CableCache: In-Network Request Deduplication for Key-Value Stores

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Contents

The load imbalance problem in key-value stores

- Key-value stores are widely deployed in modern data centers.
- Key-value stores face a key challenge posed by skewed dynamic workloads, which can lead to load imbalances.
    - Facebook: 10% of objects account for 60%~90% of requests.
    - Alibaba: The Zipfian parameter reaches 0.9~0.99 in daily scenarios and 1~1.22 in extreme cases.

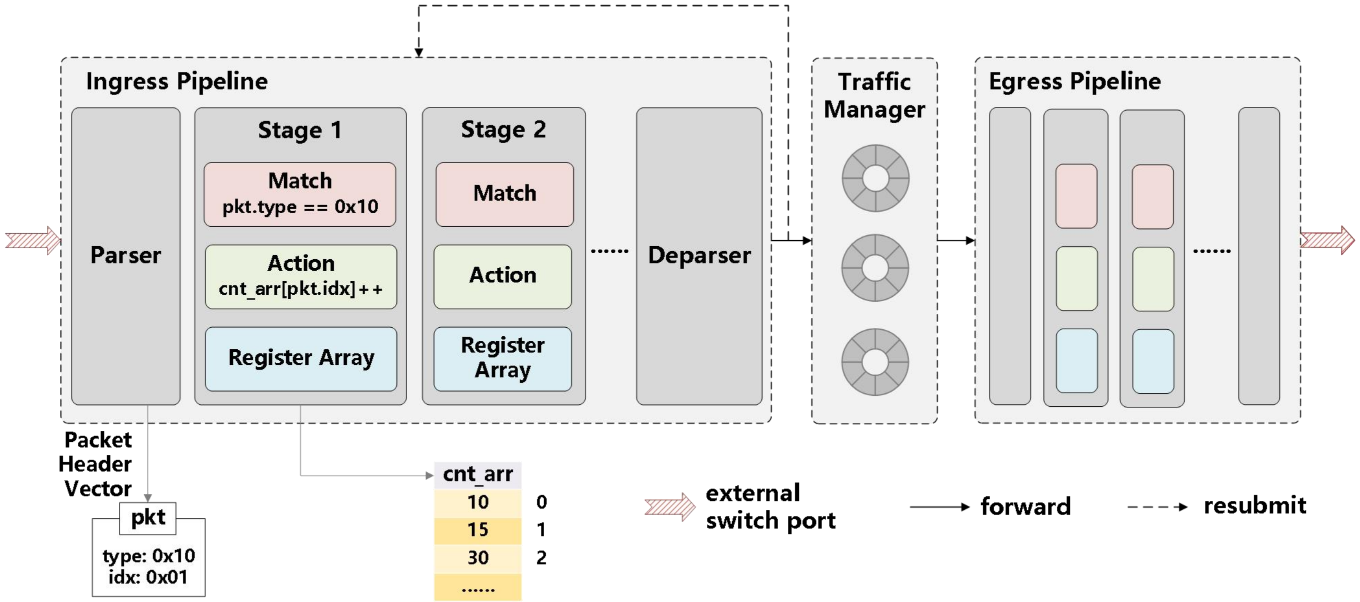
RocksDB

redis

MEMCACHED

A novel network hardware —— programmable switch

- Programmable switches utilize programmable acceleration chips to support user-defined network protocols and packet forwarding logic.
- Current programmable switches contain multiple ingress and egress pipelines.
- A single pipeline consists of multiple stages.



Two advantages of the programmable switch

Position:

processes network packets in the transfer path between clients and storage servers.

Performance:

enables line-rate packet forwarding with throughput on the order of Tbps.

Existing methods' limitations

NetCache / **FarReach**: caches hot objects directly in programmable switches

- The size of object values **cannot exceed 128 B**.
- NetCache does not support write caching.
- FarReach supports write caching but needs complex measures to handle switch failure.

Pegasus: ransfers the directory of selective replication to programmable switches

- The size of object values **cannnot exceed MTU**.
- Directing all requests to storage servers results in longer access paths.
- A complex chain replication protocol is required to prevent data inconsistency caused by switch failure.

Real workloads analysis

- **Twitter**: the top 1% hot objects in 54 workloads of different clusters
  - 35 workloads contain hot objects >128B.
  - 18 workloads contain hot objects >1500 B (Ethernet MTU).
  - 10 workloads contain hot objects >9000 B (jumbo frame max).
  - 25 workloads show median hot object sizes >128 B.
  - 16 workloads include read-modify-write requests (not supported by previous work).
- **Facebook**: the top 1% hot objects in October 2022 sampled workloads
  - 19.35% of top 1% hot objects exceed 128B, yet they generate 86.99% of network traffic.

Request collision analysis

- **processing latency**: refers to the time interval between a switch receiving a request and its corresponding reply.
- **request collision**: occurs when the processing latency periods of requests for the same object overlap.

α	L (μs)				
	10	25	50	75	100
0.99	41.67%	49.56%	55.56%	59.09%	61.59%
1.11	61.66%	67.86%	72.53%	75.12%	76.90%
1.22	72.41%	79.41%	82.81%	84.61%	85.81%

The weighted probability of request collisions for the top 65536 objects.

keyspace: 250 M, **system-wide throughput**: 100 MRPS

α: Zipfian parameter, ***L***: processing latency

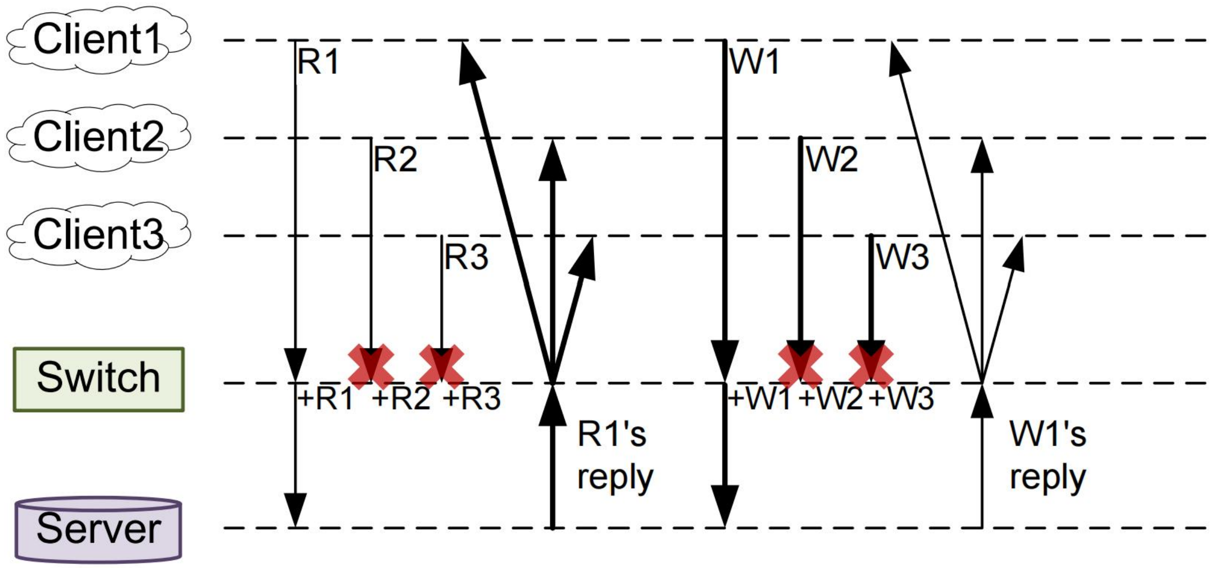
Comparison of Different Methods

Name	Operation	Object Size	Access Path	Switch Failure Handling
NetCache	read	$\leq$ 128 B	short	simple
FarReach	read & write	$\leq$ 128 B	short	complex
Pegasus	read & write	$\leq$ 1 MTU	long	complex
CableCache	read & write & read-modify-write	$\leq$ 32 MTU	medium	simple

CableCache's core idea: Maintaining an object request information directory in the programmable switch to avoid repeated requests for hot objects.

Packet flow

- CableCache separates the deduplication processing of read and write requests.
- The first read request **R1** will be recorded in the switch and sent to the storage server.
- The read request **R2** and **R3** will be recorded and then dropped.
- The write packet flow is similar.



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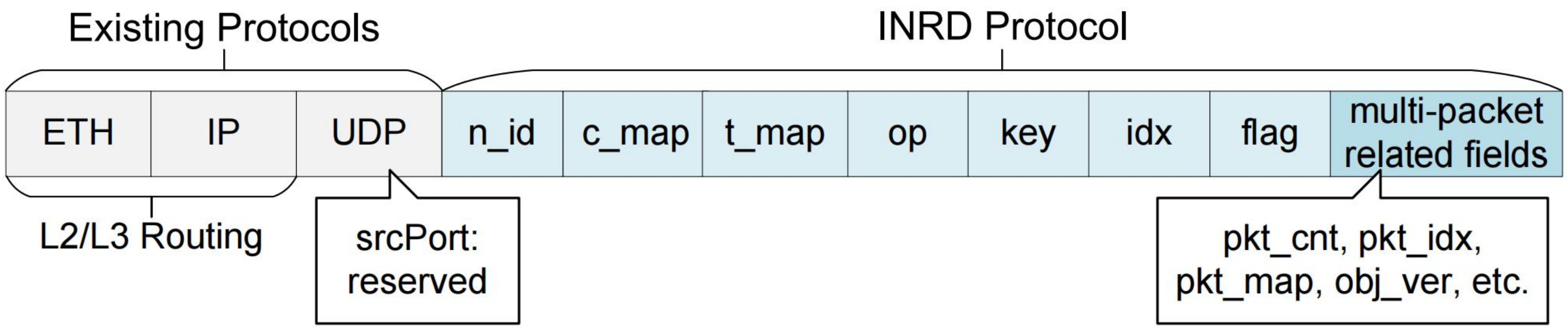
Packet header format

- We propose the **I**n-**N**etwork **R**equest **D**eduplication (INRD) protocol, an application-layer protocol using a specific UDP source port.
  - **n_id**: the target node ID
  - **c_map**: the one-hot encoding of the client ID
  - **t_map**: the one-hot encoding o the thread ID
  - **op**: the operation type (e.g. read request, read reply, write request, write reply)



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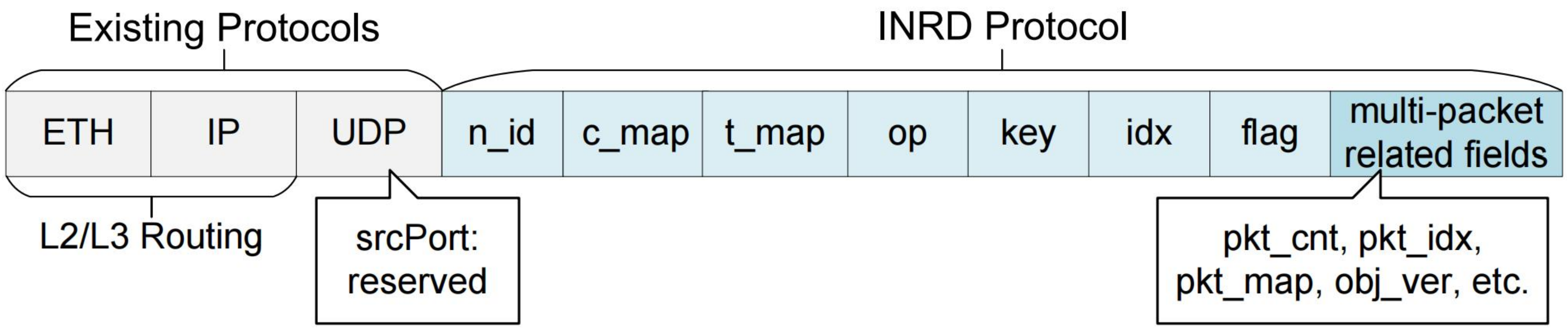
Packet header format

- We propose the **In-Network Request Deduplication** (INRD) protocol, an application-layer protocol using a specific UDP source port.
  - **key**: the target key (fixed length, 32 bits)
  - **idx**: the record index within the switch (hash the 32-bit key to 16 bits)
  - **flag**: “0”: direct forwarding; “1”: executing deduplication logic (client default value)
  - **multi-packet related fields**: to handle multi-packet objects’ requests



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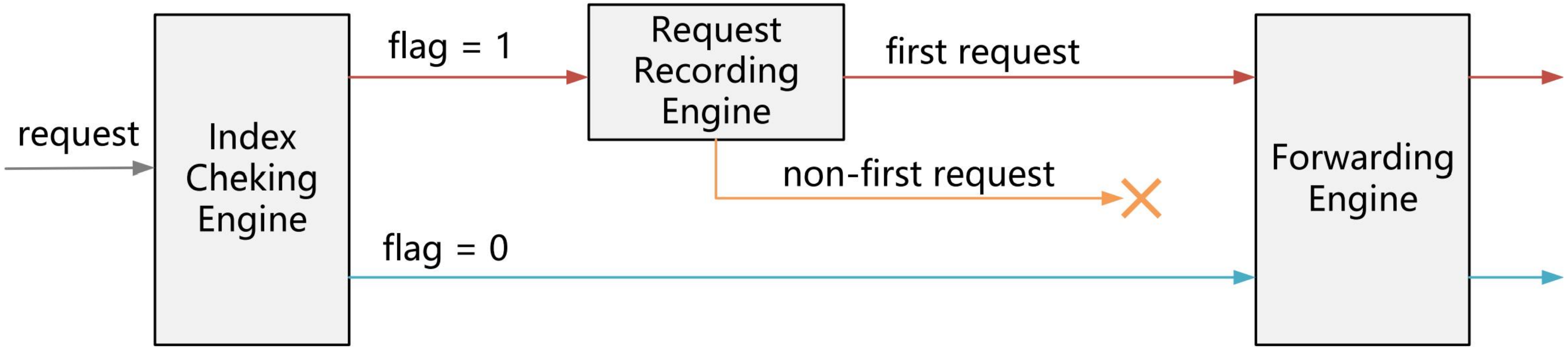
Switch request processing

- **index checking engine**: state register array + key register array
  - If the state register value is “0”, set the state register to “1”, set the key register to the key field value, and mark the request as “first request”.
  - If the state register value is “1”, when the key register value mismatches the key field, set the flag field to “0” and forward the request packet directly.



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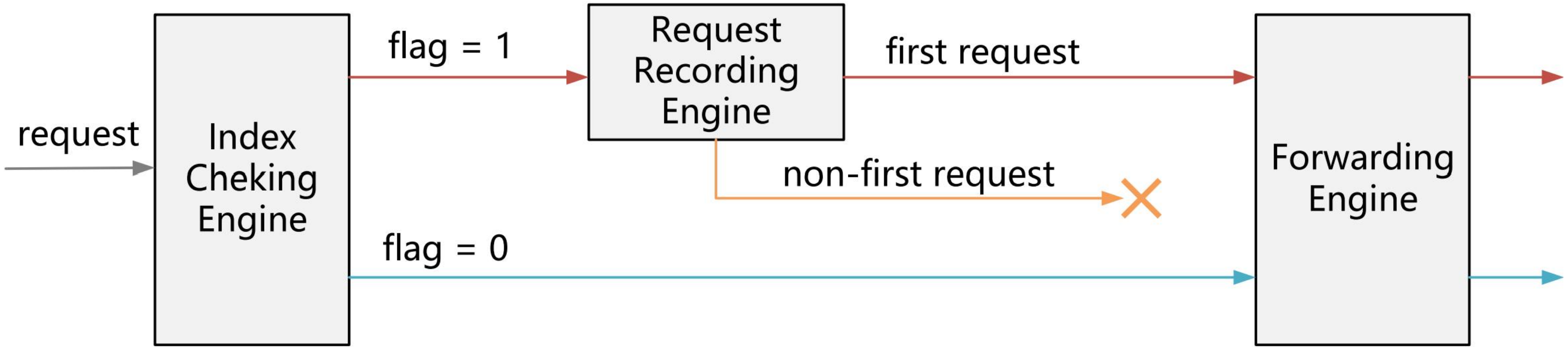
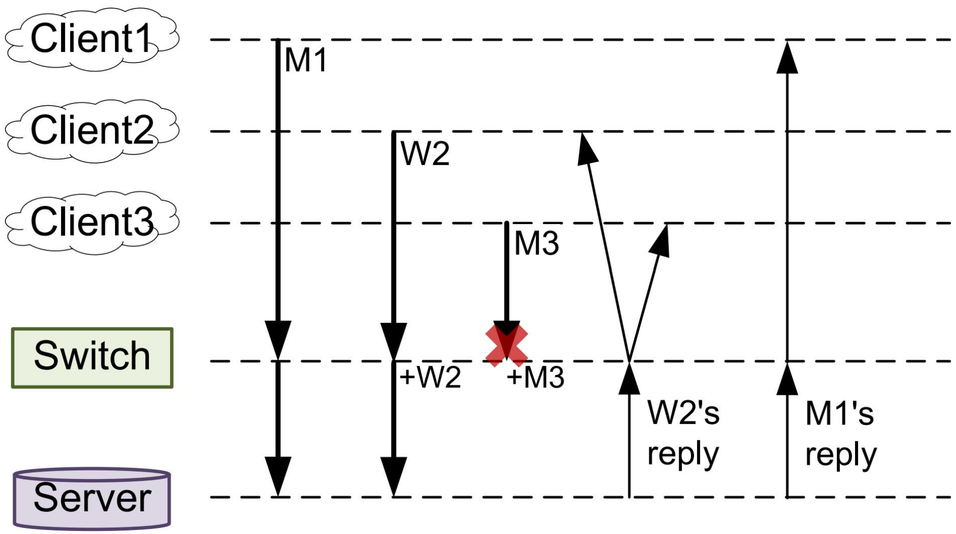
Switch request processing

- **request recording engine**: client bitmap register array + thread bitmap register array
  - The client bitmap register and the corresponding thread bitmap register are updated with the c_map and t_map fields using the bitwise OR operation.
  - If the request is marked as “first request”, forward it to the storage server.
  - If the request is not marked as “first request”, drop it directly.
- **forwarding engine**: set forwarding information for the packet



Complex scenario #1: read-modify-write request

- CableCache integrates RMW requests into the write request deduplication module.
- RMW requests can’t be marked as “first request” to guarantee linearizability.
- The switch will set the flag field to “0” and directly forward the RMW request **M1**.
- The first write request **W2** will be recorded in the switch and sent to the storage server.
- The RMW request **M3** will be recorded and then dropped.



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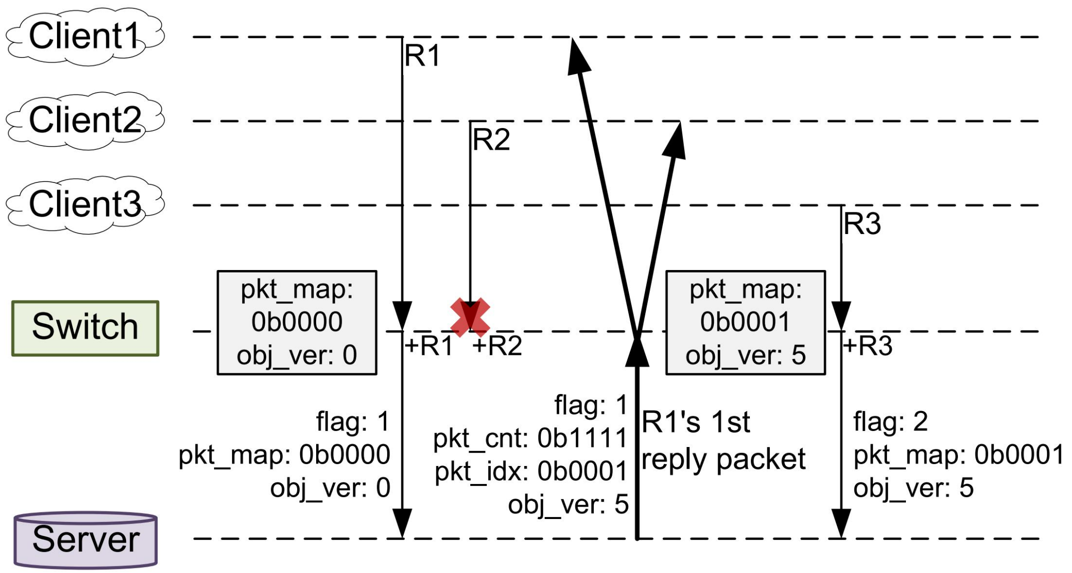
Complex scenario #2: multi-packet object

- CableCache employs a **compensatory read mechanism** to handle multi-packet objects' read requests.
- The switch maintains a **pkt_map register array** and an **obj_ver register array**, representing received reply packet IDs' bitmap and the object version number.



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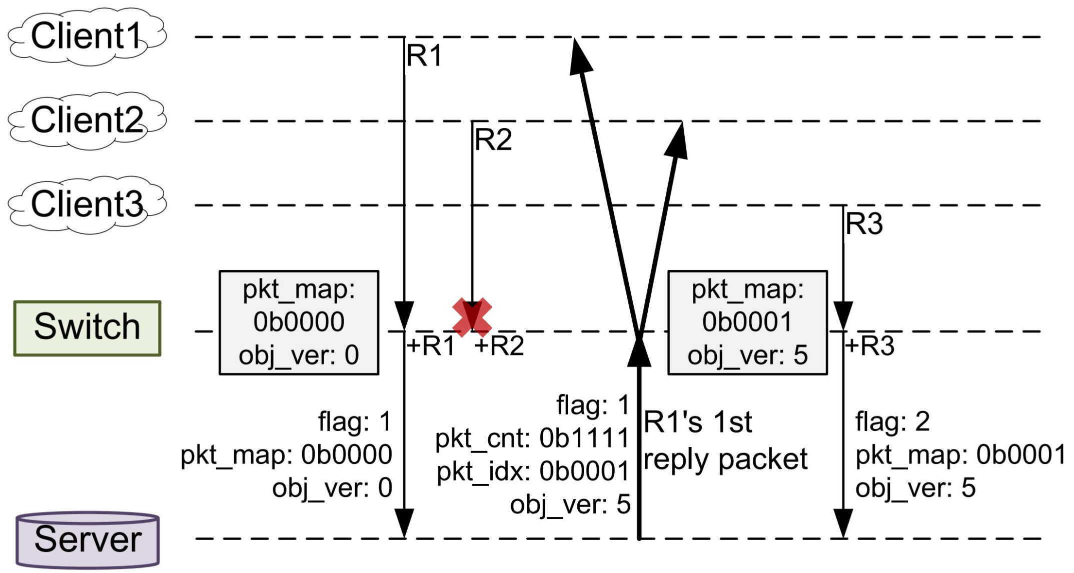
Complex scenario #2: multi-packet object

- When the non-first read request arrives, if the pkt_map register value is “0”, the request will be recorded and dropped (e.g., **R2**).
- Otherwise, the pkt_map and obj_ver registers will be set, and the flag field will be set to “2”, which means the compensatory read mechanism should be used (e.g., **R3**).



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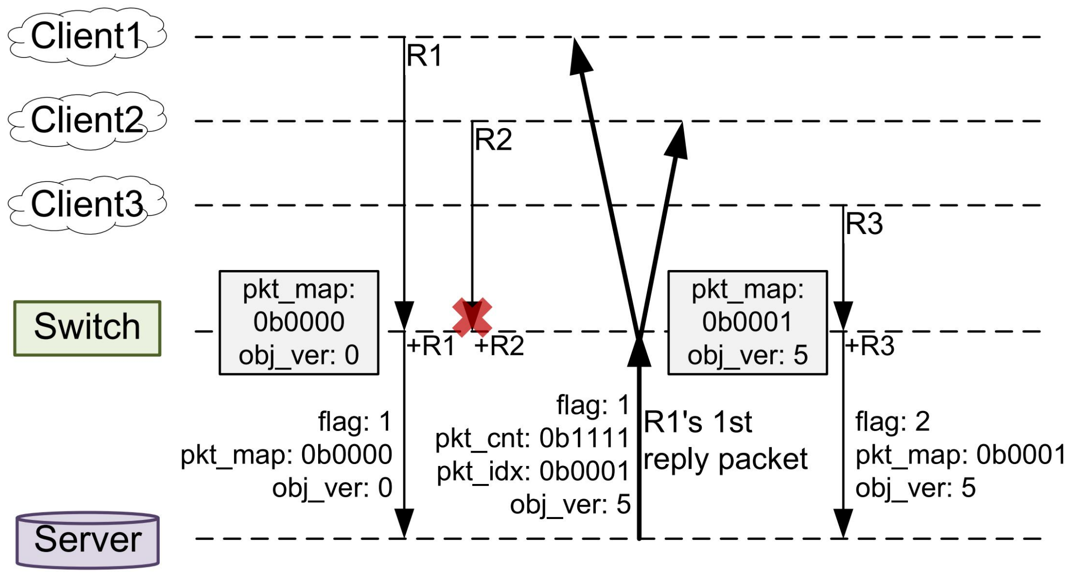
Complex scenario #2: multi-packet object

- The storage server checks whether its recorded object version number is ahead of the packet's obj_ver field.
- If not, the server only returns the reply packets indicated by the pkt_map field.
- Otherwise, the server must return all reply packets.



Discussion #1: variable-length key

- The variable-length key needs to be mapped to 32 bits using a hash function.
- The original key must be included after the header.
- If a client receives the reply packet mismatching its target key, it should resend the request while bypassing the request deduplication logic.

Discussion #2: packet loss

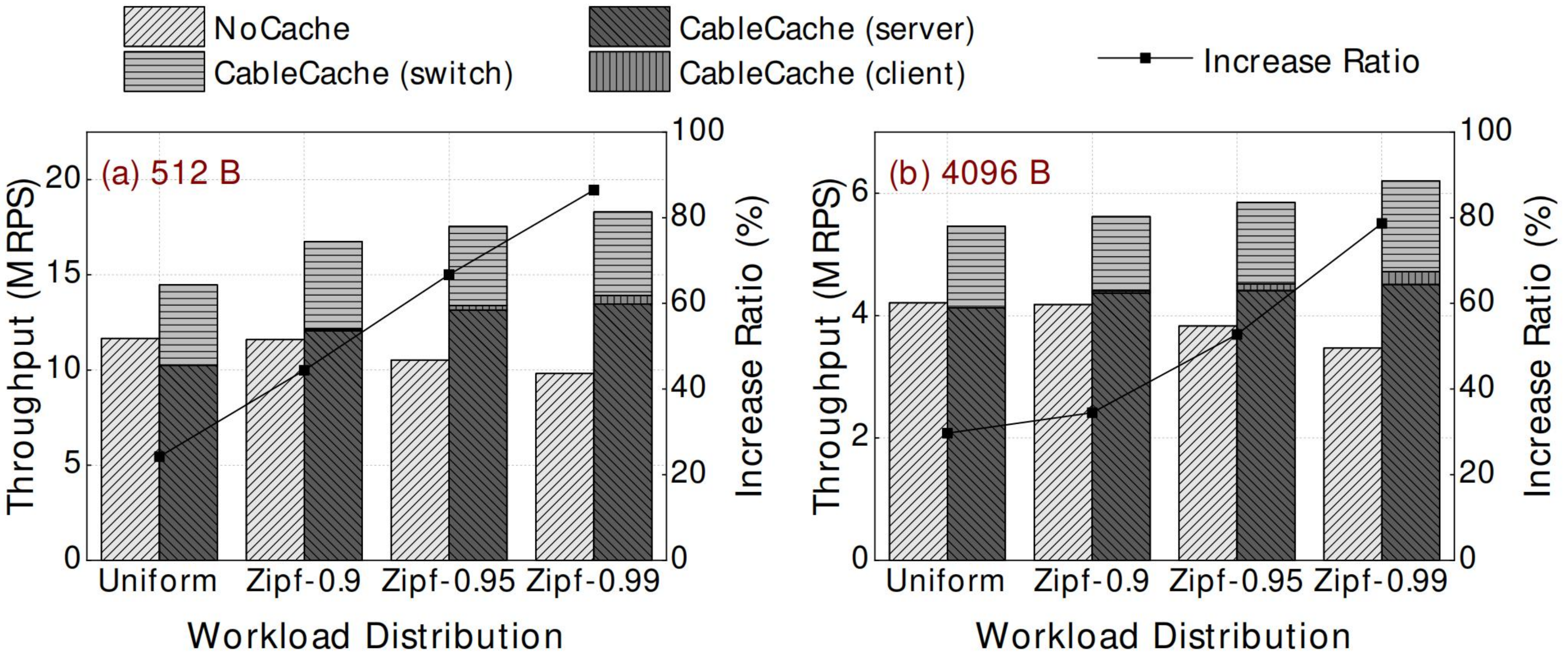
- A timeout mechanism can be used by clients to address packet loss issues.
- A timestamp checking mechanism can be introduced to prevent the issue of record indexes being continuously occupied.

Methodology

- **Testbed**
  - 6 hosts are connected by a Barefoot Tofino Wedge 100BF-32X switch.
  - 4 hosts act as clients, each running 12 threads.
  - 2 hosts each run 12 threads to simulate 24 storage servers.
- **Default workload**
  - **keyspace**: 100 MB, **Zipfian parameter**: 0.99
  - **proportion of request types**: 90% (read) : 8% (write) : 2% (CAS)
- **Default configuration**
  - **MTU**: 1092 B, **storage backend**: Redis, **cache record count**: 65536
  - **object value size**: 512 B (single-packet) and 4096 B (multi-packet)
  - **coroutine count per client thread**: 16

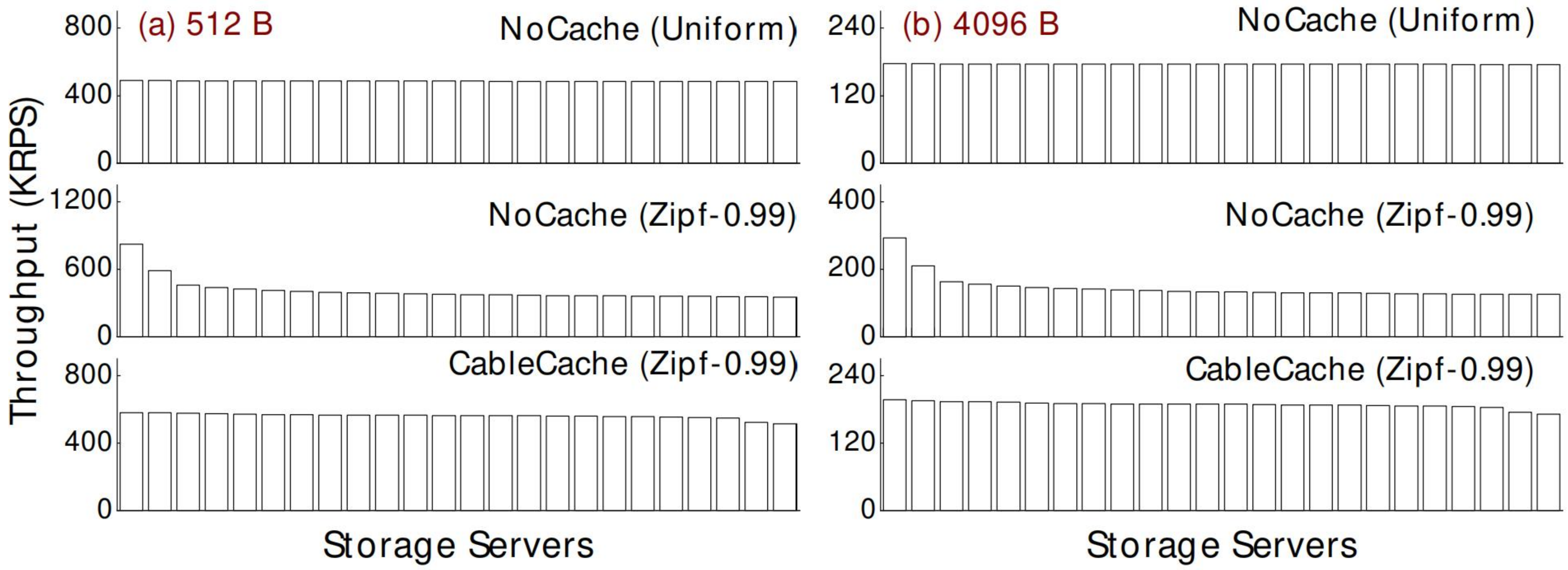
Throughput analysis

- The increase ratio of throughput grows significantly as the workload skew intensifies.
- Higher workload skew exacerbates load imbalance across storage servers, leading to more frequent request collisions.



Throughput analysis

- The figure presents the load distribution across different storage servers, sorted in descending order.
- CableCache significantly improves load balancing across storage servers.



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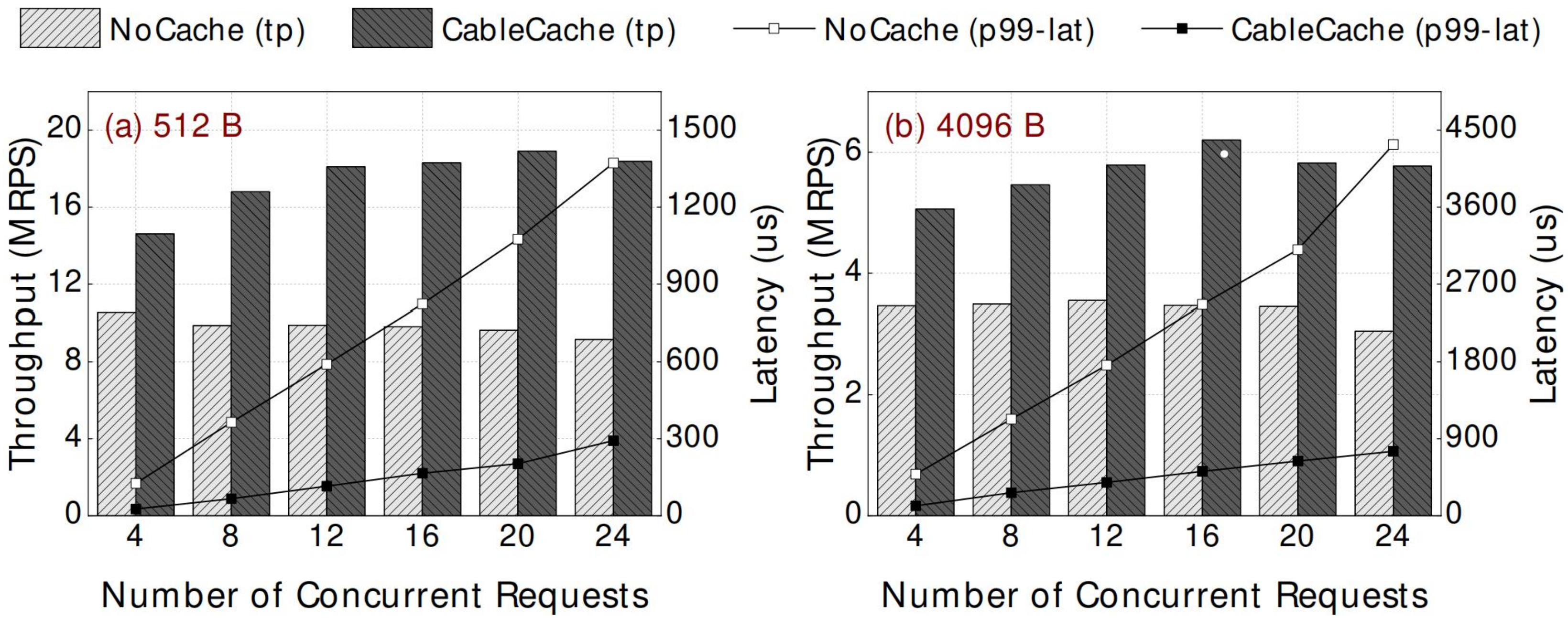
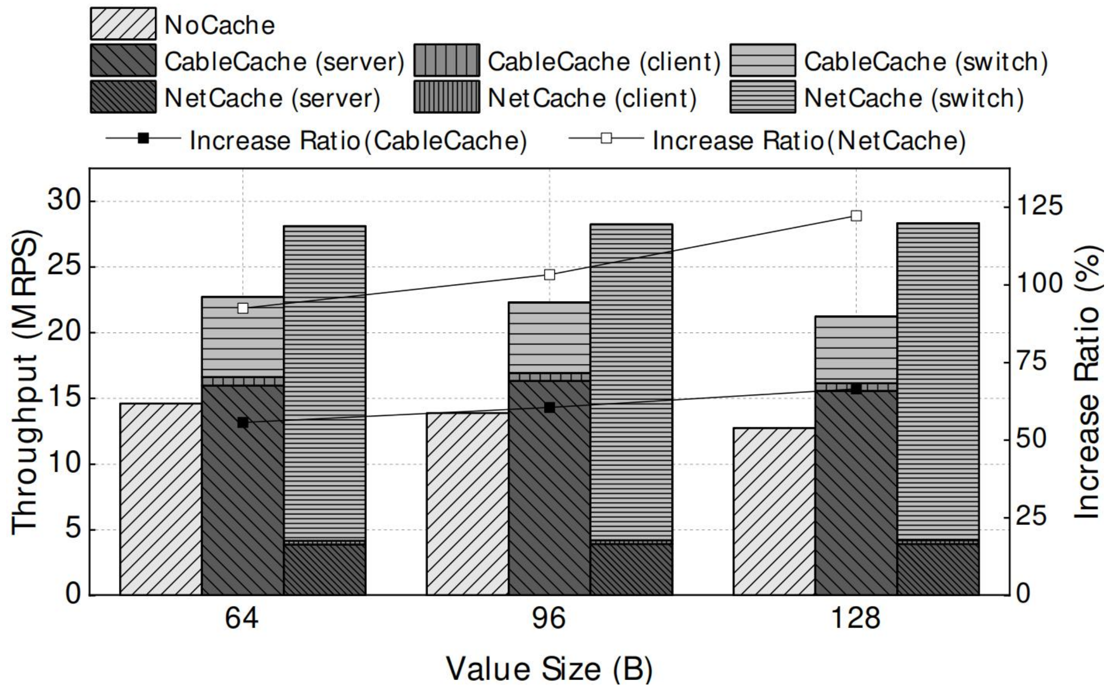
Latency analysis

- The number of concurrent requests equals to the number of coroutines per thread.
- CableCache can mitigate tail latency escalation caused by higher concurrency levels effectively.



Handling small objects

- Employ a read-only workload to conduct a comparison between **CableCache** and **NetCache**.
- NetCache enables the majority of small objects to be cached within switches.
- CableCache still requires forwarding most requests to storage servers, resulting in a lower increase ratio of throughput.



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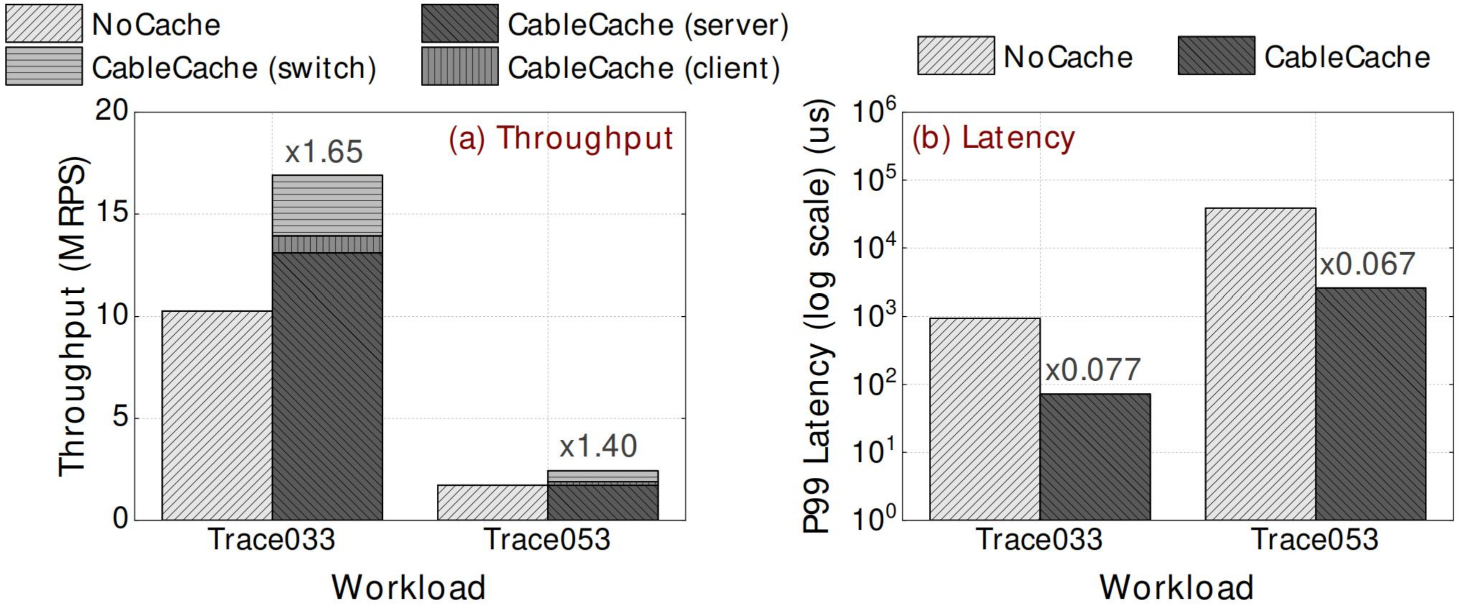
Handling real workloads

- Select **Trace033** (average value size: 1118 B) and **Trace053** (average value size: 9213 B) from two different clusters in Twitter's workload.
- CableCache improves system-wide throughput and reduces the P99 latency effectively under real workloads.



CableCache: an in-network request deduplication system

- Leverages programmable switches to maintain a directory of object request information.
- Introduces the INRD protocol to deduplicate hot object requests.
- Effectively handles complex scenarios such as the presence of read-modify-write requests and multi-packet target objects.

Experimental results show CableCache's effectiveness

- Alleviates load imbalance under both synthetic and real workloads.
- Improves system-wide throughput, and reduces tail latency of requests.

Thanks for Listening!
Q & A

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