High-Performance I/O @ Mistral

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Outline

1 Mistral's Storage System

2 Performance

3 Tunables

4 Obstacles and R&D

ClusterStor Servers

Figure: Photo by Carsten Beyer

I/O Architecture (to be extended)

- 29 ClusterStor 9000 Scalable Storage Units (SSUs)
  - SSU: Active/Active failover server pair
- Single Object Storage Server (OSS)
  - 1 FDR uplink
  - GridRaid: (Object Storage Target (OST))
    - 41 HDDs, de-clustered RAID6 with 8+2(+2 spare blocks)
    - 1 SSD for the Log/Journal
  - 6 TByte disks
- 29 Extensions (JBODs)
  - Do not provide network connections
  - Storage by an extension is managed by the connected SSU
- Multiple metadata servers
  - Root MDS + 4 DNE MDS
  - Active/Active failover (DNEs, Root MDS with Mgmt)
  - DNE phase 1: Assign responsible MDS per directory

Parallel File System

Lustre 2.5 (+ Seagate patches: some backports)

Distribution of data

- Lustre can distribute a file across multiple servers (and storage devices called OST)
- Stripe size: Amount of data per OST
- Stripe count: Number of OSTs to store data

General Performance Characteristics

- Client-side caching of reads/writes
  - Dirty data can be drained later
- No server-sided caching
  - I/O requests are directly served by a local file system
- Locking for consistency
  - Read/writes require some communication
- Pre-fetching for sequential reads

Filesystem

Filesystem

- We have only one file system: /mnt/lustre01
- Symlinks: /work, /scratch, /home, ...
- However, each metadata server behaves like a file system

Assignment of MDTs to Directories

- In the current version, directories must be assigned to MDTs
  - /home/* on MDT0
  - /work/[projects] are distributed across MDT1-4
  - /scratch/[a,b,g,k,m,u] are distributed across MDT1-4
- Data transfer between MDTs is currently slow (mv becomes cp)
- Lustre will be updated with a fix :-)

Peak Performance

- 29 SSUs · (2 OSS/SSU + 2 JBODs/SSU) = 58 OSS and 116 OSTs
- 1 Infiniband FDR-14: 6 GiB/s $\Rightarrow$ 348 GiB/s
- 1 ClusterStor9000 (CPU + 6 GBit SAS): 5.4 GiB/s $\Rightarrow$ **313 GiB/s**

Performance Results from Acceptance Tests

- Throughput measured with IOR
  - Buffer size 2000000 (unaligned)
  - 84 OSTs (Peak: 227 GiB/s)
  - 168 client nodes, 6 procs per node

Type	Read	Write	Write rel. to peak
POSIX, independent[1]	160 GB/s	157 GB/s	70%
MPI-IO, shared[2]	52 GB/s	41 GB/s	18%
PNetCDF, shared	81 GB/s	38 GB/s	17%
HDF5, shared	23 GB/s	24 GB/s	10%
POSIX, single stream	1.1 GB/s	1.05 GB/s	0.5%

- Metadata measured with a load using Parabench: 80 kOPs/s
- 25 kOP/s for the root MDS and 15 kOP/s for each DNE MDS

[1] 1 stripe per file

[2] 84 stripes per file on 21 SSUs

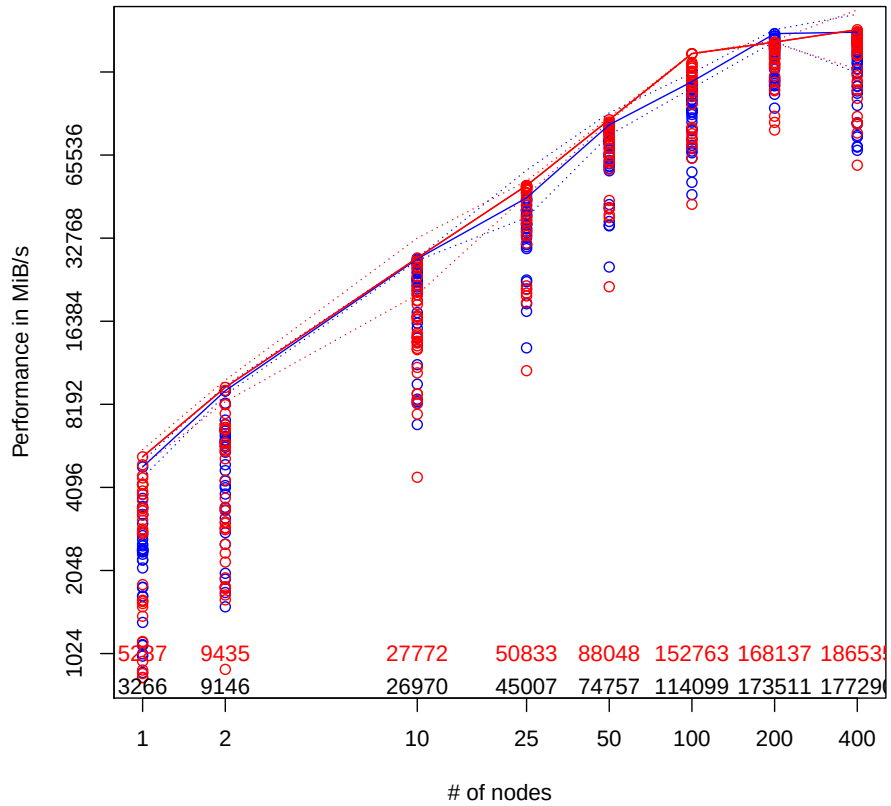
Observations to Take Away

- Single stream performance is much lower than on Blizzard
- Multiple threads need to participate in the I/O
  - 12 to 16 are able to (almost) utilize Infiniband
- Independent I/O to independent files is faster
- An optimized file format is important for fast I/O
  - e.g. NetCDF4/HDF5 achieves $< 1/2$ performance of PNetCDF
- Benchmarking has shown a high sensitivity with proper configuration
  - 4x improvement is often easy to achieve

  $\Rightarrow$ Let us vary the thread count (PPN), stripe count and node count

Performance with Variable Lustre Settings

- Goal: Identify good settings for I/O
- IOR, indep. files, 10 MiB blocks
  - Measured on the production system
  - Slowest client stalls others
  - Proc per node: 1,2,4,6,8,12,16
  - Stripes: 1,2,4,16,116



Best settings for read (excerpt)

Nodes	PPN	Stripe	W1	W2	W3	R1	R2	R3	Avg. Write	Avg. Read	WNode
1	6	1	3636	3685	1034	4448	5106	5016	2785	4857	2785
2	6	1	6988	4055	6807	8864	9077	9585	5950	9175	2975
10	16	2	16135	24697	17372	27717	27804	27181	19401	27567	1940

Testing Defaults: Which Stripe Count & PPN to pick?

Average performance values per node (running on various number of nodes)

Stripes	PPN	RNode	WNode	R arithmetic mean	W arithmetic mean	RHarmonic	WHarmonic
1	1	788	780	34	32	52	53
1	2	1214	1155	53	47	75	71
1	4	1352	1518	59	62	81	79
1	6	2179	1835	95	75	91	88
1	8	1943	2235	84	92	86	93
1	12	1974	1931	86	79	92	84
1	16	1890	1953	82	80	84	72
2	1	734	763	32	31	51	51
2	2	1165	1182	50	48	72	72
2	4	1814	1745	79	71	87	85
2	6	1935	1693	84	69	88	83
2	8	1726	2039	75	84	88	89
2	12	1780	2224	77	91	90	92
2	16	1806	1752	79	72	79	75
4	1	726	761	31	31	49	51
4	2	1237	1185	54	48	70	66
4	4	1737	1744	75	71	85	84
4	6	1719	1888	75	77	85	86
4	8	1751	1931	76	79	87	90
4	12	1841	1972	80	81	87	89
4	16	1745	2064	76	85	72	74
16	1	743	726	32	29	48	49
16	2	1109	1216	48	50	66	71
16	4	1412	1554	61	64	75	81
16	6	1489	1812	65	74	72	85
16	8	1564	1841	68	75	79	90
16	12	1597	1939	69	79	71	78
16	16	1626	1900	71	78	64	68
116	1	588	432	25	17	34	31
116	2	871	773	38	31	44	52
116	4	1270	1258	55	51	53	69
116	6	1352	978	59	40	52	51
116	8	1397	901	61	37	56	47
116	12	1470	1020	64	42	55	46
116	16	1503	1147	65	47	55	42

I/O Duration with Variable Block Granularity

- Performance of a single thread with sequential access
- Two configurations: discard (/dev/zero or null) or cached
- Two memory layouts: random (rnd) or re-use of a buffer (off0)

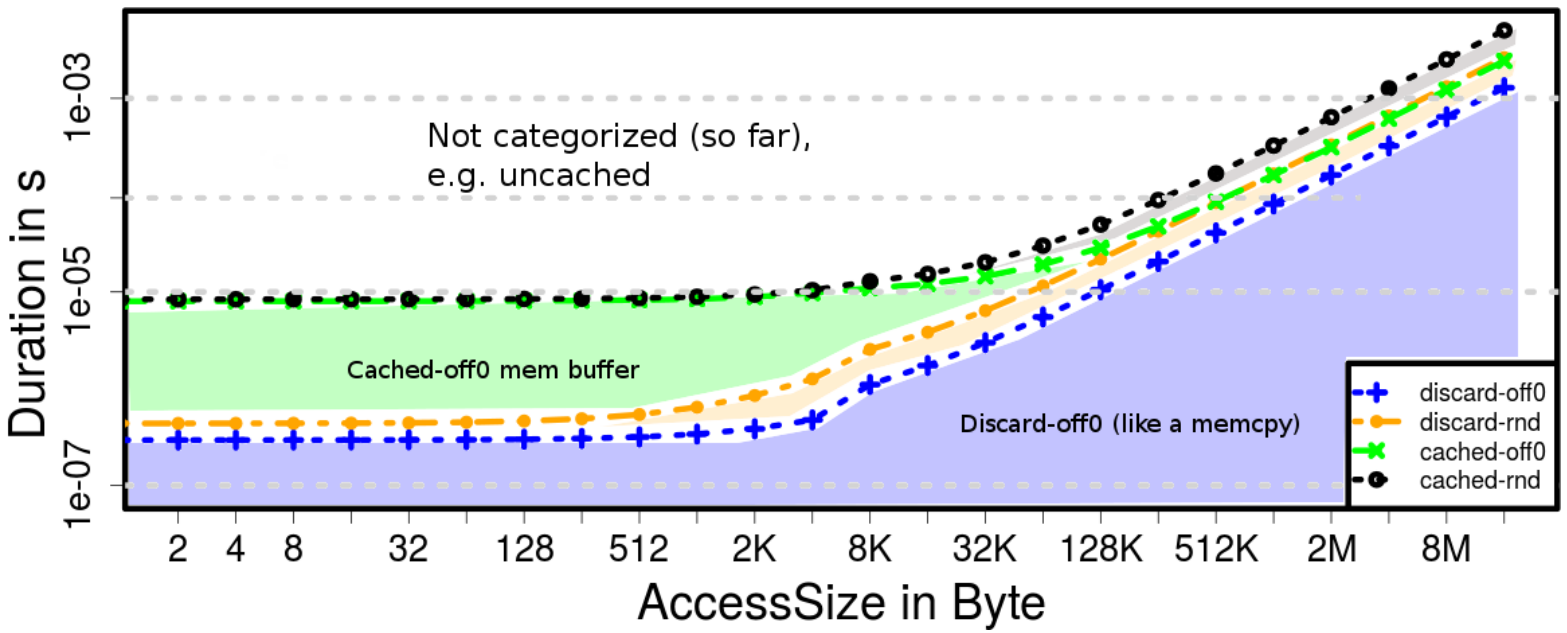


Figure: Read

I/O Duration with Variable Block Granularity

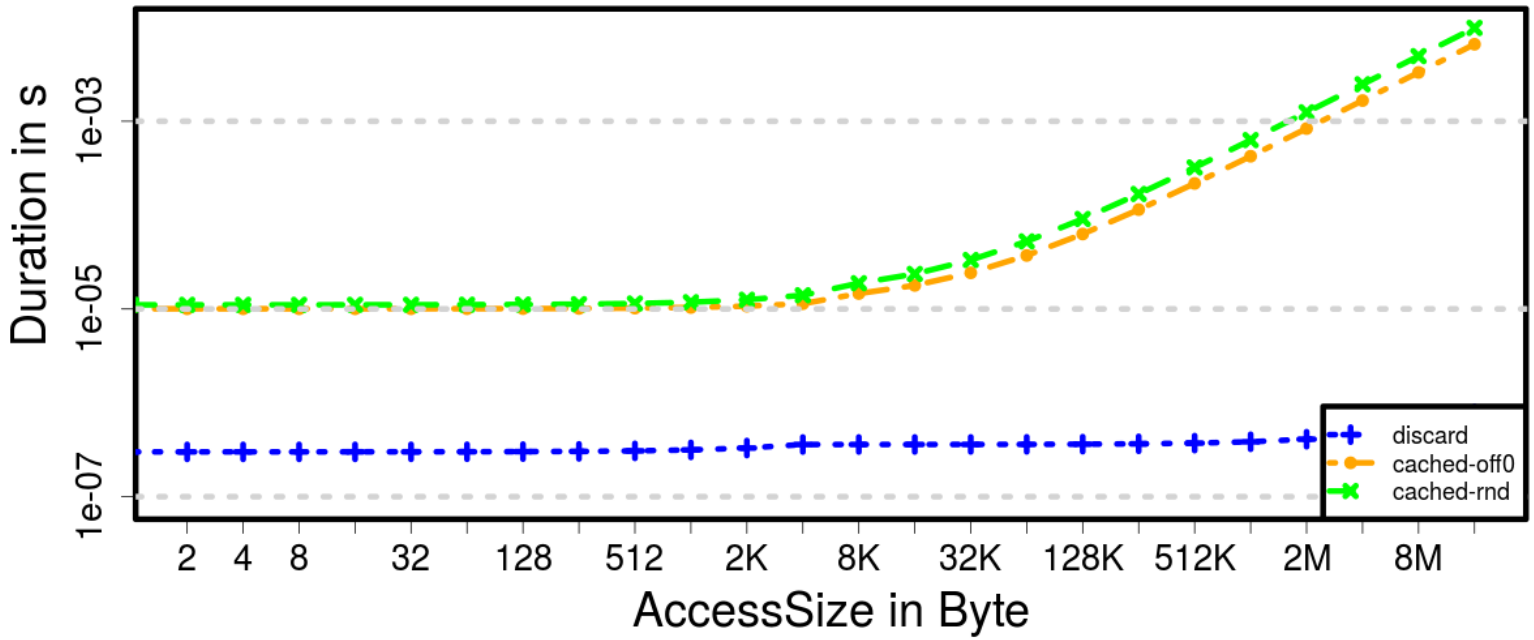


Figure: Write

- Memory layout has a minor impact on performance

$\Rightarrow$ In the following, we'll analyze only accesses from one buffer

Throughput with Variable Granularity

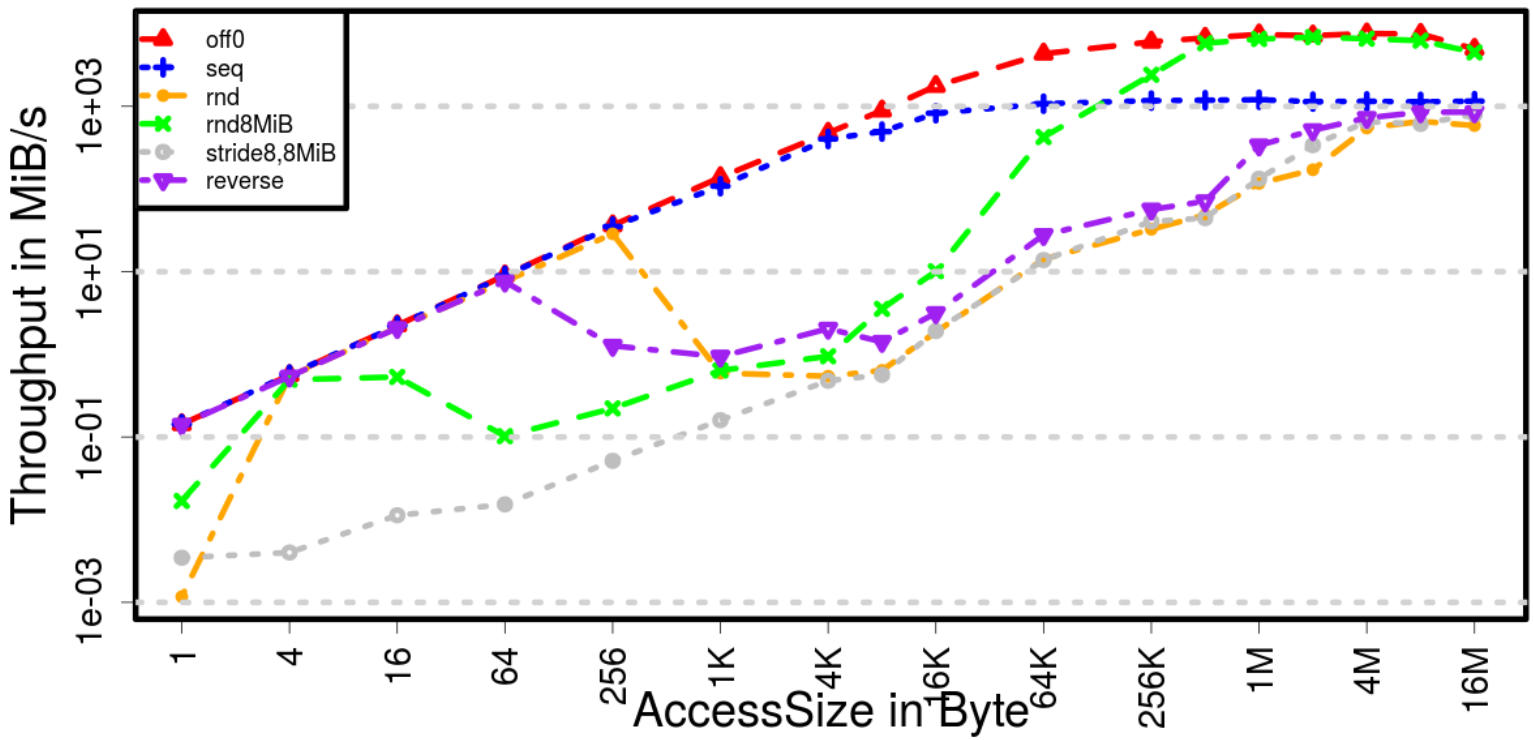


Figure: Read – cached data

- Caching (of larger files, here 10 GiB) does not work
- Sequential read with 16 KiB already achieves great throughput
- Reverse and random reads suffer with a small granularity

Throughput with Variable Granularity

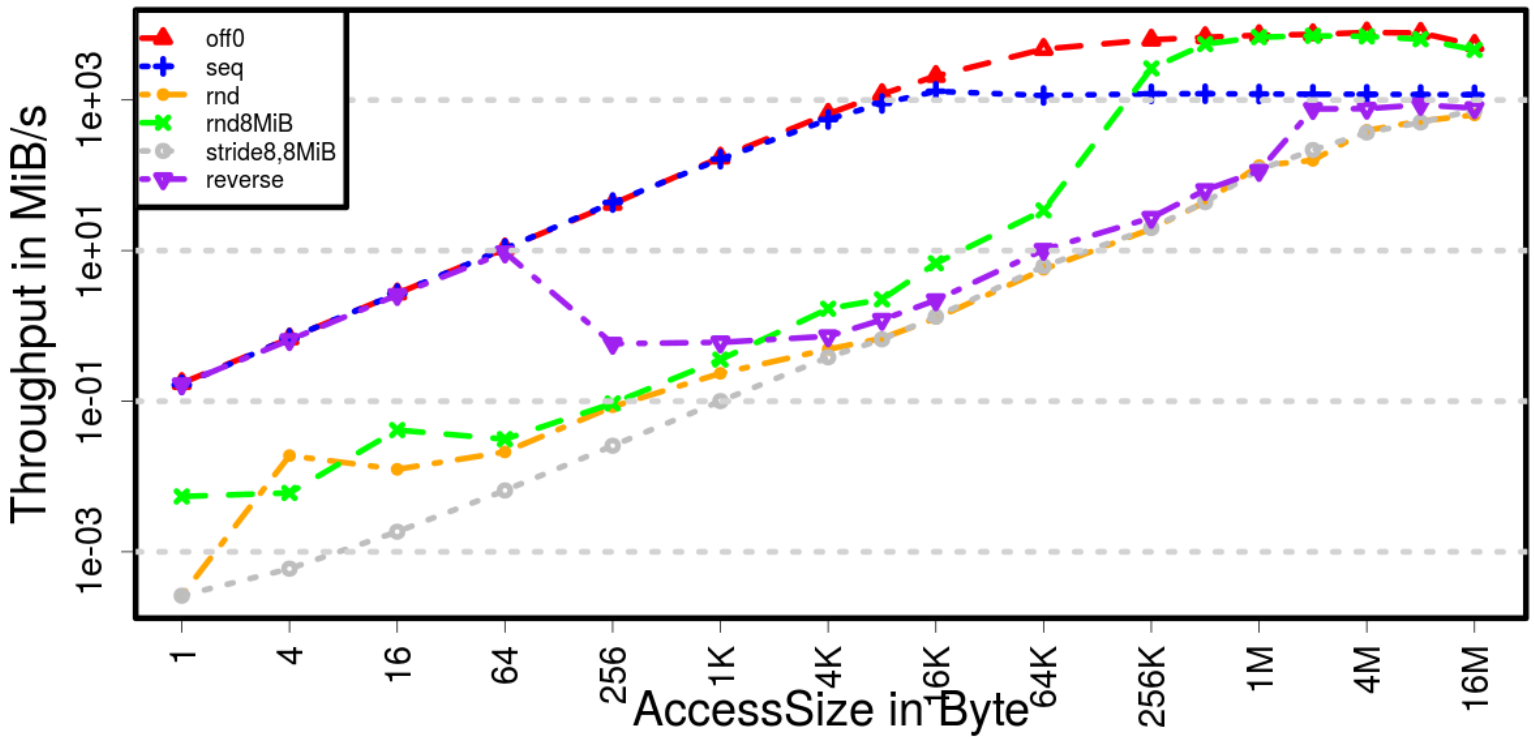


Figure: Read – clean cache

- Read cache is not used
  - Except for accesses below 256 bytes (compare to the prev. fig.)

Throughput with Variable Granularity

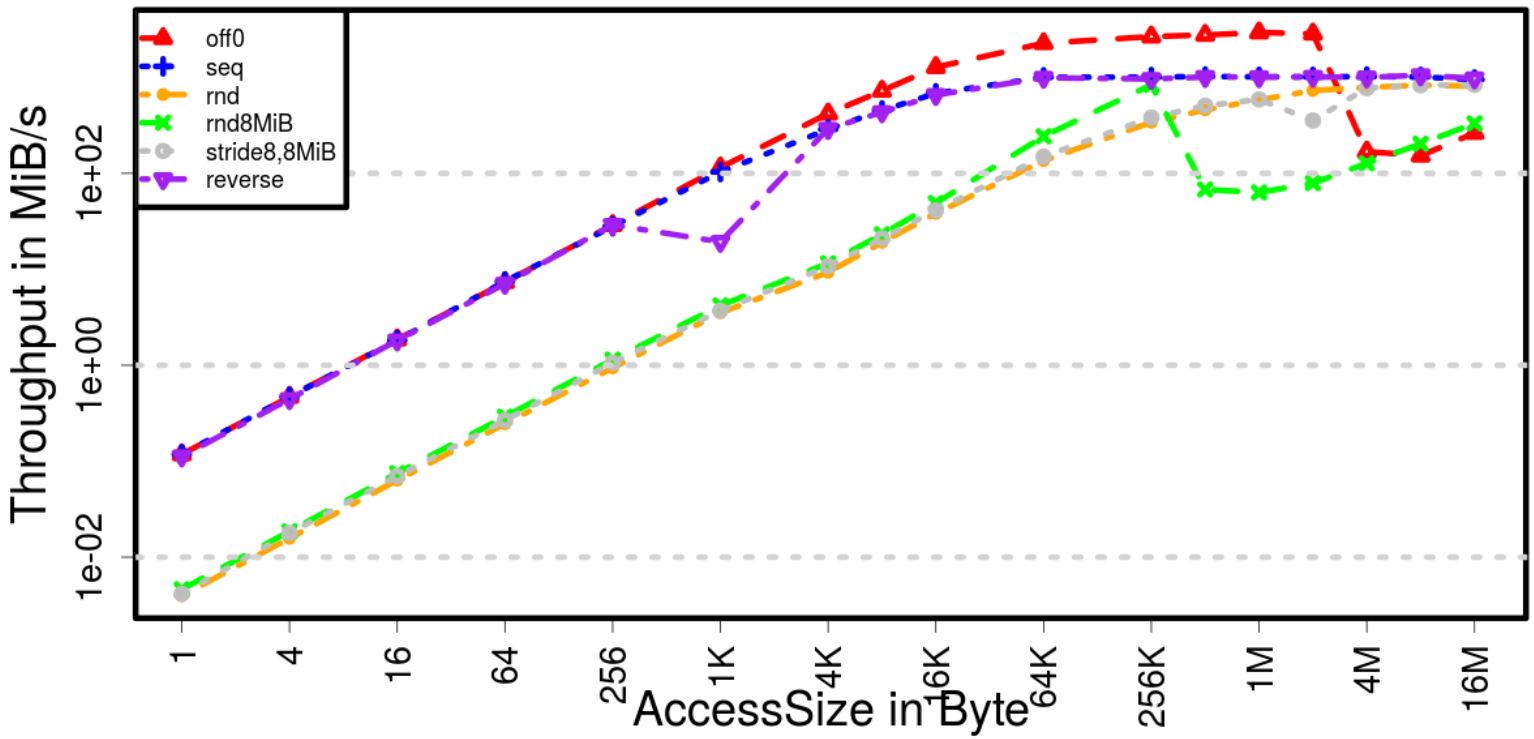
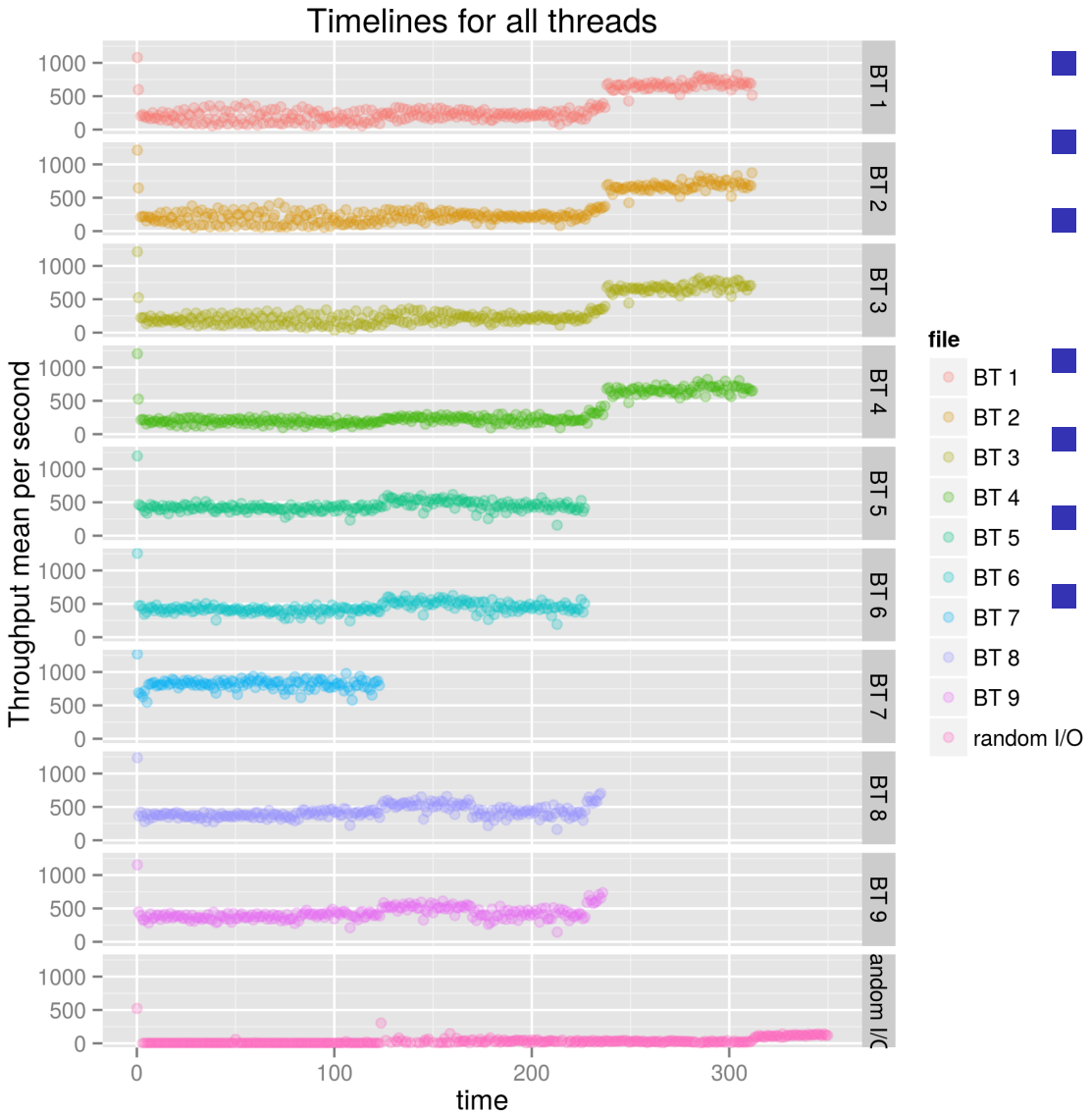


Figure: Write

- Writes of 64 KiB achieve already great performance
- Reverse file access does not matter
- Abnormal slow behavior when overwriting data with large accesses (off0, rnd8MiB)

(Unfair) Sharing of Performance



- Storage == shared resource
- Independent file I/O on one OST
- Running 9 seq. writers concurrently (10 MiB blocks)
- One random writer (1 MiB blocks)
- Each client accesses 1 stripe
- Each client runs on its own node
- Observations
  - BT: 3 performance classes
  - RND without background threads: 220 MiB/s
  - RND with 9 background threads: 6 MiB/s
  - Slow I/O gets dominated by well-formed I/O

Performance Issues & Tunables

- I/O has to wait for the slowest server
  - A few slow servers significantly reduce IOR performance
  - Also: Congestion on IB routes degrade performance
- Interference between I/O and communication intense jobs
- Use a small number of stripes (for small files up to a few GiB)
  - On our system the default is 1
  - Create a new file with a fixed number: `lfs setstripe <file>`
  - Information: `lfs [getdirstripe|getstripe] <file|dir>`
- For highly parallel shared file access increase the striping
  - Performance is max. 5 GiB/s per stripe
- Avoid "ls -l"
  - It must query the size of all stripes from the OSTs
- Avoid moving data between different MDTs
- MPI Hints

Performance Issues & Tunables (2)

Changing Lustre's striping policy

```
# create two stripes with 10 MiB striping
$ lfs setstripe -c 2 -S $((1024*1024*10)) myfile
# query the information about myfile
# obidx shows the OST number
$ lfs getstripe myfile
myfile
lmm_stripe_count:   2
lmm_stripe_size:    10485760
lmm_pattern:        1
lmm_layout_gen:     0
lmm_stripe_offset:  6
obdidx  objid  objid  group
     6        9258354      0x8d4572             0
    40        5927139      0x5a70e3             0
```

Performance Issues & Tunables (3)

MPI Hints

- Hints that have been proven useful during the acceptance test
- Collective access to shared files is useful for writes

```
# collective I/O
romio_cb_read = disable # serve each operation individually
romio_cb_write = enable # use two-phase I/O optimization

romio_no_indep_rw = false # can be true only if using collective I/O
# non-contiguous optimization: "data sieving"
romio_ds_read = disable # do not use data sieving
romio_ds_write = enable # may use data sieving to filter
romio_lustre_ds_in_coll = enable # may use ds in collective I/O
romio_lustre_co_ratio = 1 # Client to OST ratio, max one client per OST
direct_read = false # if true, bypass OS buffer cache
direct_write = false # if true, bypass OS buffer cache
```

Obstacles We Face When Are Optimizing the System

Lack of knowledge

- Usage of file formats and middleware libraries is limited
  - Analysis of file extensions does not suffice
  - Library usage could theoretically be monitored, but ...
- The workflows are sometimes diffuse
- The cause of innefficient operations is unknown

Shared nature of storage

- With 1/60th of nodes one can drain 1/7th of I/O performance
  - $\Rightarrow$ 10% of nodes drain all performance
  - Since applications are not doing I/O all the time this seems fine
- But: interaction of I/O may degrade performance
  - I/O intense benchmark increased application runtime by 100%
- Metadata workloads are worse, problematic with broken scripts

Obstacles

Difficulties in the analysis

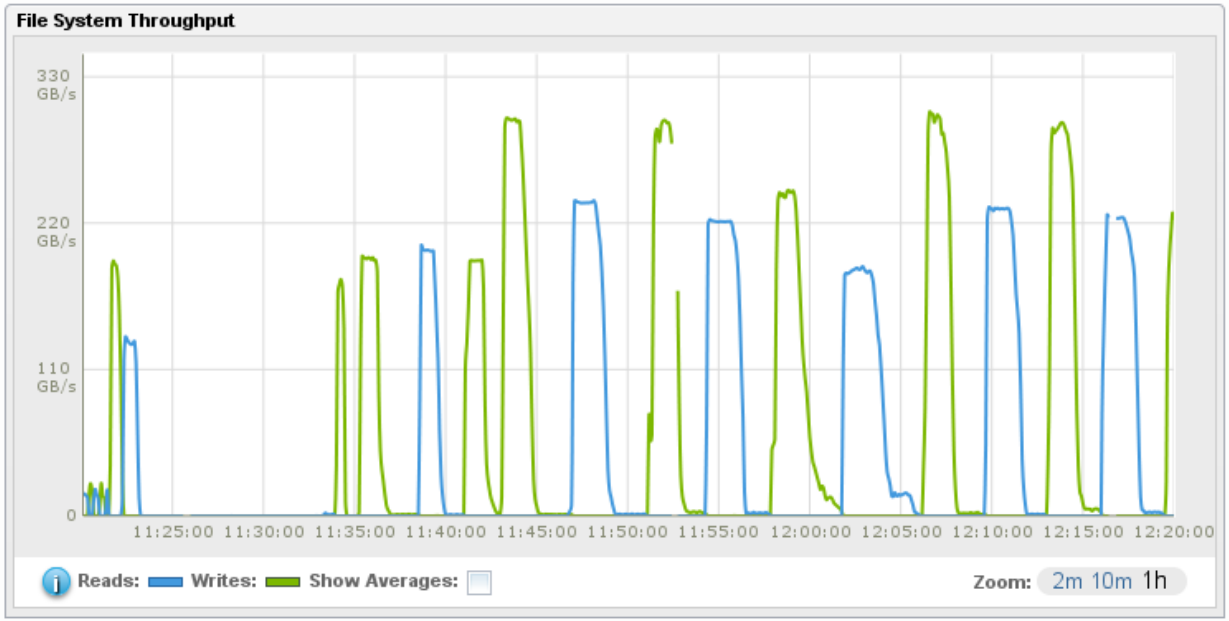
- Performance is sensitive to I/O patterns, concurrent activitity
- Infiniband oversubscription
- Application-specific I/O servers increase complexity
- Capturing a run's actual I/O costs vs. shared access
- Lustre's (performance) behavior

Others

- Outdated (and inefficient) file formats are still dominant
- Capability increase from Blizzard to Mistral[3]
  - Compute performance by 20x
  - Storage performance by 20x
  - Storage capacity by 7x

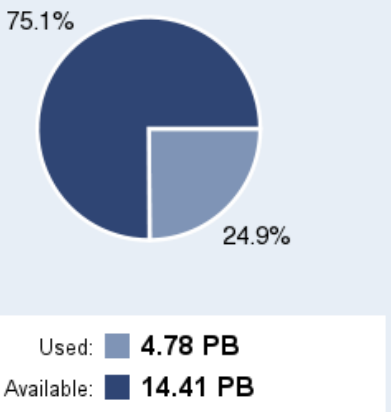
[3] This is a projection for the full system

Monitoring I/O Performance with ClusterStor



Top System Statistics

	Metric			Capacity Overview
File System	Peak Read	274.34	GB/s	
	Current Read	45.6	KB/s	
	Peak Write	308.37	GB/s	
	Current Write	222.54	GB/s	
Metadata	Current Operations	0	Op/s	
Storage	Number of OSTs in use	116		
	Number of Disks in use	4,882		
	Capacity in use	4.78	PB	
	Capacity available	14.41	PB	
Power	Current cluster usage	70.17	KW	



Lustre I/O Statistics

- Statistics on the client help understand behavior (a bit)
- `/proc/fs/lustre/llite/lustre01-*/stats`
- `/proc/fs/lustre/llite/lustre01-*/read_ahead_stats`

Typ	Lay-out	Acc-Size	numa_ local	hits	misses	intr	softirq	read b_avg	read calls	write b_avg	write calls	osc_read avg	osc_read calls	osc_write avg	osc_write calls	Perf. in MiB/s
W D	off0	256K	263K	0	0	0.9-1K	1.8-2K	201	3	40K	5	0	0	32K	0-6	1.1T
W C	off0	256K	264K	0	0	2.8-3.3K	6.1-7.1K	201	3	262K	10005	0	0	256K	1.1	2.6G
W C	seq	256K	940K	0	0	16-18K	26-30K	201	3	262K	10005	0	0	4M	625	1G
W C	rnd	256K	937K	0	0	125K	34K	201	3	262K	10005	4096	19K	3.9M	673.6	341M
W C	rev	256K	942K	0	0	23K	28-77K	201	3	262K	10005	0	0	4M	626	963M
R D	off0	256K	263K	0	0	1.1-1.4K	2.4-3K	201	3	40K	5	0	0	42K	0.4	14G
R C	off0	256K	264K	63	1	1.4-1.9K	2.9-3.9k	256K	10003	40K	5	256K	1	0	0	5.9G
R C	seq	256K	931K	640K	3	25-60k	28-111K	256K	10003	57K	5	1M	2543	80K	0.4	1.1G
R C	rnd	256K	1559K	615K	16K	136-142k	43k-65k	256K	10003	58K	5	241K	20K	180K	4	33M
R C	rev	256K	930K	629K	10K	70-77K	23-47K	256K	10003	58K	5	256K	9976	104K	0-3	56M
R U	off0	256K	264K	63	5	1.5-2k	2.9-3.9k	256K	10003	40K	5	64K	5	0	0	6.2G
R U	seq	256K	946K	640K	6	25-42k	32-74k	256K	10003	57K	5	1M	2546	0	0	1.2G
Runs with accessSize of 1 MiB and a 1 TB file, caching on the client is not possible. For seq. 1M repeats are performed, for random 10k:																
W	seq	1M	259M	0	1.3	8-12M	14-23M	201	3	1M	1000013	0-8K	0-4	4M	250K	1007
W	rnd	1M	2.9M	0	0-3	161K	114K	201	3	1M	10006	4097	20K	3.2M	3309	104
R	seq	1M	257M	255M	2	16-22M	28-38M	1M	1000003	2.5M	12	1M	1000K	3M	10	1109
R	rnd	1M	5M	2M	9753	206K	157-161K	1M	10003	60K	5	836K	24K	100K	3	55
Accessing 1 TB file with 20 threads, aggregated statistics, but performance is reported per thread:																
W	seq	1M	260M	0-1	0-3	12M	23M	201	58	1M	990K	2-17K	1-3	4.1M	254K	250
W	rnd	1M	246M	0	0	18M	13M	201	58	1M	960K	4096	1.8M	3.1M	320K	138
R	seq	1M	254M	250M	480K	9.8M	12M	1M	970K	21-24K	0.2-1.2K	1.6M	630K	717K	41	168
R	rnd	1M	481M	240M	900K	20M	16M	1M	950K	20-23K	0.2-1.2K	832K	2.3M	523K	36	47

Table: Deltas of the statistics from `/proc` for runs with access granularity of 256 KiB and 1 MiB (mem-layout is always off0). In the type column, D stands for discard, C for cached and U for uncached. 1TB files do not fit into the page cache.

Relevant R&D at DKRZ

We are doing various R&D to improve the situation:

- Monitoring and analysis of I/O on system AND application level
- Optimized data layouts for HDF/NetCDF
- QoS for I/O (interactive vs. large scale runs)
- Evaluate of alternative storage for random workloads
- Compression of data (lossless 1:2.5, lossy $>$ 1:10)
- ! At best without changes on YOUR applications

Please talk to us, if you think you have an I/O issue

Appendix

File Formats

- Problem: File extensions do not match the content

⇒ Sample of files analyzed with `file` and cdo

- 25% from home
- 20% from work/scratch: 1 PB, 26 M files

Scientific file formats for work/scratch

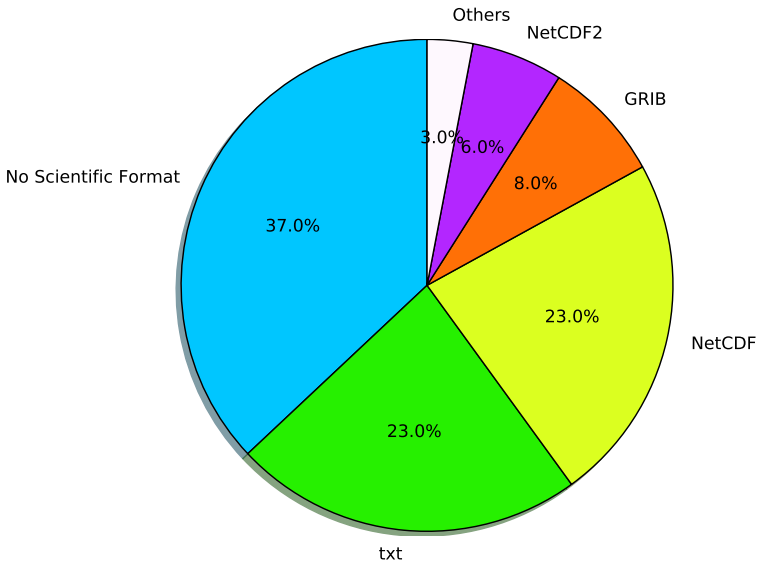


Figure: % file count

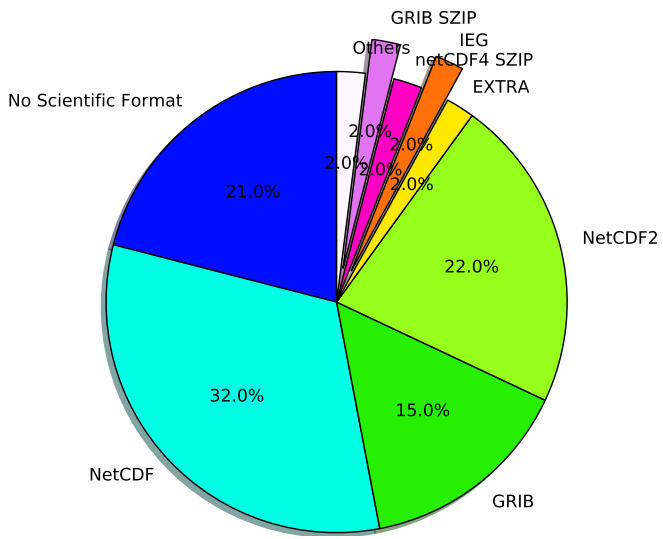


Figure: % file size

Insights from File Analysis

Home:

- Not much insight
- Mostly code/objects
- Many empty directories, broken links ...

Work/Scratch:

- Many old/inefficient file formats around
- Many small files + TXT
- A small fraction of data volume is compressed:
  - 2% NetCDF and 2% GRIB SZIP, 3% GZIP compressed
- A small fraction (3% of volume) of NetCDF4/HDF5

Dealing with Storage in ESiWACE

H2020 project: ESiWACE Center of Excellence

Work package 4

Partners: DKRZ, STFC, ECMWF, CMCC, Seagate

1. Modelling costs for storage methods and understanding these
2. Modelling tape archives and costs
3. Focus: Flexible disk storage layouts for earth system data
   - Reduce penalties of „shared“ file access
   - Site-specific data mapping but simplify import/export
   - Allow access to the same data from multiple high-level APIs