MAD2: A Scalable High-Throughput Exact Deduplication Approach for Network Backup Services

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Target Application

- backup storage systems
- network backup services
  - decentralized peer-to-peer schemes based on peer-cooperation over distributed network
    - trade local resources for remote storage capacity
  - **centralized storage provided by storage service providers (SSPs)**
    - trade money for reliable backup and provide better quality-of-service (QoS)

Build a Scalable and Cost-effective Backup/Archiving Storage System

- deduplication technology has been widely applied in disk-based secondary storage systems
- two technical challenges
  - *duplicate-lookup disk bottleneck*
    - determine if an incoming data object is a duplicate, the index can become too large for RAM to hold in its entirety
  - *storage node island effect*
    - eliminate duplicates among multiple servers

Find the Key

- ***Duplicate Detection Methods***
  - **examine the file system metadata**
  - **adopt content-based fingerprint**
    - **Granularity: whole files, fixed-size blocks, or variable-sized chunks**
- ***Duplicate Lookup Acceleration Methods***
  - **exploit data locality – DDFS, Sparse Indexing**
  - **exploit file similarity – Extreme Binning**

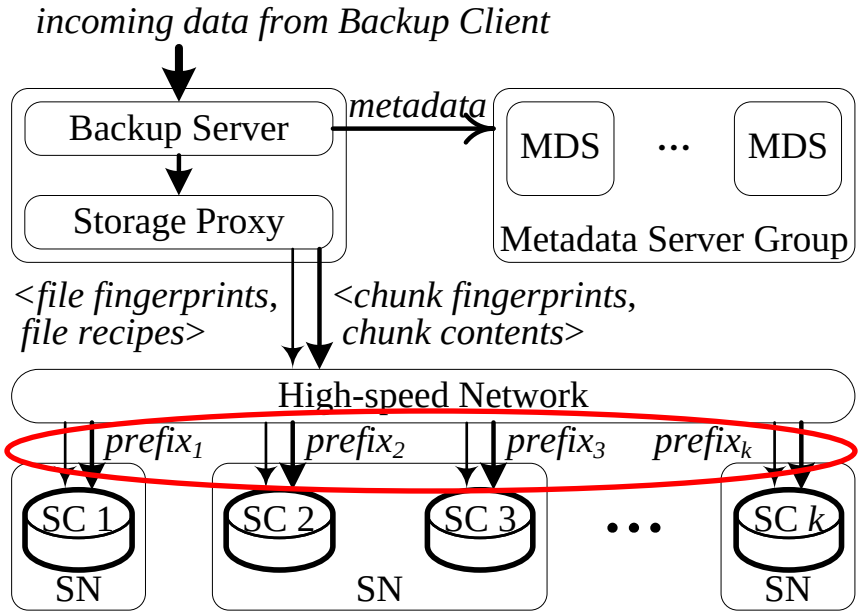
  (fast membership determination of incoming data objects)
- ***Enable Scalability***
  - **distributed hash table – Extreme Binning, HYDRAstor**

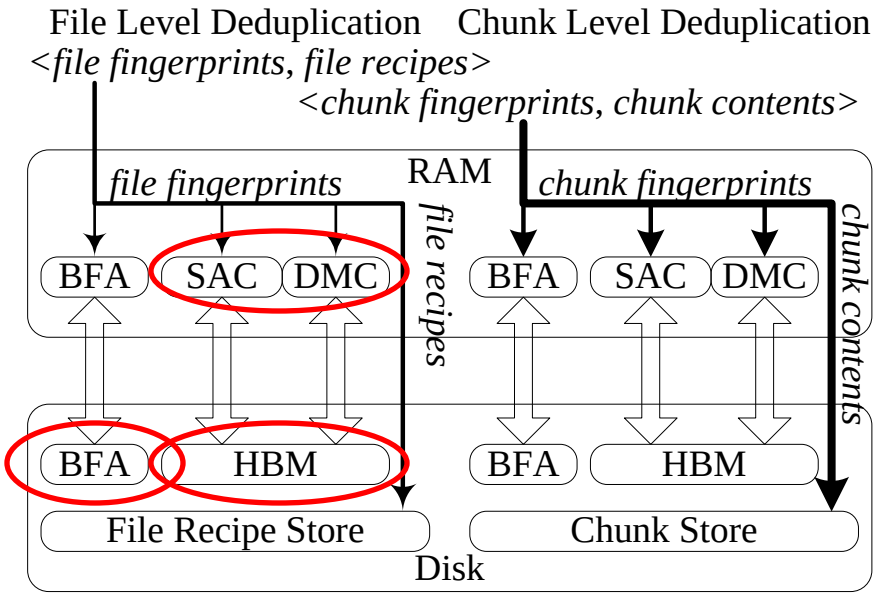
  (partition data into dissimilar or less similar groups)

Outline

- Background and Motivation
- The MAD2 Architecture and Design
- Prototype Implementation and Evaluation
- Conclusions, Questions

The MAD2 Architecture

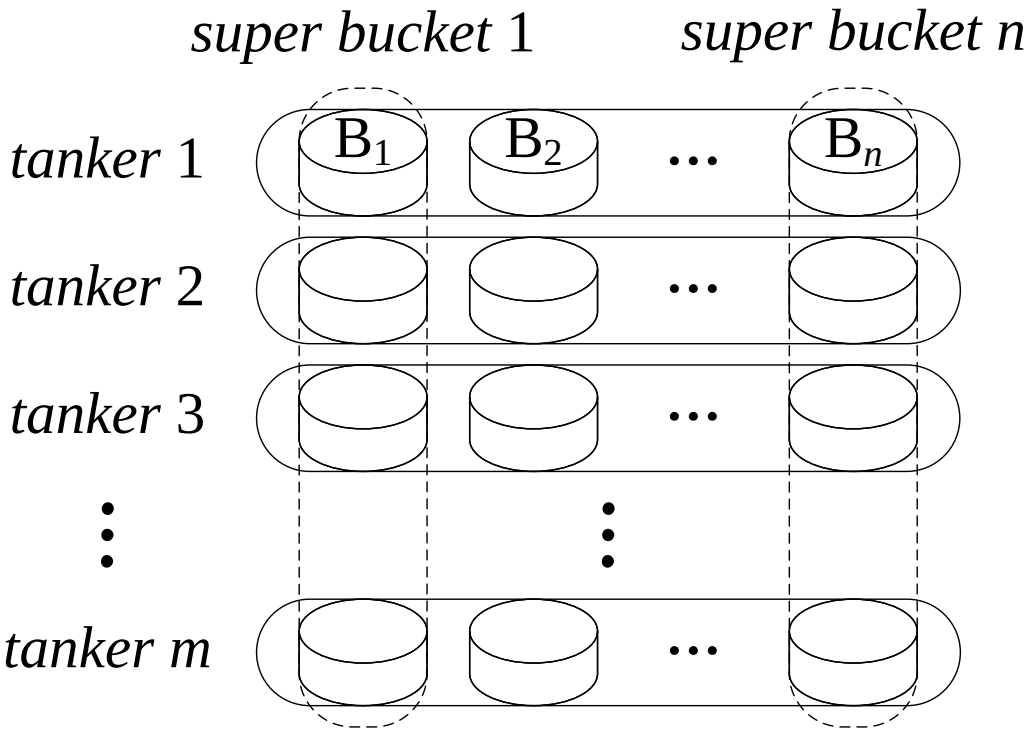




- **Hash Bucket *M*atrix (HBM)**
- **Bloom Filter *A*rray (BFA)**
- ***D*ual Cache**
- ***D*HT-based Load-Balance**

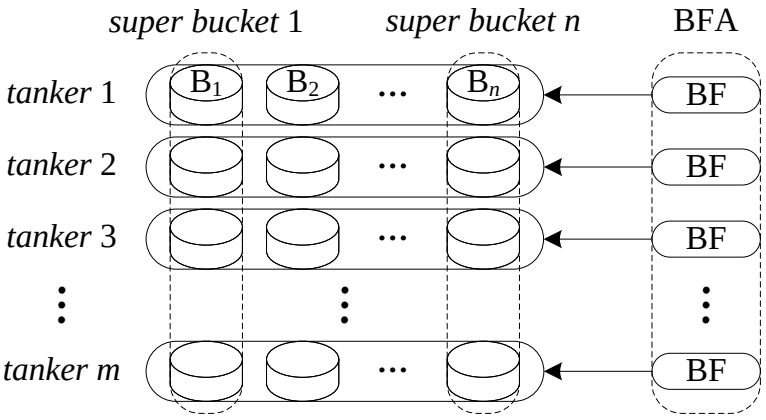
Locality-Preserved Hash Bucket Matrix

- Consecutive fingerprints belonging to the same backup job have a high probability of being stored in the same tanker.



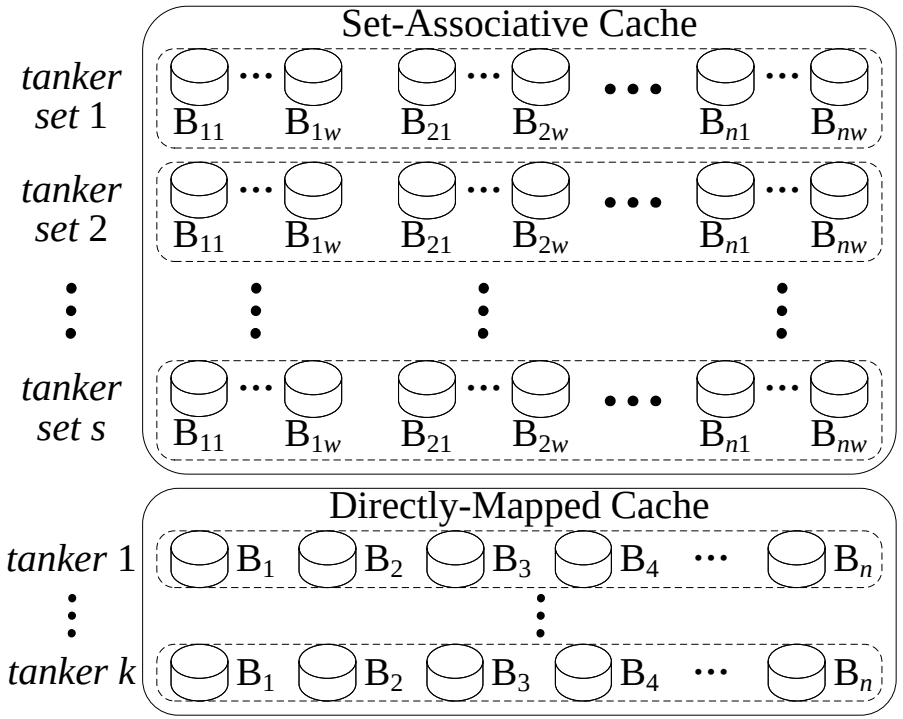
Using Bloom Filter Array as Quick Index

- Single Bloom Filter - Drawbacks
  - potential total number of fingerprints is difficult to estimate.
  - a single BF is ineffective in locating possible duplicates.
  - physical fingerprint deletion will result in rebuilding of the whole BF.
- Employ a Bloom Filter Array (BFA)
  - associate each tanker with a Bloom Filter, add a Bloom Filter along with a new tanker.
  - all the Bloom Filters are isomorphic and share the same hash functions.
  - add a Bloom Filter along with a new tanker.



Dual Cache Mechanism

- *Dual Cache* is designed to improve disk access efficiency while locating duplicate fingerprints.
  - *directly-mapped cache* (DMC)
    - capture the fingerprint locality in backup streams
    - periodically rebalance the hash bucket matrix
  - *set-associative cache* (SAC)
    - exploit the fingerprint locality in backup data



DHT-based Load Balancing

- Each SC is only responsible for file recipes and chunks with the same specific fingerprint prefix.
  - Because fingerprints with different prefixes are collision free, and if each SC performs exact deduplication in its responsible hash sub-space, the entire backend storage can achieve global exact deduplication.

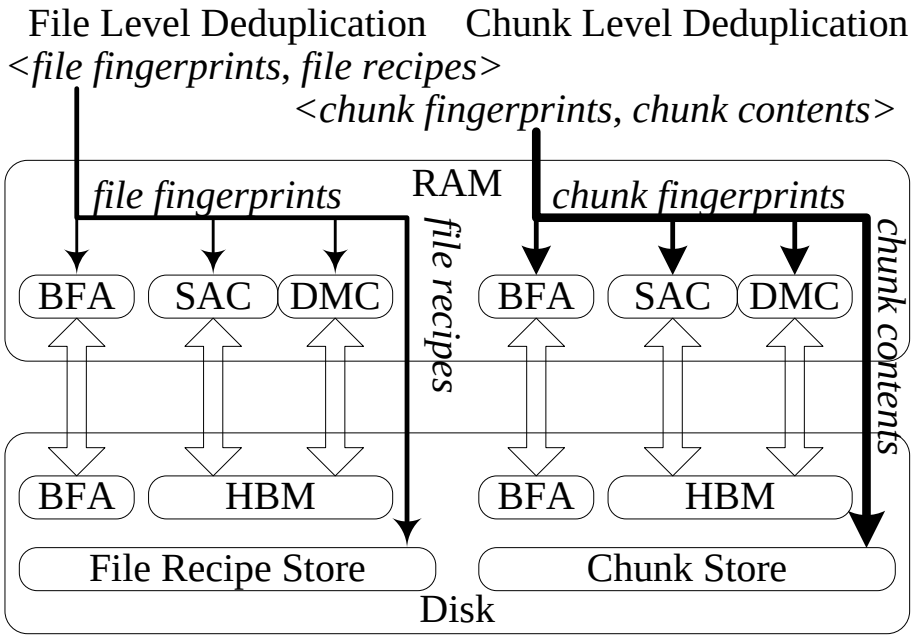
- Both file recipes and chunk contents will be distributed in their backup sequences to preserve locality.
  - Consider a sequence of fingerprints with two different prefixes (*a*1, *b*0, *c*1, *d*1, *e*0, *f*1, *g*0). MAD2 divides them into two sub-sequences (*a*1, *c*1, *d*1, *f*1) and (*b*0, *e*0, *g*0), and distributes each sub-sequence to one responsible SC.

Data Organization and Deletion Support

- all the chunk contents are kept in *chunk store*, which consists of *chunk tankers* corresponding to *tankers* in HBM.
- inside each chunk tanker, chunks are grouped and packaged into *chunk containers* in a stream-locality-preserved manner.
- *counting fingerprint:* structured as <*fingerprint*, *data length*, *reference count*>
  - a file or a chunk will not be physically deleted until the associated reference count drops to *zero*.
  - adjacent tankers can be merged if they are sparse enough.
  - all the involved Bloom Filters will be reconstructed.
  - a physical delete operation is executed in a batch mode. all involved tankers must be changed to the read-only mode to maintain data consistency.
  - exposes only a file-level delete interface to SC clients.

Workflow of the MAD2 Approach

- two phases:
  - ***eliminate duplicate files***.
  - ***eliminate duplicate chunks***.
- two inline deduplication modes:
  - ***exclusive mode***: targets at high-speed backup streams that can finish data transmission in short time windows.
  - ***round-robin mode***: aims at low-speed backup streams that will be buffered by SP (storage proxy).



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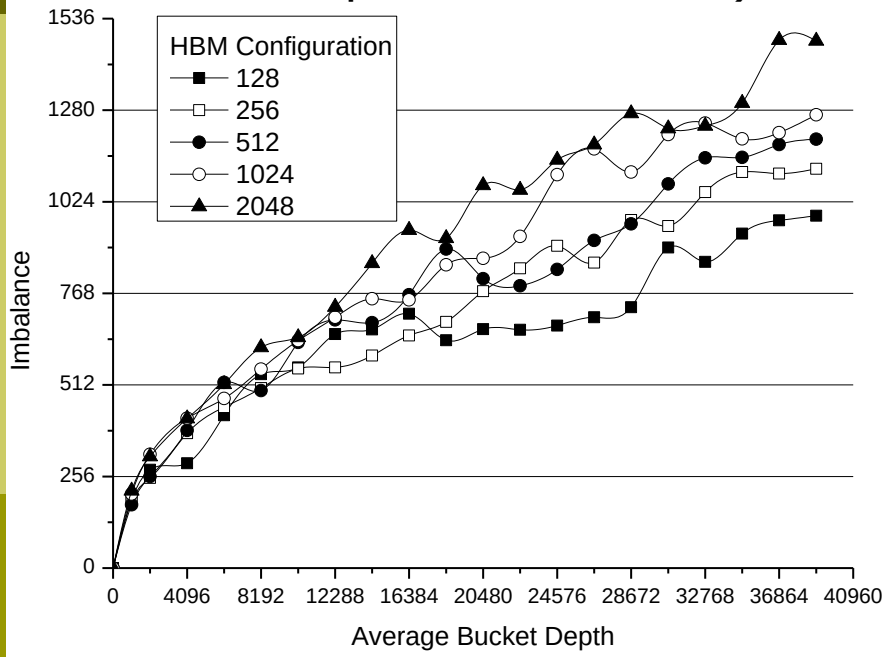
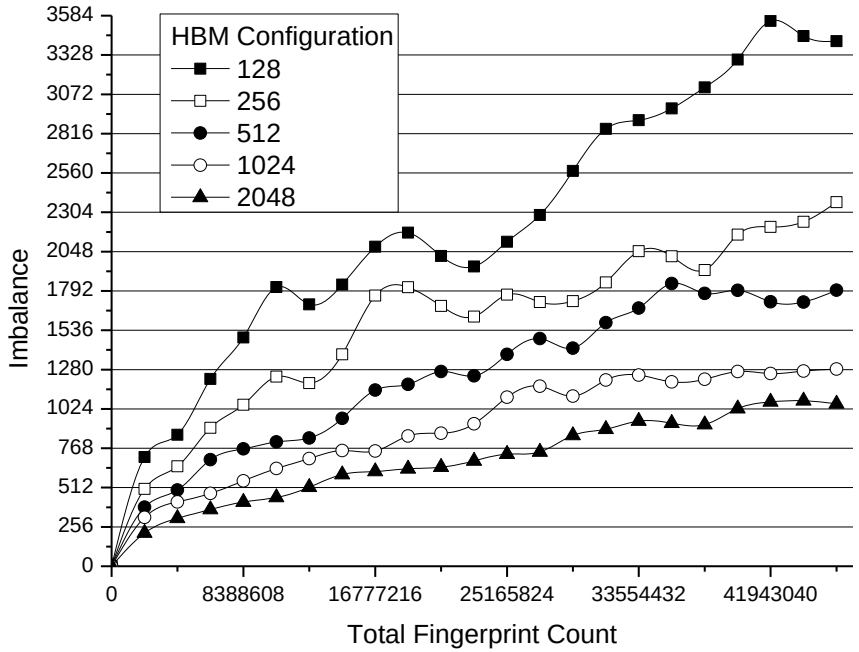
Experiment Datasets

- *Workgroup* set
  - collected from an engineering group consisting of 15 graduate students
  - 12.1 million files, 6.0TB data
- *Campus* set
  - collected from 26 users on a campus network, including personal website owners, small file transfer site managers and other individuals.
  - 15.4 million files, 4.7TB data

Locality-Preserving Capability of HBM

- Let each super bucket consist of only one bucket, we examine five different configurations of HBM (i.e., 128-, 256-, 512-, 1024-, and 2048-super-bucket HBM)





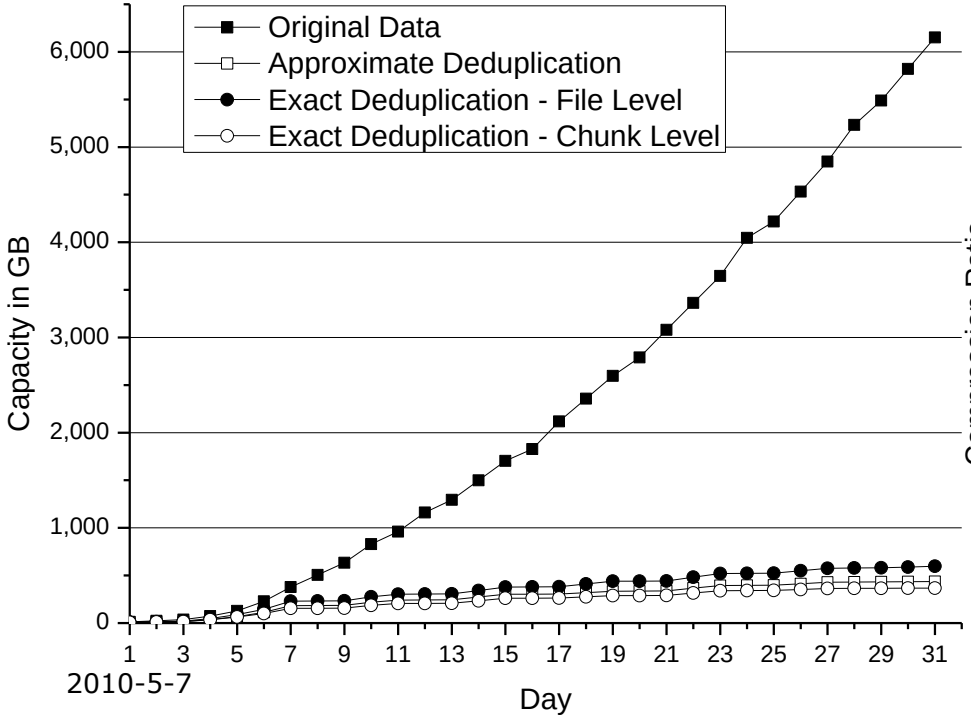
- Tanker Structure: 1,024 buckets plus 1,024 fingerprint cells
- Rebalancing Threshold: 1,024

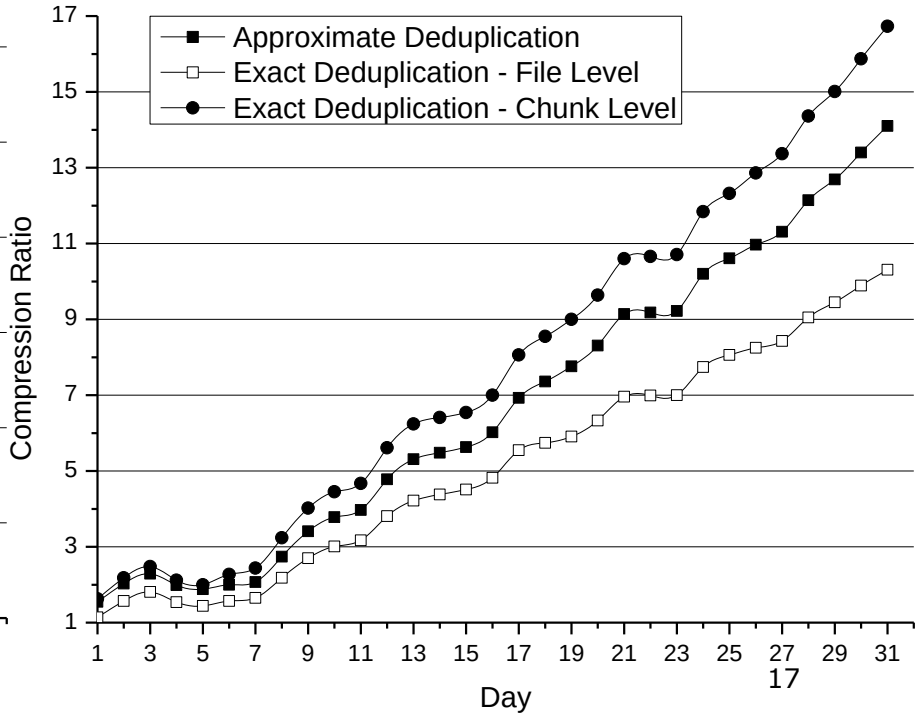
Hot Fingerprint

- *detected 84,876,504 duplicate chunks with the same content of 1,024-byte zeros*.
- *zero-chunks* may be widely shared even among dissimilar files.
  - can disrupt the chunk locality and affect the efficiency of our cache mechanism.
  - pre-calculate the SHA-1 hash of 1KB *zero-chunk*, and define it as a built-in fingerprint.

Deduplication Efficiency

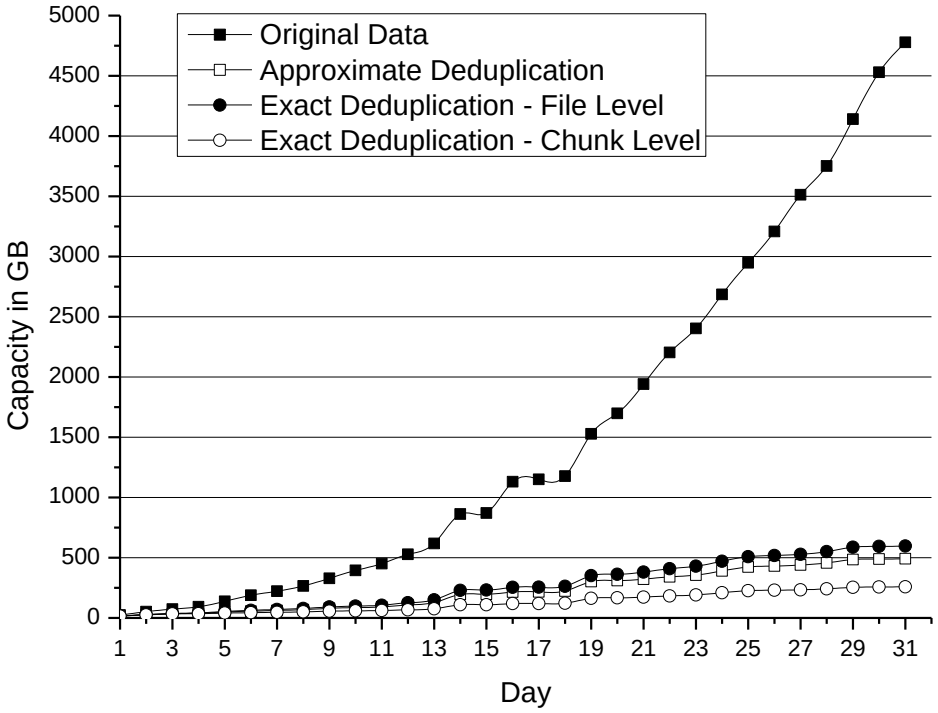
- Workgroup Set
  - implemented a simple version of Extreme Binning to represent *approximate deduplication*.

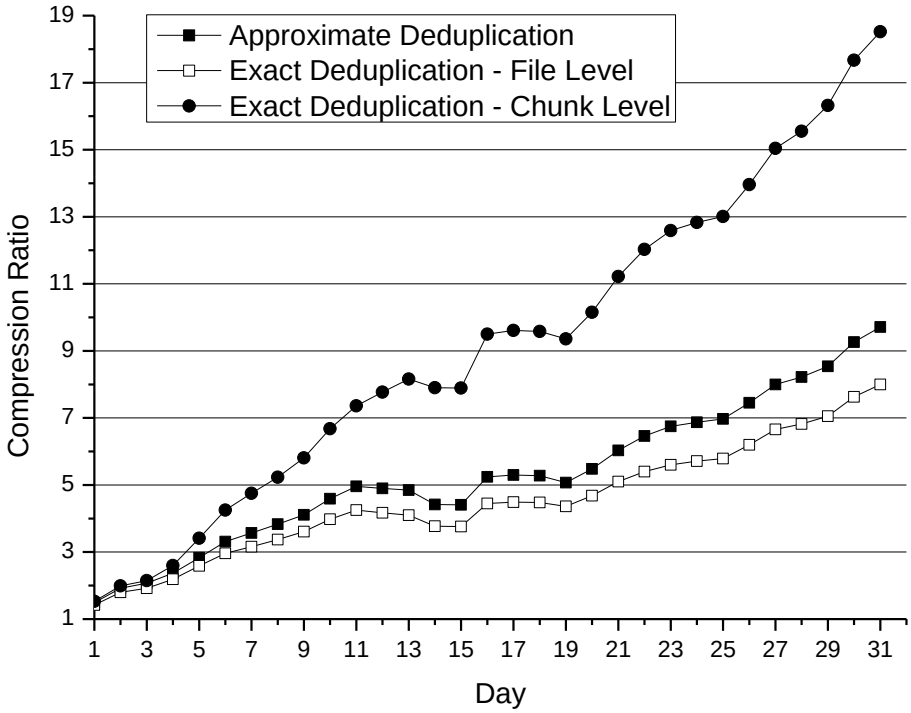




Deduplication Efficiency

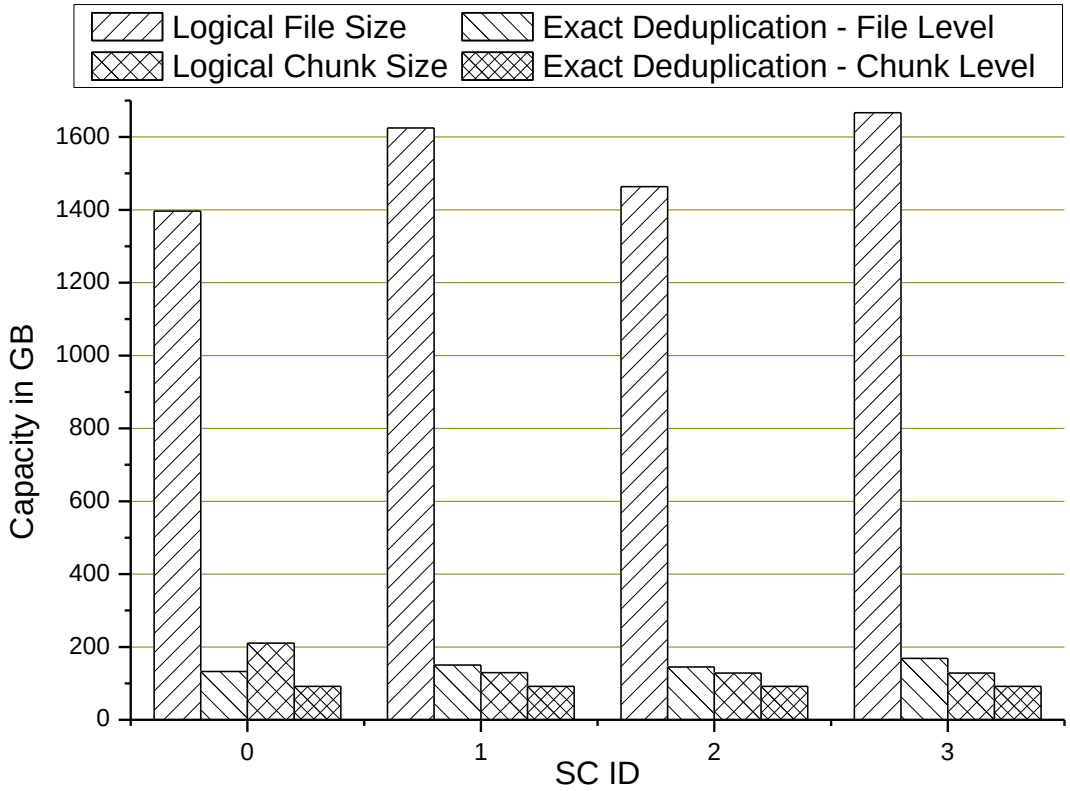
- Campus Set





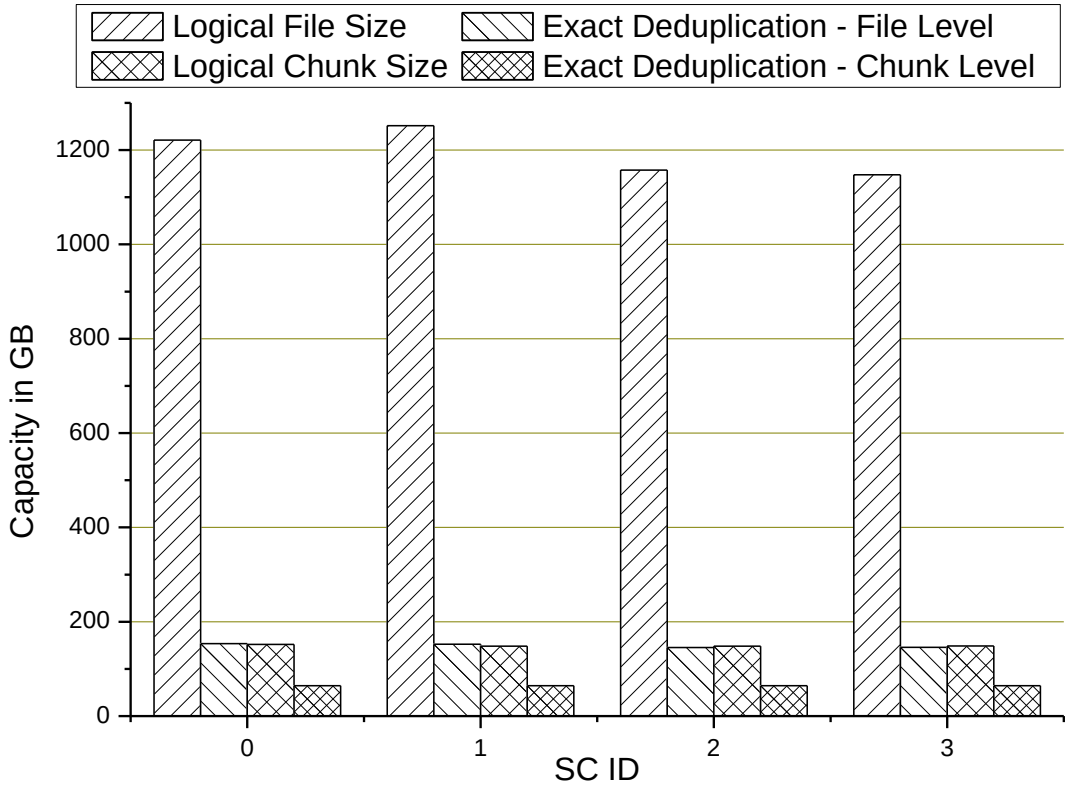
Load Balancing

- Workgroup Set
  - 84,876,504 hot fingerprints were detected at the chunk level, which means that there are about 80.9GB *zero-chunks* being distributed among files.



Load Balancing

- Campus Set
  - A total of 3,953,486 hot fingerprints are detected in the *Campus* set, corresponding to approximately 3.8GB *zero-chunks*.



Throughput

- **We trace and report the fingerprint deduplication efficiency.**
- Considering an average chunk size of 4KB, 25,600 chunk fingerprints must be deduplicated per second to achieve a 100MB/s raw deduplication throughput.
  - Note that one duplicate fingerprint found at the file level means that all the chunk fingerprints belonging to that file can be directly skipped.
- *Workgroup* set: 12,154,807 file fingerprints and 207,856,782 chunk fingerprints are actually transferred and deduplicated in a period of 982 seconds.
  - Chunk level: 211,667 fingerprints/sec, 827MB/s
  - Overall: **6,415MB/s**
- *Campus* set: 15,391,112 file fingerprints and 132,110,642 chunk fingerprints are actually transferred and deduplicated in a period of 814 seconds.
  - Chunk level: 162,298 fingerprints/sec, 634MB/s
  - Overall: **6,011MB/s**

RAM Usage

- 10TB ***deduplicated*** data set – 10GB RAM
  - 40×2^{20} files, assuming the average file size is 256KB
  - 2.5×2^{30} chunks, assuming the average chunk size is 4KB
  - Assuming a capacity of 2^{20} fingerprints
    - 40 tankers to hold the file fingerprints
    - 2,560 tankers to hold the chunk fingerprints.
  - limiting the false positive rate of Bloom Filter Array (BFA) to an extremely low level of $1/2^{20}$
    - 144MB to hold the file-level BFA
    - 9.2GB to hold the chunk-level BFA
    - 800MB to construct the in-memory cache

Minimizing the RAM Consumption

- Increase the average chunk size.
  - at the expense of less detectable duplicate data.
- Allow a much higher false positive rate.
  - by increasing the false positive rate from 1/220 to 1/29, the total RAM consumption by BFA will be reduced from 9.2GB to 4.2GB.
  - cause more cache replacement operations and affect the throughput.
- Configures the chunk-level deduplication to run on a round-robin manner among multiple SCs on the same storage node.
  - with *n* SCs rotating to execute the chunk-level deduplication one at a time on a round-robin basis, the memory requirement will be reduced to approximate 1/*n.*
  - at the cost of reduced chunk-level deduplication throughput.

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Conclusions, Questions

- Organizes fingerprints into a **Hash Bucket *M*atrix (HBM)**, whose rows can be used to **preserve** the data locality in backups.
- Uses **Bloom Filter *A*rray (BFA)** as a quick index to quickly **identify** non-duplicate incoming data objects or indicate where to find a possible duplicate.
- Integrates in-memory ***D*ual Cache** to **capture** and **exploit** locality.
- Employs a ***D*HT-based Load-Balance** technique to evenly **distribute** data objects among multiple storage nodes in their backup sequences to further enhance performance with a well-balanced load.
- Experimental results show that the MAD2 approach is effective and efficient.

Thank you! Questions?