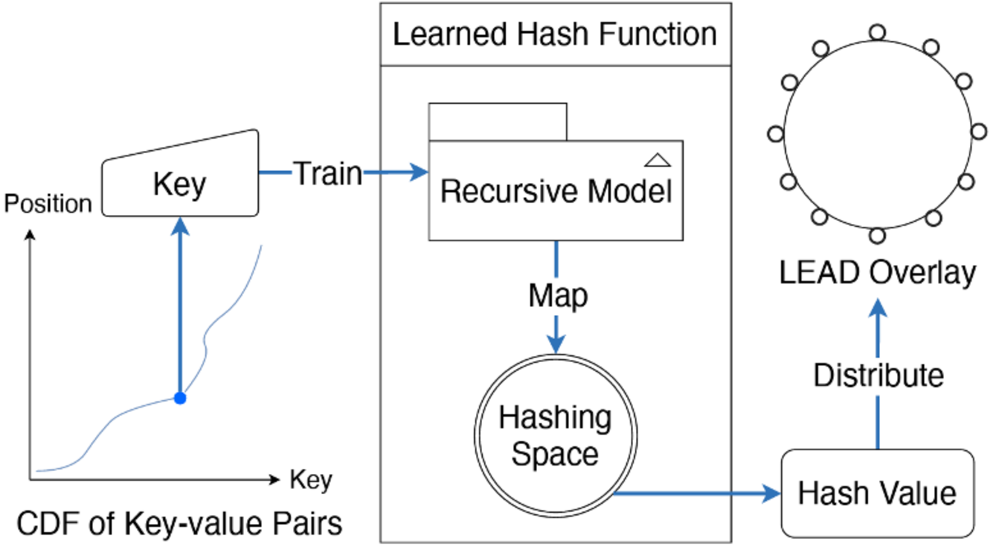


Fig. 3. Key mapping with a learned hash function

Learned Hash Function (LHF).

Mapping keys into order-preserving hash

- At the final stage, leaf models **predict the relative position of a key** and **map the key to the hashing space**.

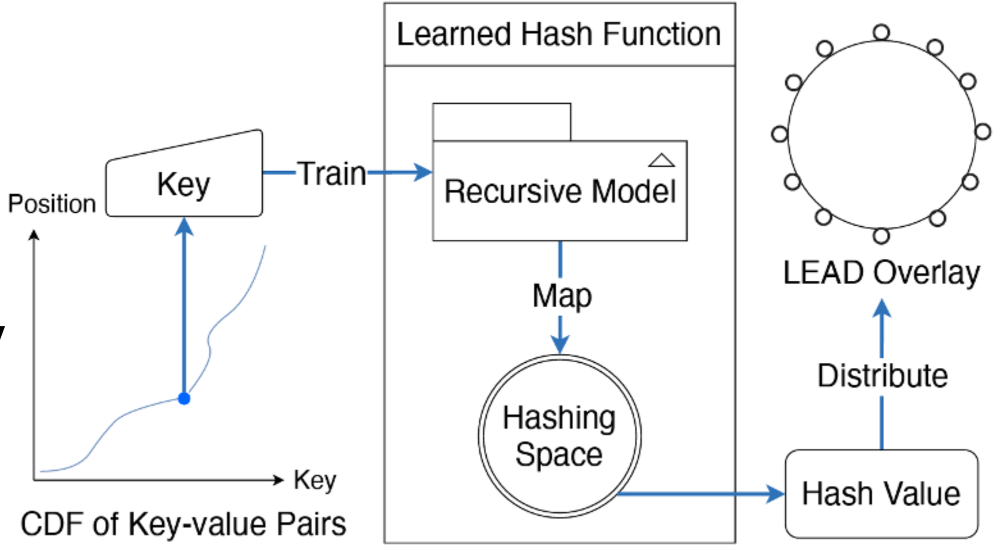


Fig. 3. Key mapping with a learned hash function

Learned Hash Function (LHF).

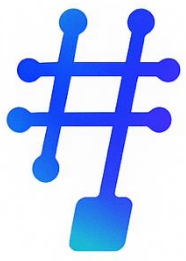
Mapping keys into order-preserving hash

Considering a two-stage LH trained on N key-value pairs, the learned hash function, denoted as $LearnedHASH$, can be articulated as:

$$LearnedHASH(key) = \lfloor \frac{N}{H} \times f_2^{\lfloor \frac{B^{a} \times f_1(x)^{b}}{N} \rfloor}(K) \rfloor \quad (1)$$

[a] B referred to as the branching factor that determimines the number of "buckets" that data is divided into by the stage-one model

[b] f_i referred to as the ith stage model



Data Retrieval with LHF.

Peer Addressing

- Route via **picking farthest preceding finger**
- O(log N) hops to owner
- Separated hash space for ownership with ***PeerHASH***

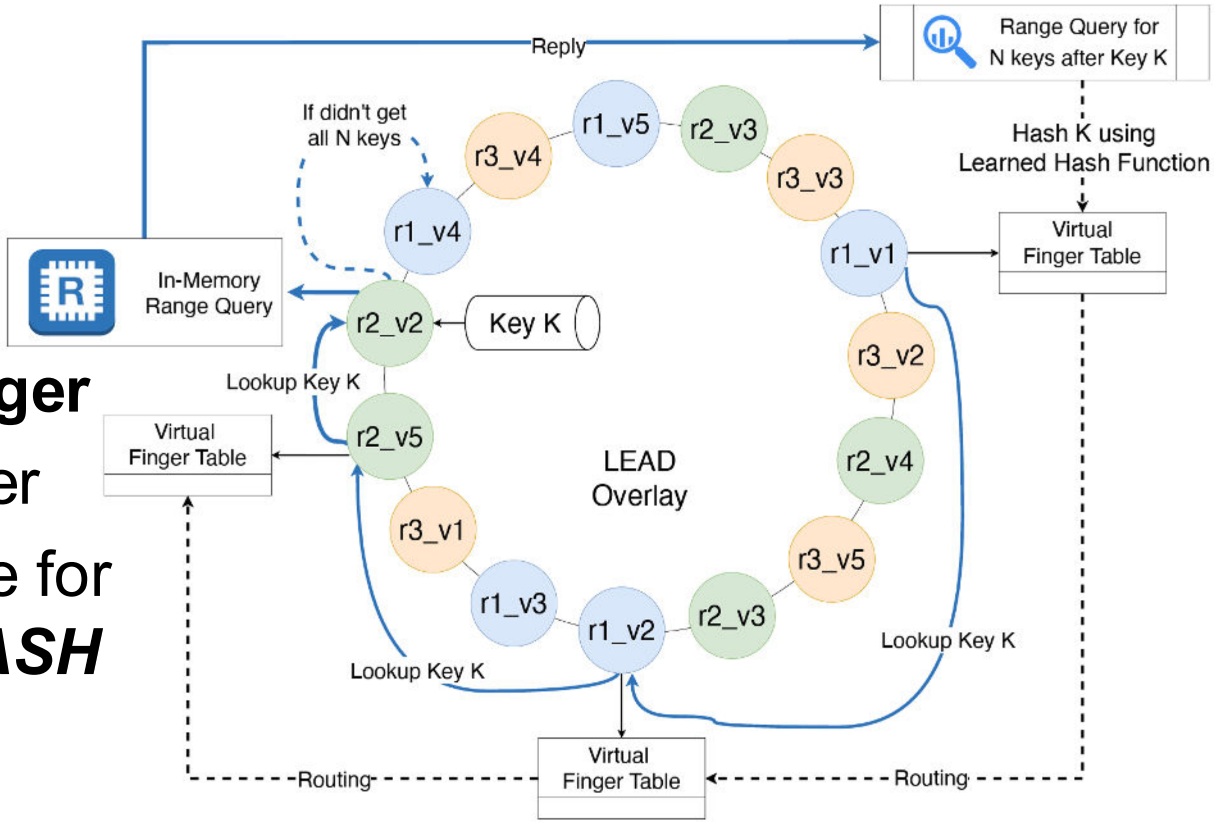


Fig. 5. Range Query in LEAD

Data Retrieval with LHF.

Range Query

- **Hash start key *K*** via Learned hash function
- **Route to owner *S***, do local in-memory range, then **successor chain** if needed (typically 0/1 hops)

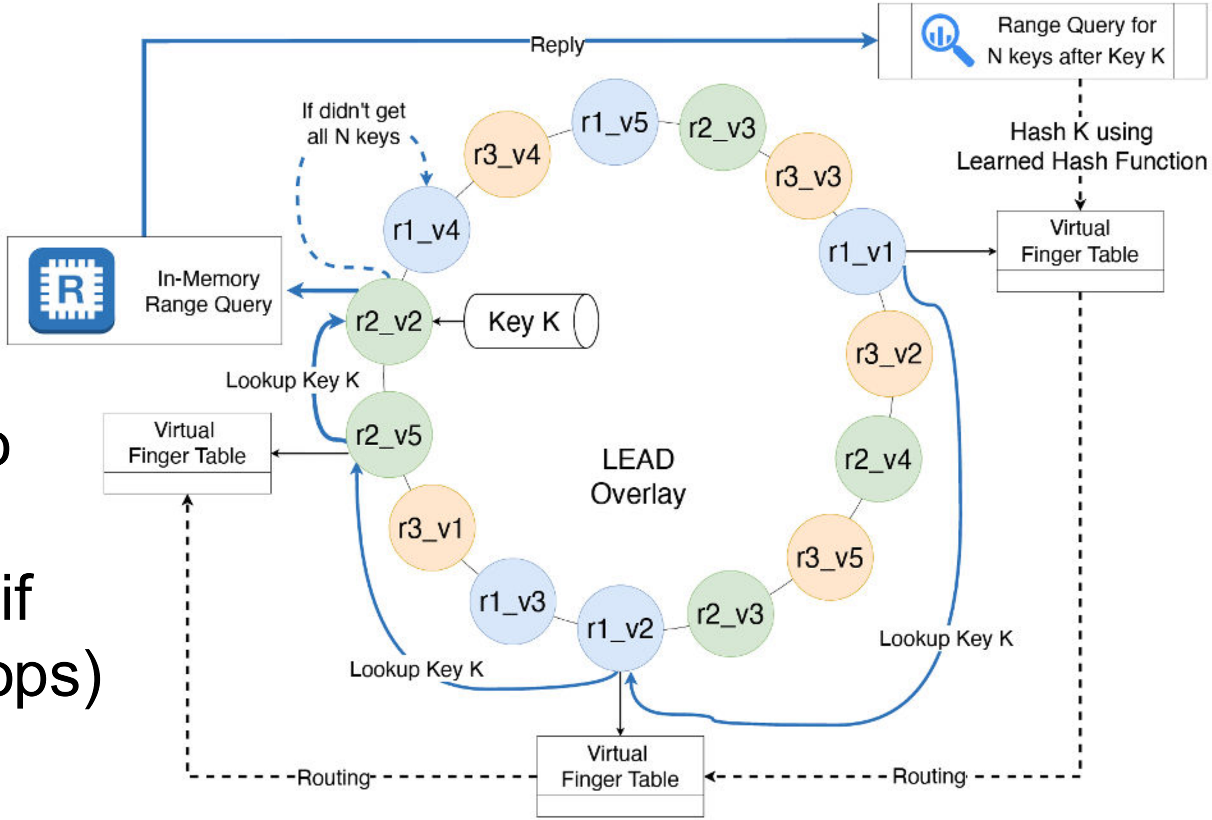


Fig. 5. Range Query in LEAD

Federated Recursive Model (FRM)

Model Update for LH

- **Leaves** refined locally
- **Transient** coordinator aggregates neighbors (**avg-reduce**)
- **Consistency** via heartbeats
- System remains **operational**

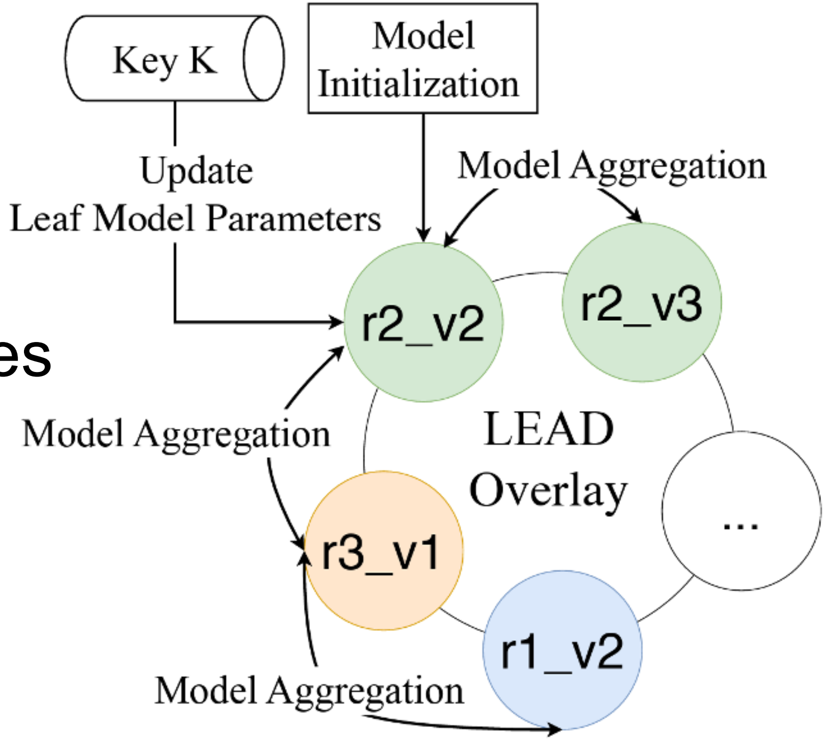


Fig. 4. Collaborative Model Update

LEAD, Leading Performance

Large-scale simulation and Real-world measurement

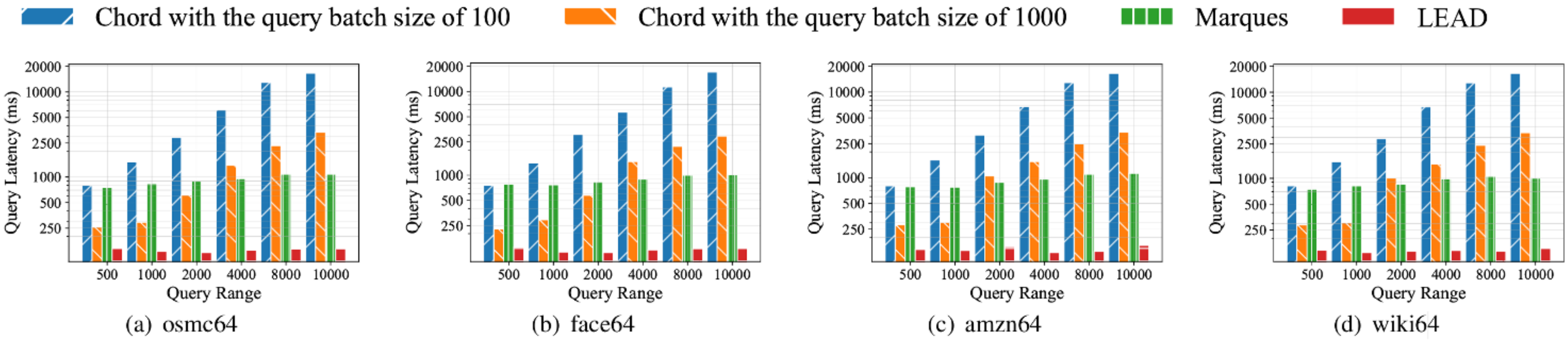


Fig. 6. Latency of range queries on various datasets in the real-machine testbed

- Four baselines covering **batched query** and **range-partition** style (*Marques*)
- LEAD **reducing query latency and message cost by 80% to 90%+**

LEAD, Leading Performance

Large-scale simulation and Real-world measurement

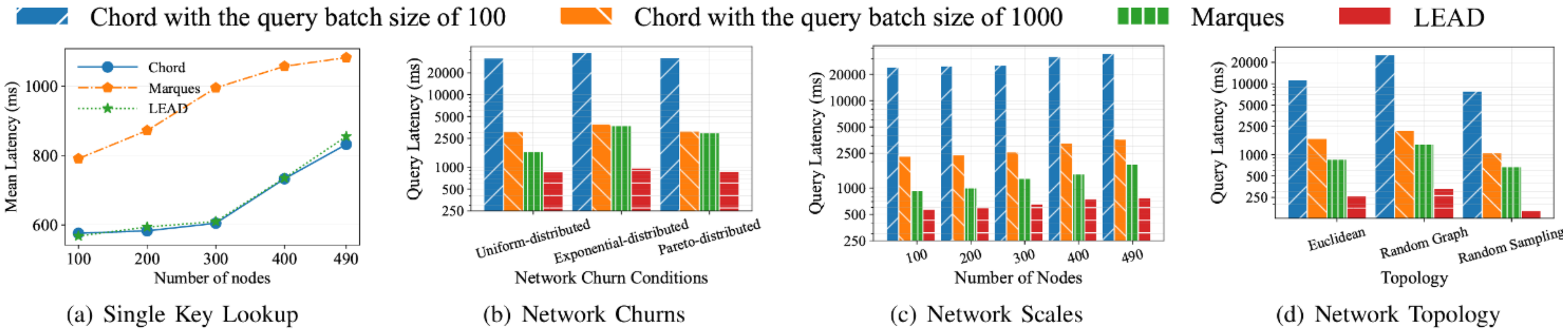


Fig. 9. Latency of range queries under various conditions

- <u>No trade-off with range improvement</u>
- SoTA single-key in O(log N) hops

- **Scale** with network
- Strong network churn **resistance**
- **Minimal** maintenance overhead

LEAD, Leading Performance

Case study I : KV Cache Management for LLM Serving

- 8 × A100×1 nodes, Llama-3 8B, block size 16, **~500M KV blocks**
- Long-DocQA workload; need **contiguous KV ranges**
- LEAD ≈ upper-bound retrieval latency; **dramatically fewer messages** than DHT; **better load balance and scalability**

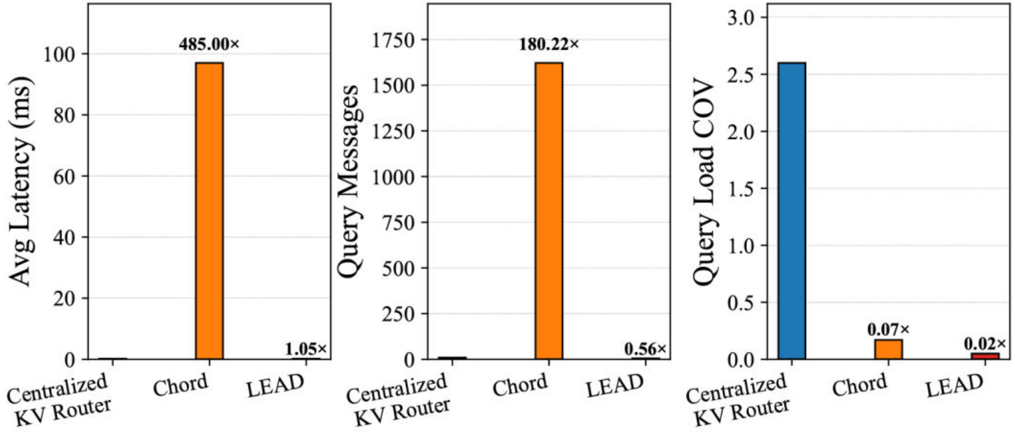


Fig. 15. KV Cache Management

LEAD, Leading Performance

Additional details available

- Detailed setups and results
- Load balancing with *Shadow Balancer*
- Model update during churn
- Benchmark of Learned models
- Shadow Balancer, Learned Model overhead analysis
- Stabilization and Failure Recovery
- Security Considerations
- Case study II : InterPlanetary File System (IPFS)
- Case study III: Blockchain application

LHF

Expanding LEAD into Emerging Domains

Integrating learned models with distributed systems.

- LEAD, a novel distributed key-value storage and lookup system designed to **significantly enhance the efficiency** of range queries by incorporating learned models with DHTs.
- LEAD opens <u>a completely new field for further research on integrating learned models with distributed systems</u>. E.g., **Vector Databases**, **LLM Cache**, **Edge-AI**, **CDN**, **Blockchains**, etc.
- The implementation details are publicly available at https://github.com/ShengzeWang/LEAD.

LHF

Thank you!

Learning to Hash for Networked Systems

- **Opportunity: <u>Your Domain!</u>** , Switch, Blockchain, Edge, etc.
- **Our efforts with LHF: LEAD** (LEArned DHT, ICNP’25), **Vortex** (Vector Overlay for Similarity Search and Delivery, undergoing, ICNP’25 Best Poster), **Knowledge Delivery for LLM Serving** (undergoing)
- Also, check our recent work on **Open LLM Serving**:

GenTorrent: Scaling Large Language Model Serving with An Overlay Network (arXiv:2504.20101)

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