S4D-Cache: Smart Selective SSD Cache for Parallel I/O Systems

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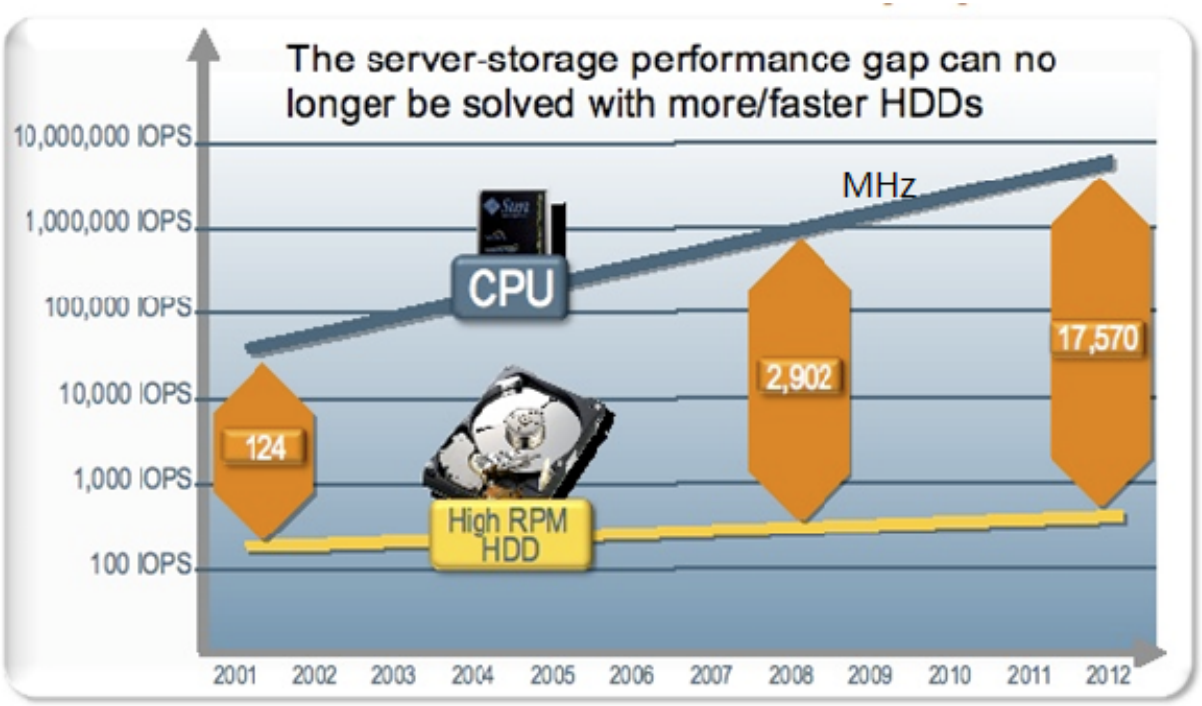
Speed Gap Between CPU and Hard Drive



http://www.velobit.com/storage-performance-blog/bid/114532/Living-With-The-2012-HDD-Shortage

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Computing Becoming Data Intensive

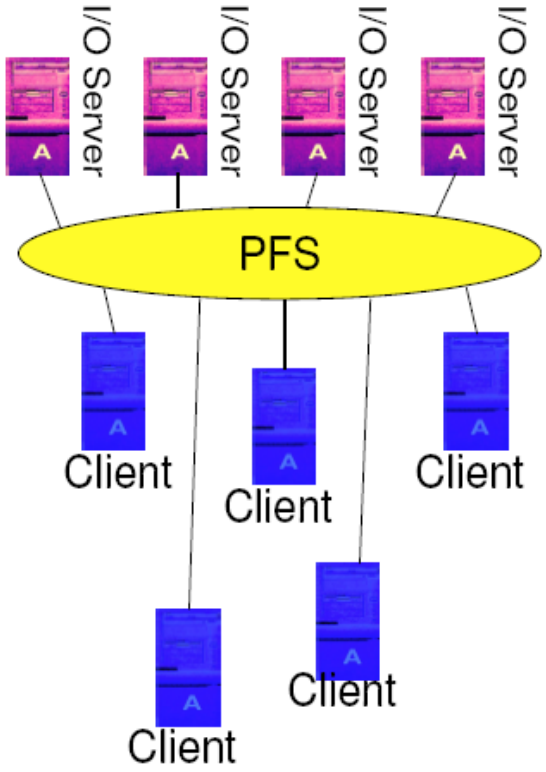
Selected 2012 INCITE applications at Argonne Leadership Computing Facility of ANL [1]

Project	On-line Data (TB)	Off-line Data (TB)
Combustion in Reactive Gases	1	17
CO2 Absorption	5	15
Seismic Hazard Analysis	600	100
Climate Science	200	750
Energy Storage Materials	10	10
Stress Corrosion Cracking	12	72
Nuclear Structure and Reactions	6	30
Reactor Thermal Hydraulic Modeling	100	100
Laser-Plasma Interactions	60	60
Vaporizing Droplets in a Turbulent Flow	2	4

[1] R. Latham, R. Ross, B. Welch, and K. Antypas, "Parallel I/O in Practice," Tutorial of the International Conference for High Performance Computing, Networking, Storage and Analysis, 2013.

Argonne NATIONAL LABORATORY

To Meet The High I/O Demands: PFS



PVFS

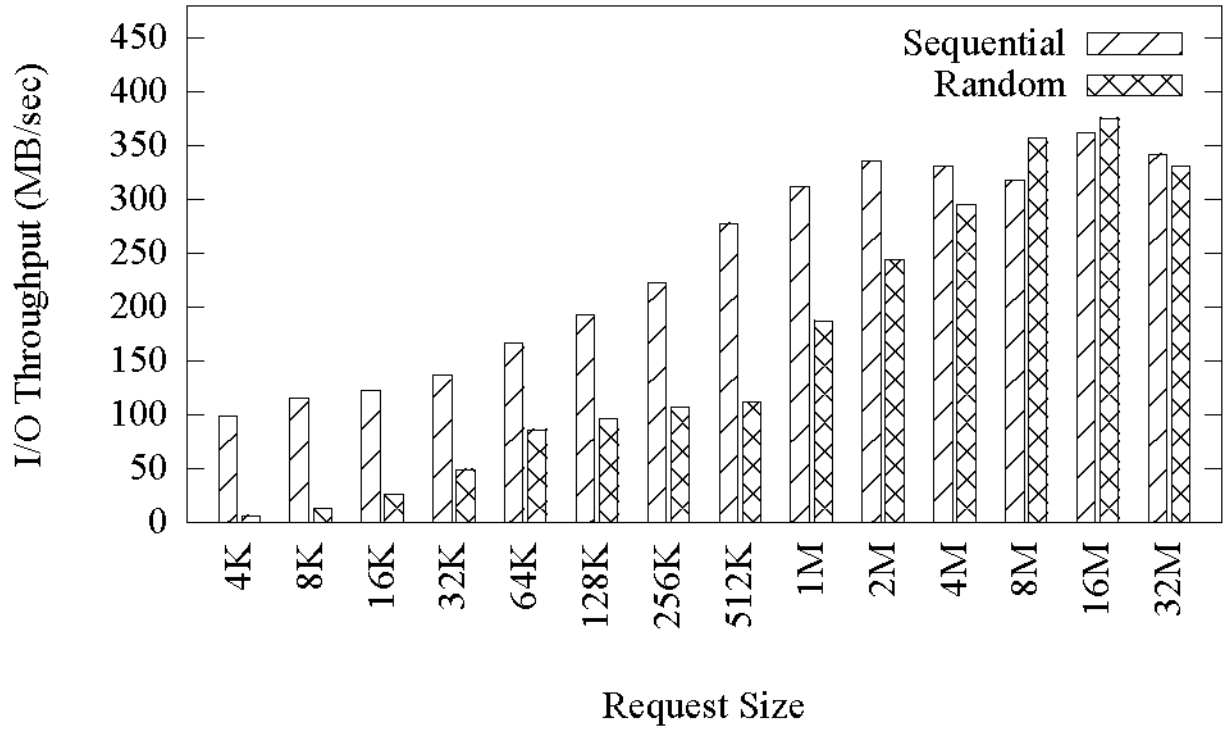
OrangeFS

lustre

panasas

IBM GPFS

Poor performance of PFSs



SSD provides new solutions for parallel I/O systems

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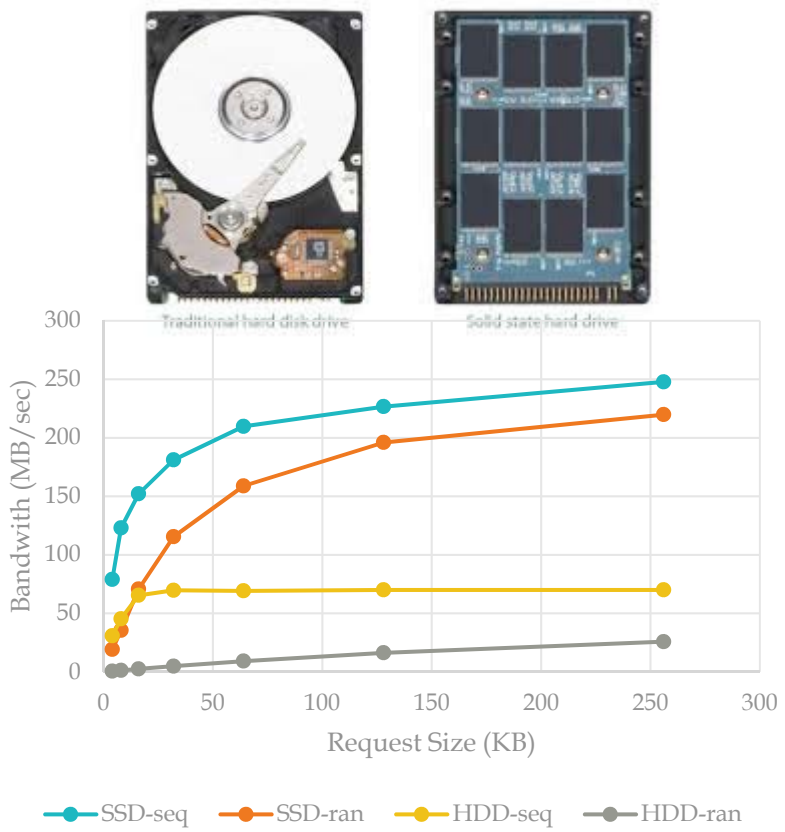
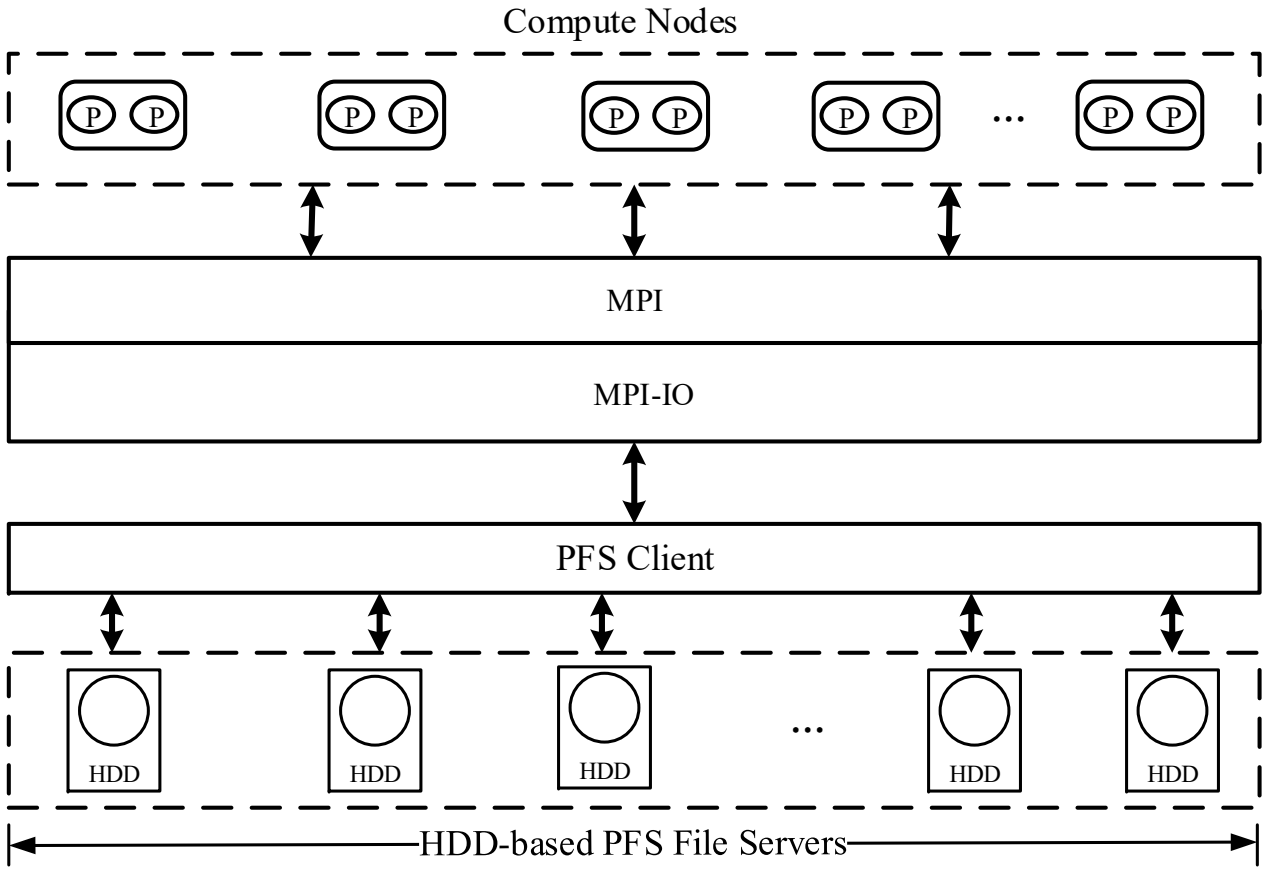
- Benefits of SSDs
  - Higher storage density
  - Lower power consumption
  - Smaller thermal footprint
  - Higher performance



Traditional Parallel I/O Systems



Problem

- How to use SSDs to improve the performance of hybrid I/O systems?
- Challenge
  - I/O workload can change
  - SSDs and HDDs have different performance characteristic's
  - The performance and cost trade off

Outline

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- Problem
- Our idea
- Design
- Evaluation

Key Idea: S4D-Cache

- Smart-Selective SSD Cache for Parallel I/O Systems
  - Integrate a small number of SSD-based file servers into the systems
  - Propose a centralizing SSD cache architecture
  - Selectively caching performance-critical data
    - Request parallelism
    - Request randomness

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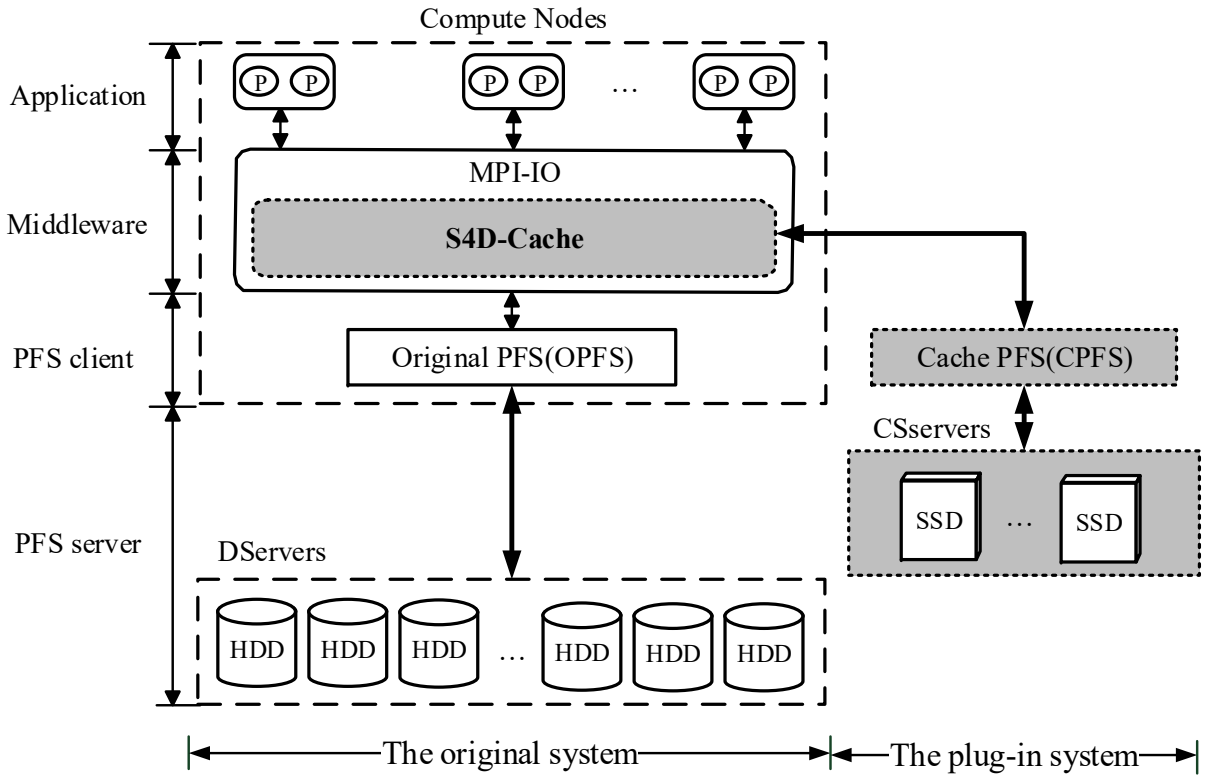
S4D-Cache Architecture Overview



Design Benefits

- Key global data access information are accessible in this layer, and can be used to help improve performance
- The solution can support multiple file systems
- The plug-in design is transparent to applications
- Only a small cluster of SSDs are deployed into the system, which makes the design highly cost effective

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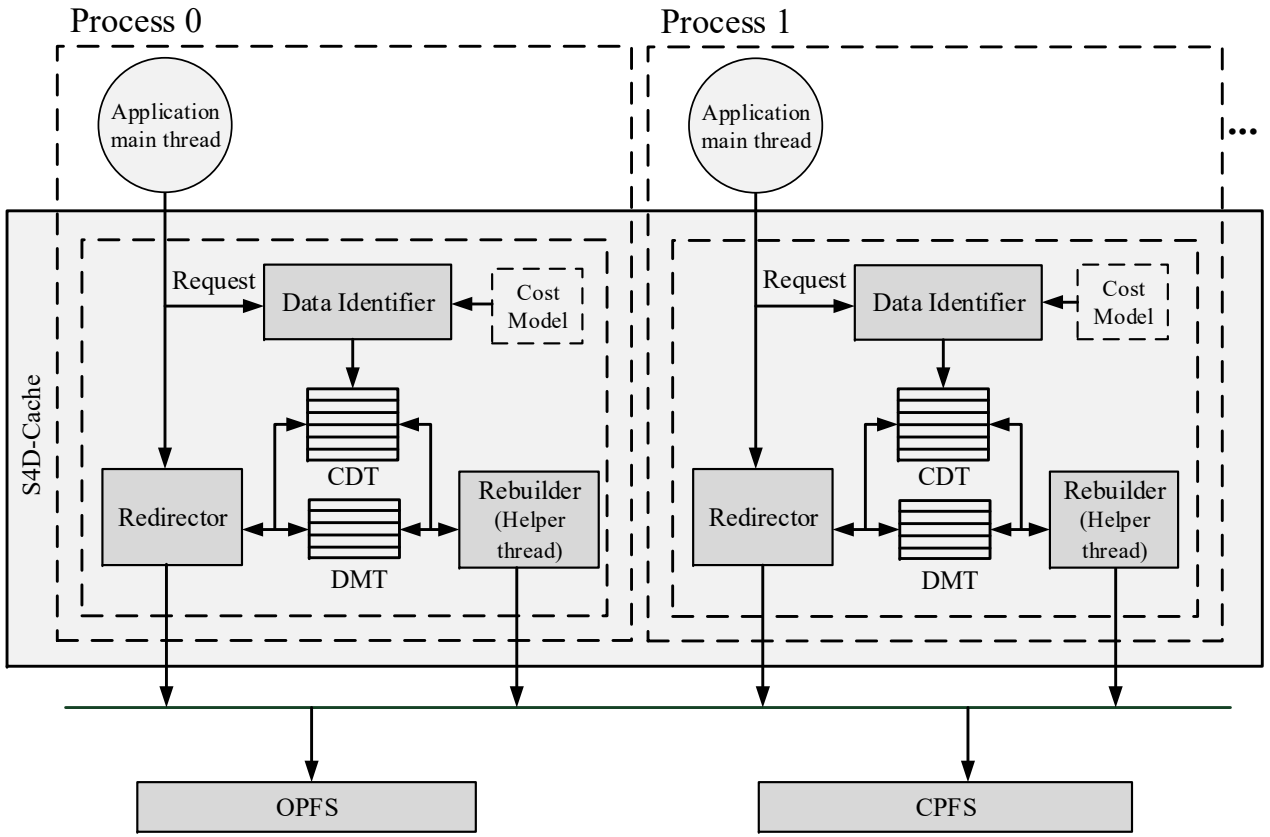
Software structure



Data Access Cost Model

Table 1. Parameters (short in Pars) in cost analysis model.

Pars	Description
M	Number of HDD file servers
N	Number of SSD file servers (N<M)
str	Stripe size of parallel file system
d	Logical address distance between r_i and r_{i-1}
f	File offset of request r_i
r	Data size of request r_i
R	Average rotation delay for HDD
S	Maximum seek time for HDD
β_D	Cost of access one unit of data for HDD
β_C	Cost of access one unit of data for SSD

We calculate the data access cost for requests on DServers and CServers respectively.

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DServer Cost Model

- Request access cost T_D:
  - $T_D = T_s + T_t$ （1）
  - Ts: startup time, Tt: data transfer time
- Ts of sub-request
  - Involves seek time, rotation time on each server
  - T_S follows uniform distribution on [a,b]
    - a=F(d)+R, F(d) is a function for converting request distance d to seek [1]
    - b=S+R
  - $P(\alpha < x) = \frac{x-a}{b-a}, a \le x \le b$ （2）
- Ts of a file request on multiple DServers
  - Ts is the maximum of all the m servers
    - $X = \max(\alpha 1,\ \alpha 2,\ \ldots, \alpha m)$
    - $T_s = \int_a^b xf(x)dx = a + \frac{m}{m+1}(b-a)$ (4)

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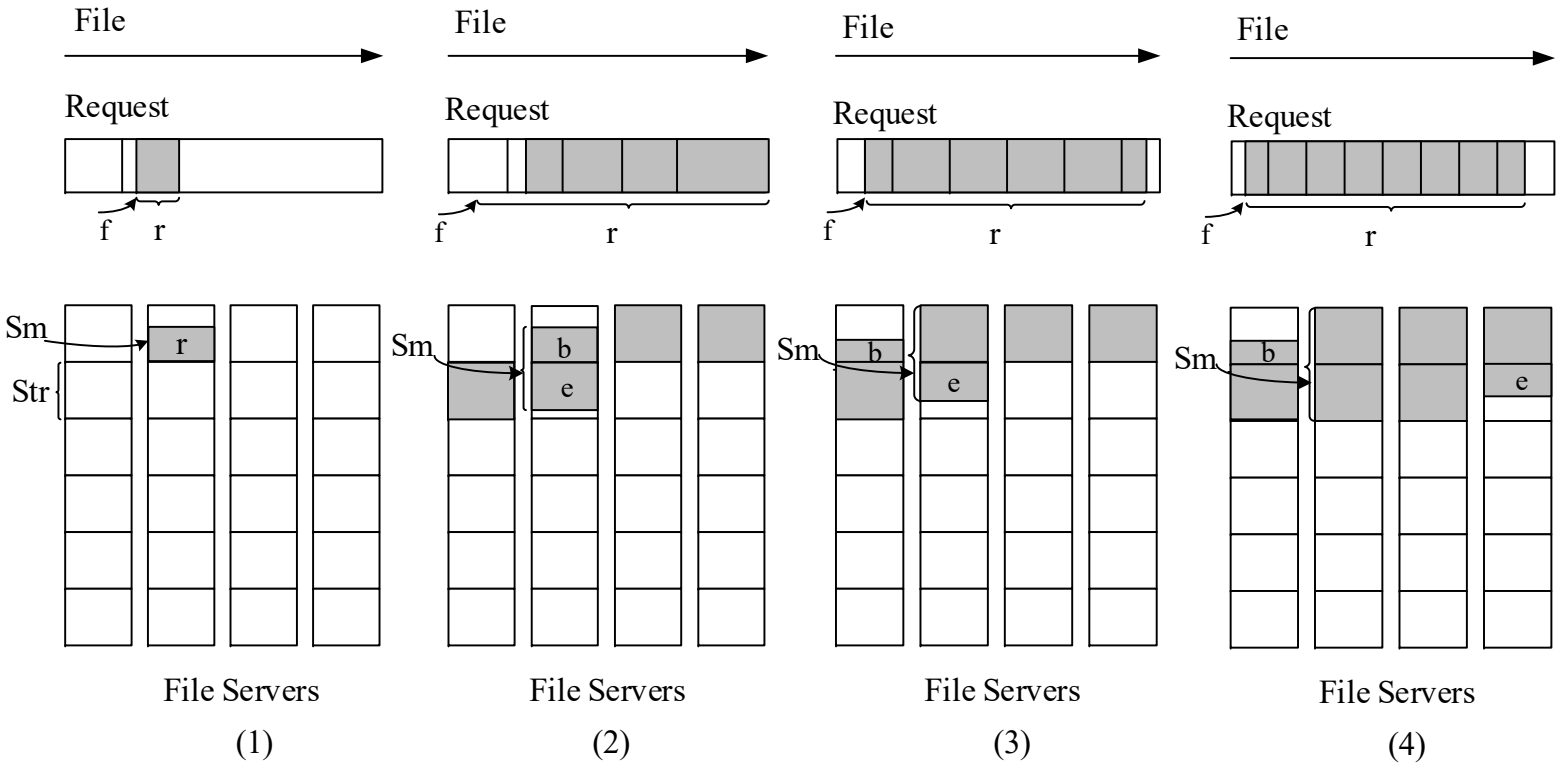
T*t* depends on sub-request size

Four cases of a file request distribution on DServers



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Maximal sub-request size of a request (Sm)

TABLE II
MAXIMUM SIZE OF SUB-REQUEST IN DIFFERENT FILE ACCESSES CASES.

Case	Maximum size of sub-request (s_m)	Conditions
1	r	$\triangle = 0$
2	$max\{b + e + (\lceil \frac{\triangle}{M} \rceil - 1) * str,$ $\lceil \frac{\triangle}{M} \rceil * str\}$	$\triangle > 0 \& \triangle \% M = 0$
3	$max\{b + (\lceil \frac{\triangle}{M} \rceil - 1) * str,$ $e + (\lceil \frac{\triangle}{M} \rceil - 1) * str\}$	$\triangle > 0 \& \triangle \% M = 1$
4	$\lceil \frac{\triangle}{M} \rceil * str$	otherwise

- $T_t = s_m * \beta_D$ (5)

SServer Cost Model

- The startup time is ignored (High-end SSDs).
- Only use the data transfer time.

$$T_C = s_n * \beta_C \quad (7)$$

Critical data identification

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- Performance benefit (B):
  - $B = T_D - T_C$ (8)
- A positive B means the request should be served at CServers
- Implications
  - Large request should be placed on DServers due to high parallelism
  - Random small requests should be placed on CServers

Cache metadata management

- Key data structure
  - Critical data table (CDT)
  - Data mapping table (DMT)

CDT

…			
D_file	D_offset	Length	C_flag
D_file	D_offset	Length	C_flag
…			

DMT

…					
D_file	D_offset	C_file	C_offset	Length	D_flag
D_file	D_offset	C_file	C_offset	Length	D_flag
…					

Selective Cache Algorithm

- Caching data on CServers based on three factors
  - The performance benefit (critical data)
  - Available free space on SServers
  - Type of I/O requests
- Read request is cached in a "lazy" way

Algorithm 1 Redirection Algorithm

Require: I/O Request: *req*, Data Mapping Table: DMT, Critical Data Table: CDT.

```
1:  if req misses in DMT then
2:    if req is write then
3:      if req is in CDT then
4:        find free space in CServers
5:        if free space is found then
6:          add new entry in DMT (mark dirty)
7:          change the req location as the DMT entry
8:        else
9:          find clean space in CServers
10:         if clean space is found then
11:           change the entry in DMT (mark dirty)
12:           change the req location as the DMT entry
13:         end if
14:       end if
15:     end if
16:   else
17:     if req is in CDT then
18:       set the C_flag of the entry in CDT
19:     end if
20:   end if
21: else
22:   change the req location as the DMT entry
23: end if
24: send request req
```

Data reorganization

- Functions
  - Flush dirty data back to DServers, indicating the data can be reclaimed
  - Read data from DServers to CServers, reset C_flag to 0 to show the data has been cached
- Reduce the interference to normal I/O requests
  - Multiple threads: main and help thread
  - Help thread issue low-priority I/O requests

Implementation

- Environments
  - I/O middleware MPICH2
  - PFS: PVFS2
- Cache metadata mapping table
  - Memory: Hash table
  - Storage file: Berkeley DB file on CServers
- I/O redirection module
  - MPI_File_open/read/write(),…
- Rebuilder
  - Multiple threads
  - Shared variables for communication between threads

Experimental Setup

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	65-nodes SUN Fire Linux Cluster
CPU	Quad-Core AMD Opteron(tm) Processor 2376 * 2
Memory	4 * 2GB, DDR2 333MHz
Network	1 Gbps Ethernet
Storage	HDD: Seagate SATA II 250GB, 7200RPM SSD: OCZ PCI-E X4 100GB
OS	Linux kernel 2.6.28.10
File system	PVFS2 2.8.2

1: 32 computing nodes, eight HServers, four SServers
2: Stock system w/o S4D-Cache enabled
3: When S4D-Cache is enabled, the cache capacity is set to 20% of the application's data size.

Benchmark

- IOR
  - 10 instances of IOR are
    - six issue sequential I/O requests
    - remaining send random I/O requests
  - In each instance, default parameters
    - Access a shared 2GB file
    - 32 processes
    - request size is kept to 16KB
- HPIO
- MPI-Tile-IO

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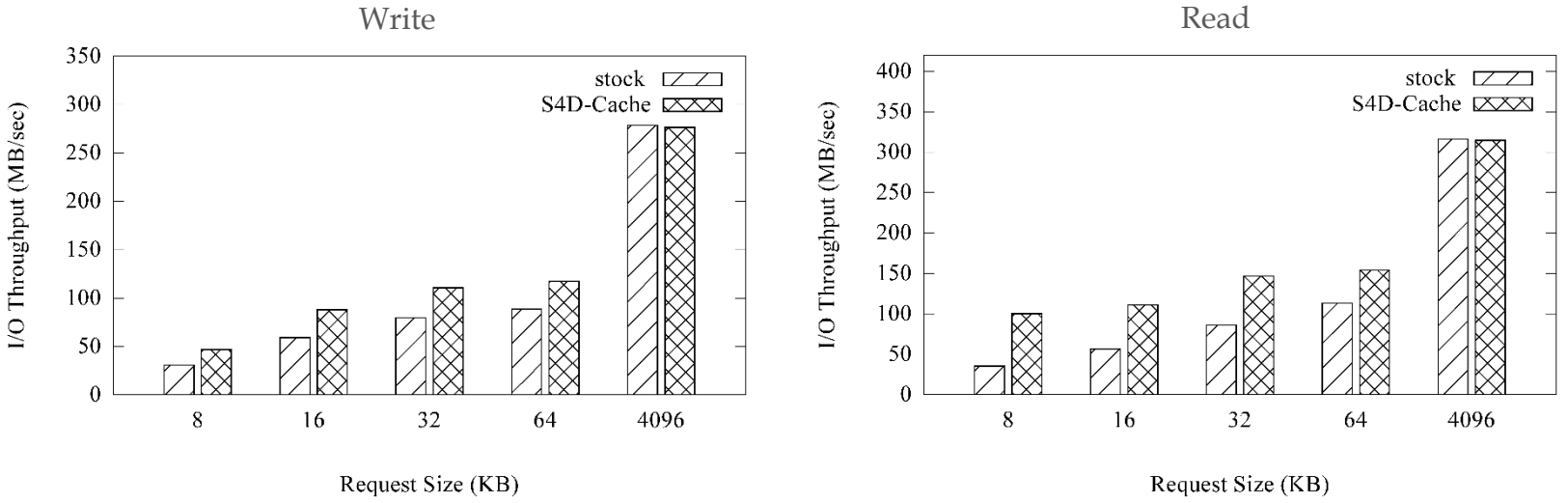
Varying Request Sizes



- For small requests, S4D-Cache significantly improve the I/O performance
- For large requests, less performance gains can be obtained
- Read has similar trend

Request distribution on different servers

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TABLE III
REQUEST DISTRIBUTION.

Request Size	DServers (%)	CServers (%)
16KB	16.3	83.7
4096KB	100.0	0.0

- Most of the random small requests are redirected to CServers, because CServer has good behaviors for them
- Nearly all large requests are absorbed by the original DServers, because DServers have higher I/O parallelism and better aggregated I/O throughput

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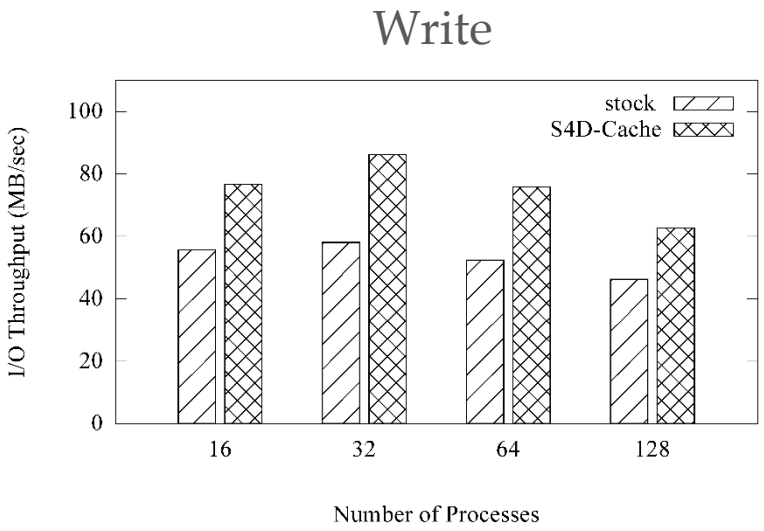
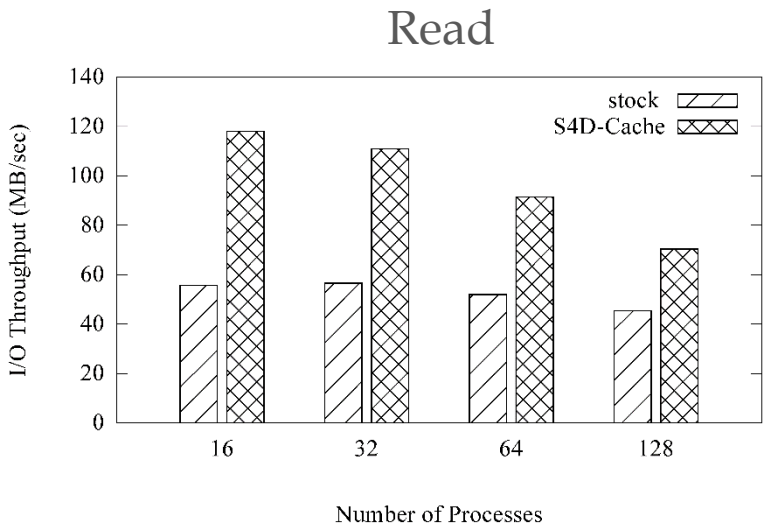
Varying Number of Processes





- S4D-Cache improves the overall I/O bandwidth for various processes
- With the number of processes increasing, bandwidth gets lower because each DServer needs to serve more processes' requests and the competition among processes gets more severe.
- Good scalability in terms of the number of processes.

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Varying SSD Cache Capacities

TABLE IV
I/O THROUGHPUTS OF IOR WITH VARIED SSD CACHE CAPACITIES.

SSD Capacity	Throughput (MB/s)	Speedup (%)
0GB	58.03	0
2GB	69.34	19.5
4GB	86.15	48.4
6GB	90.89	56.6

- Throughput improves by increasing the capacity of CServers
- More random I/O requests can benefit from CServers.
- Continuously enlarging CServers will only bring limited performance improvement.

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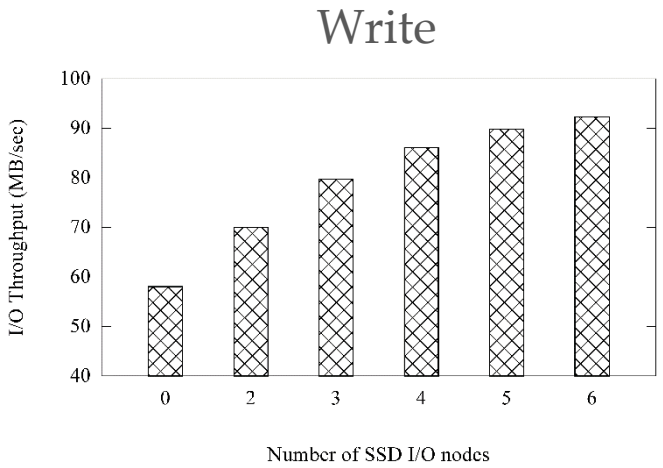
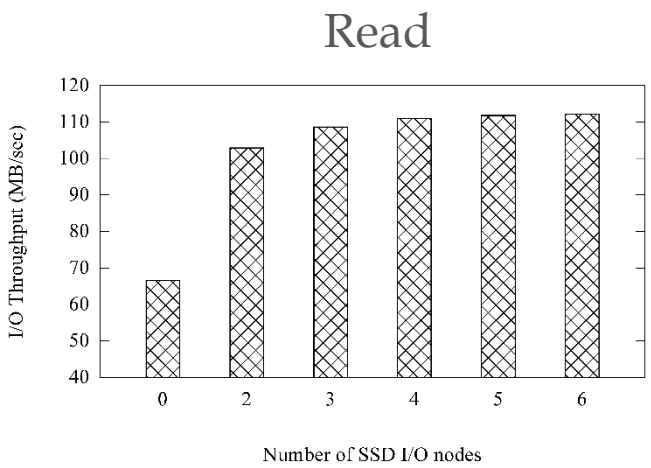
Varying Numbers of SSD File Servers





- With the number of CServers increasing, the I/O bandwidth improves because CServers provides better random performance.
- The I/O performance only slightly improves when the number of file servers is above four, because only a portion of the I/O workload is random and the improvement is bounded to these requests.
- Choosing a reasonable number of file servers is critical to make full use of the SSDs.

HPIO

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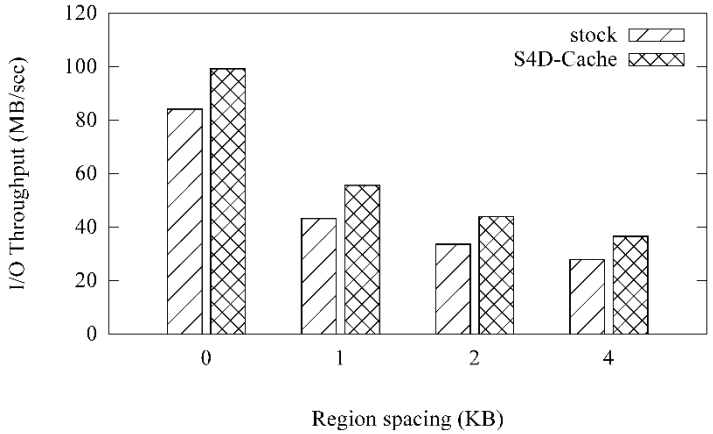
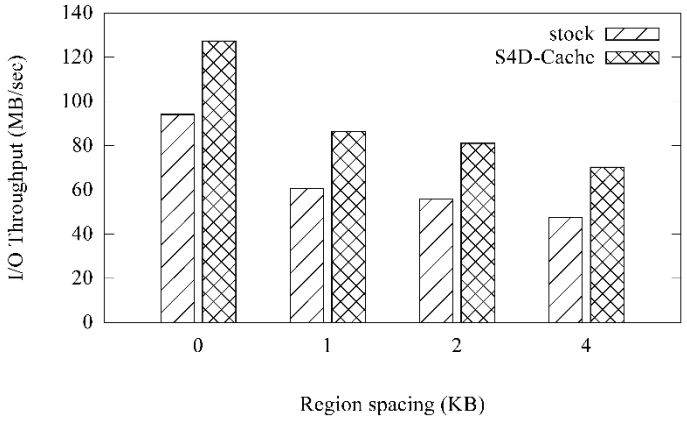
Write



Read



- S4D-Cache is effective with respect to HPIO benchmark
- Improvements for HPIO are not as significant as those for IOR because the workload is not as random as IOR.

MPI-Tile-IO

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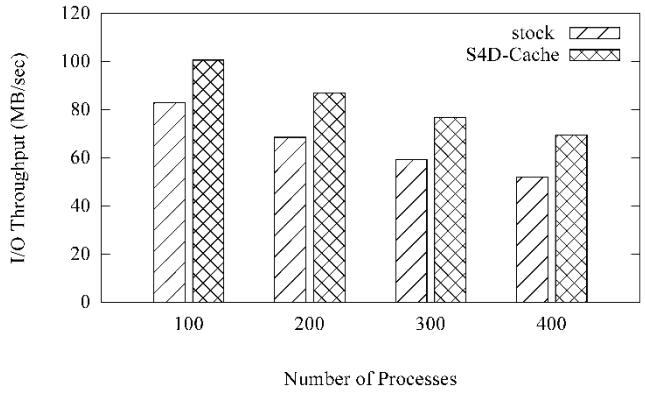
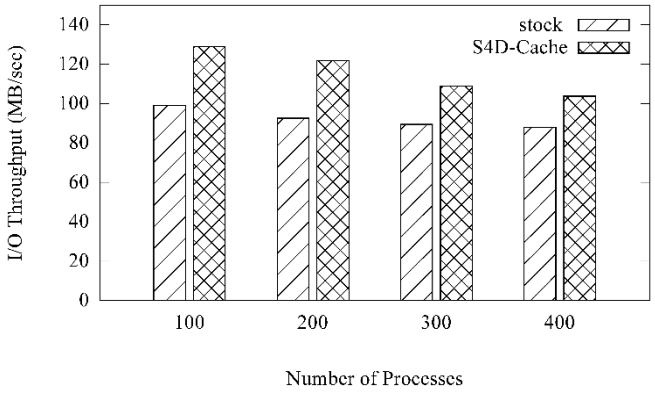
Write



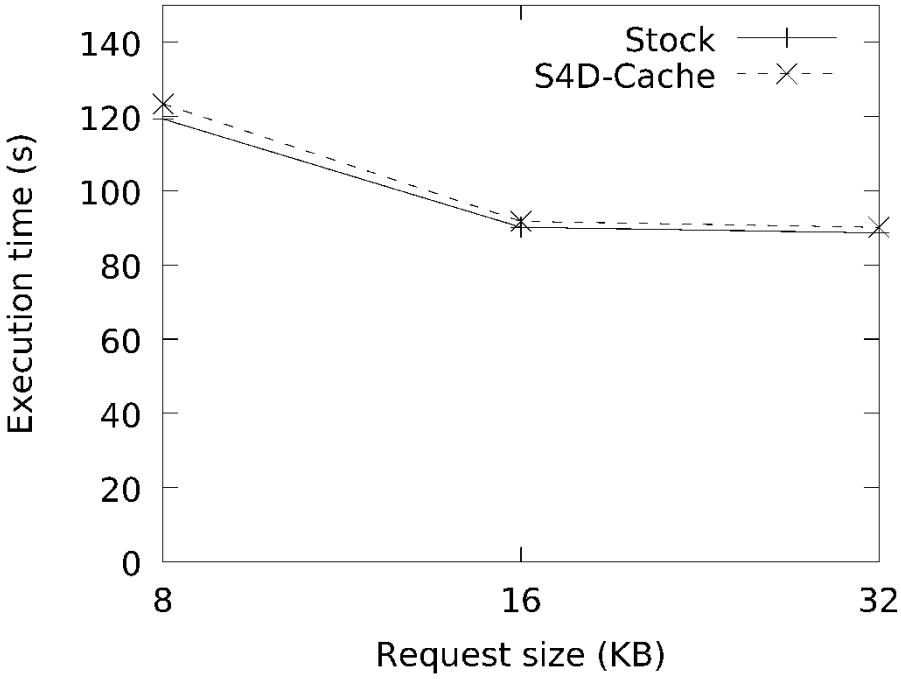
Read



- Performance improvement is still significant

Overhead

- Storage overhead: 0.6% space overhead to keep DMT in storage
- Performance overhead
  - Request cost analysis
  - Critical data identification
  - Cache metadata look-up
- When no requests are cached(Intentionally)
  - Overhead is almost unobservable.



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Conclusions

- A centralized SSD cache architecture for parallel I/O systems
- A cost model to evaluate the file request access time on CServers or DServers at the I/O middleware layer
- A selective caching algorithm to caching critical data on the limited SSD space
- The proposed caching system is feasible and effective

Thank you very much!

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