Lustre File System on ARM

Architecture Evaluation v1.1

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Motivations

ARM momentum
- 64bit evolution
- Recent debuts on HPC
- Traction in new areas such as Machine Learning and AI

Another option in the market
- Intel established as *de-facto* standard
- Market needs competitors; cost reduction

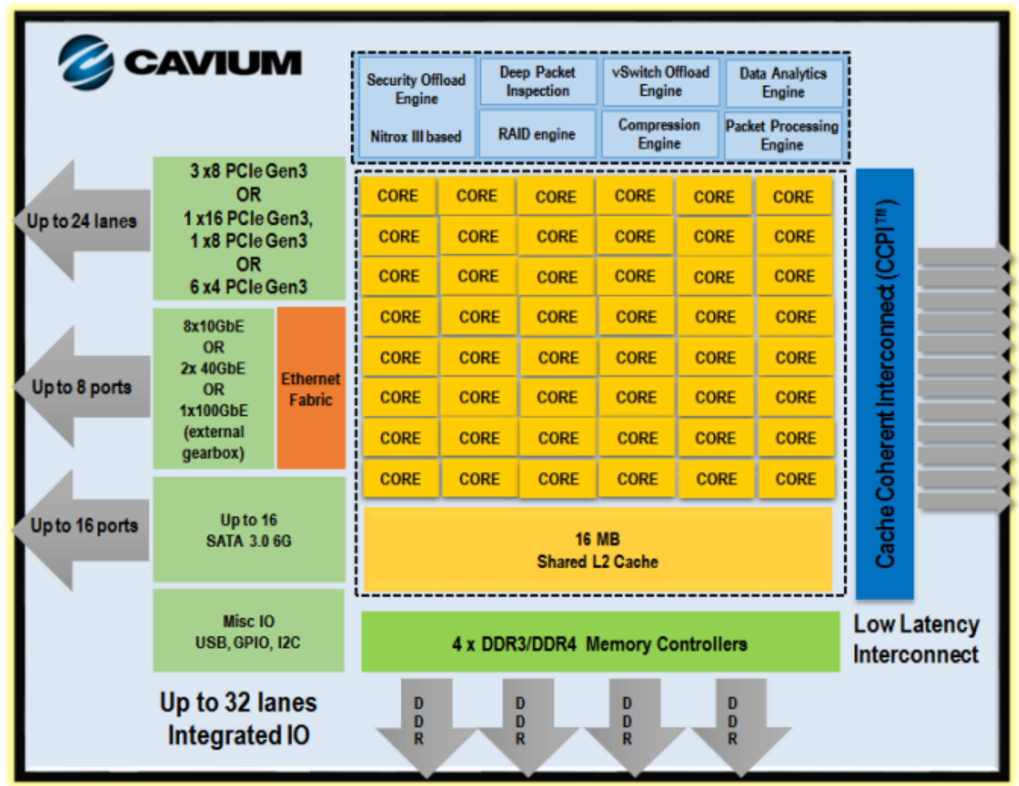
Technical reasons
- Potential high bandwidth, high throughput processor
- Low power consumption option
- The Technical challenge

The Cavium ThunderX Architecture

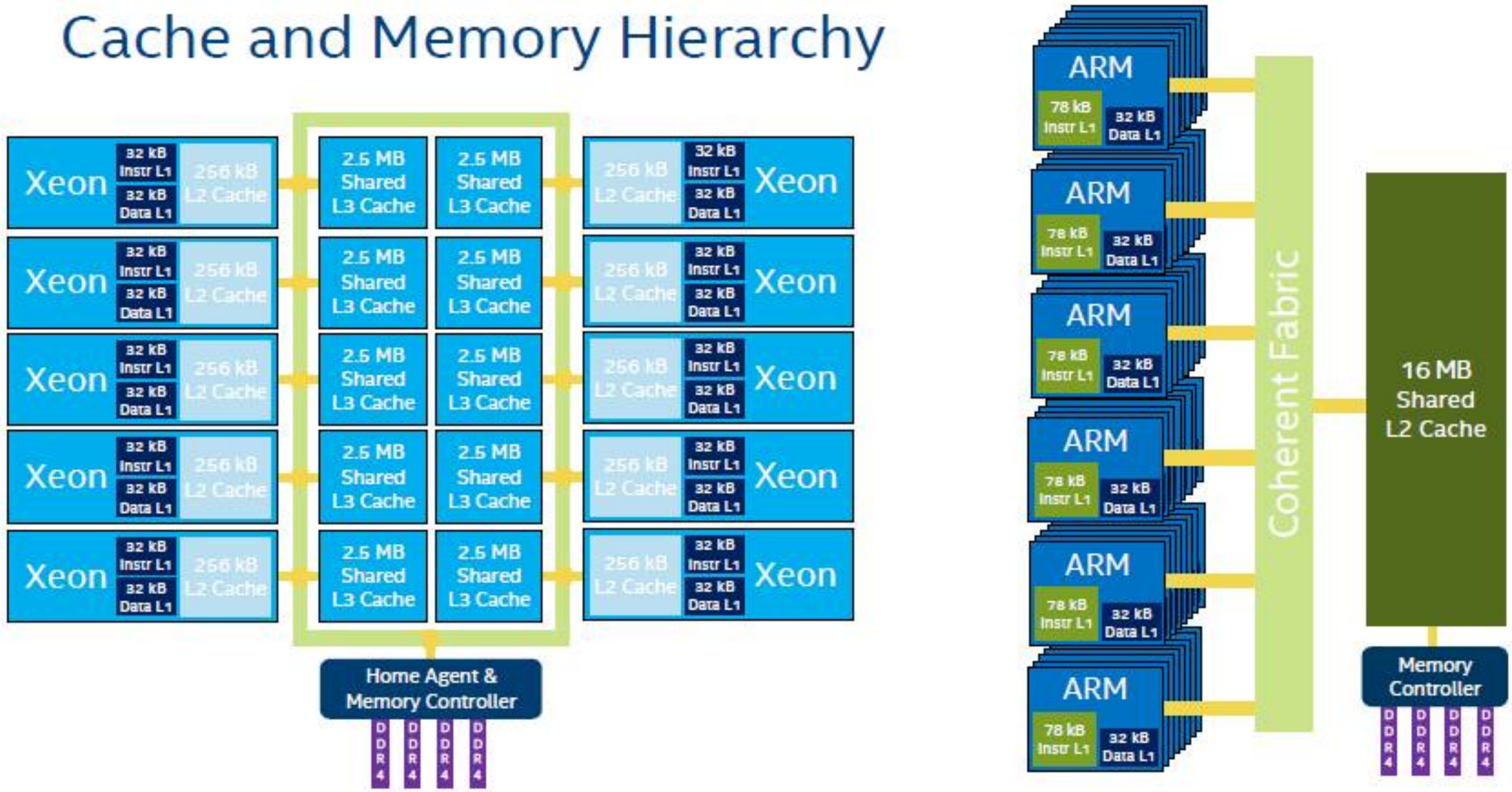
- **SoC architecture**
  - ISA: ARMV8

ARM

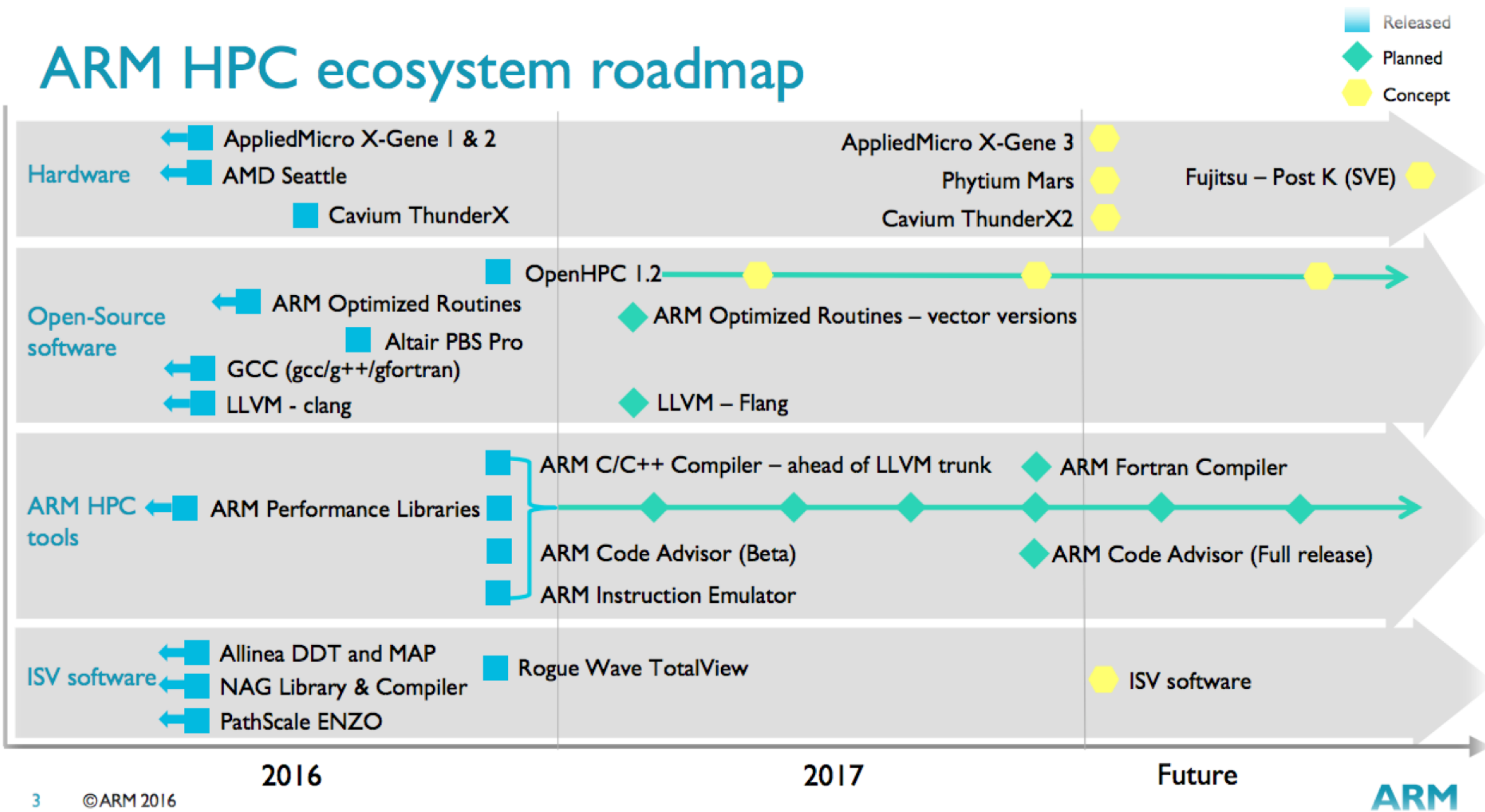
```
root@s167:/proc# lscpu
Architecture:          aarch64
Byte Order:             Little
                         Endian
CPU(s):                 96
On-line CPU(s) list:    0-95
Thread(s) per core:     1
Core(s) per socket:     48
Socket(s):              2
NUMA node(s):           2
L1d cache:              32K
L1i cache:              78KL2
cache:                16384K
NUMA node0 CPU(s):      0-47
NUMA node1 CPU(s):      48-95
```



ARM ThunderX and Intel Xeon



5 ARM Ecosystem

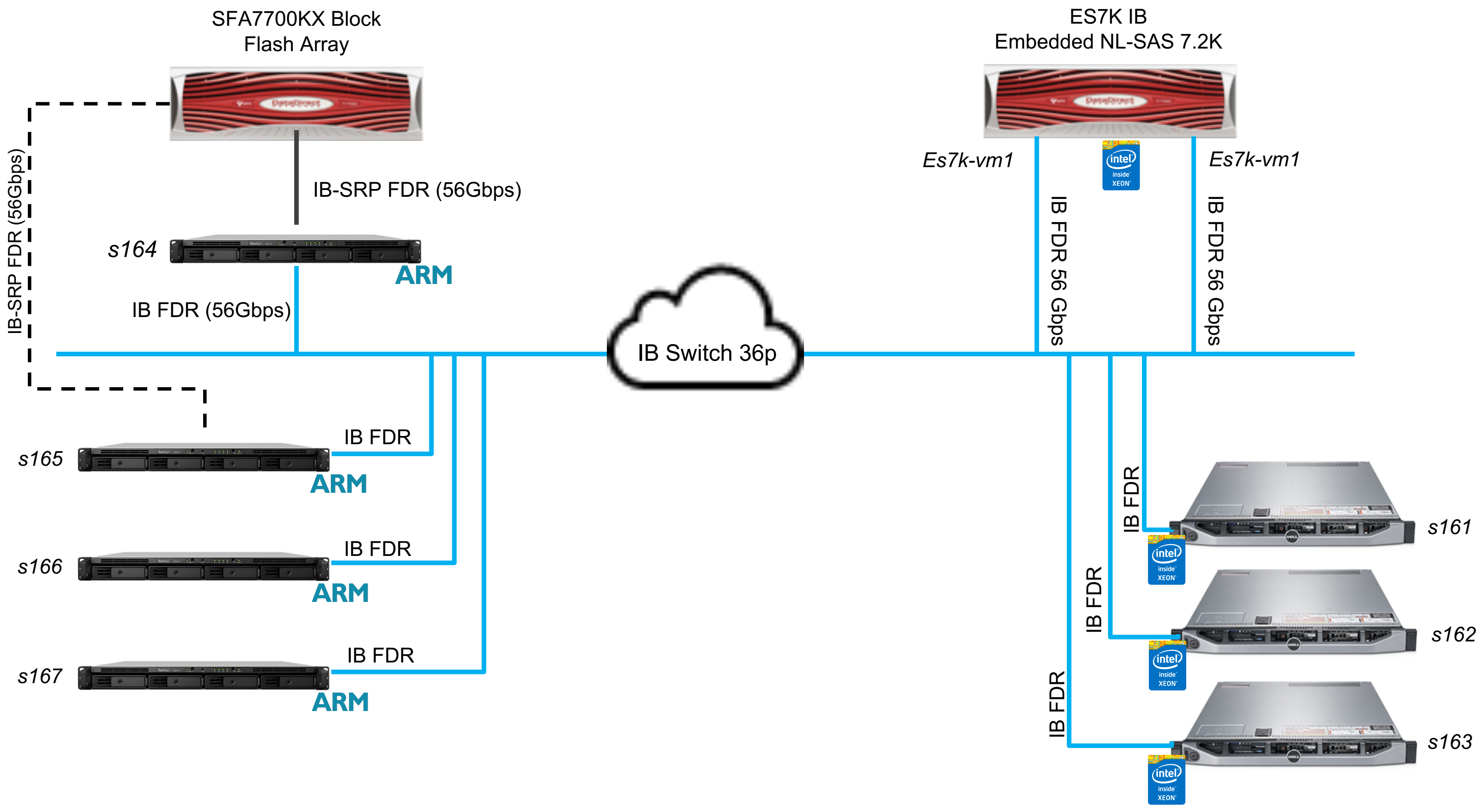


Courtesy of ARM – http://arm.com/hpc

DDN Goals evaluating ARM

- Understand if it is a viable option for mid/long term future products
- Understand what's the effort necessary to make Lustre running optimally on ARM (client and server-side)
- Understand how Lustre and general I/O behaves on ARM SoC architecture
- Contribute to the community

Test Environment used for the study



Test environment

- **4 x Gigabyte, Cavium ThunderX2 ARM servers**
  - 128GB RAM, 3 x 40GbE | 4 x 10GbE, 1 x IB FDR 56Gbps
- **1 x SFA7700-IB (ib-srp)**
  - Full flash array, 8 x RAID6 LUNs (200GB SSDs)
- **1 x ES7KE-IB (Intel based, DDN appliance)**
  - Embedded Lustre appliance, 2 controllers, 8 RAID6 pools (OSTs), 2 SSD RAID1 pools for MDT
- **3 x DELL R620 servers**
  - 2 sockets, 12 cores total, 64GB RAM

Lustre File System configuration

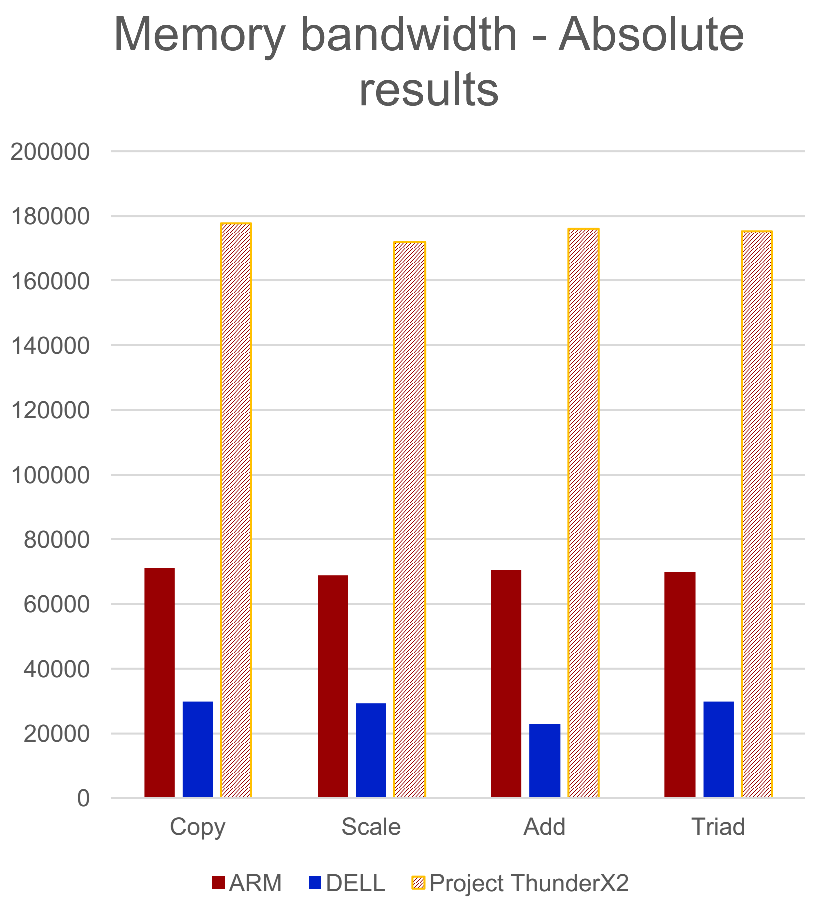
- **ARM Servers and Clients**
  - OS: `Ubuntu 16.04.03 LTS – Xenial Xerus`
  - Kernel: `Linux s166 4.4.0-31-generic #50-Ubuntu SMP Wed Jul 13 00:06:30 UTC 2016 aarch64 aarch64 aarch64 GNU/Linux`
  - Lustre: `2.10.0.0 + patches`
    - `LU-9950, LU-9951, LU-9564 (backported for Ubuntu/debian)`
- **X86 clients**
  - OS: `CentOS Linux release 7.2.1511 (Core)`
  - Kernel: `Linux s162 3.10.0-327.el7.x86_64 #1 SMP Thu Nov 19 22:10:57 UTC 2015 x86_64 x86_64 x86_64 GNU/Linux`
  - Lustre: `2.10.0.0`
- **ES7K Embedded Lustre Server**
  - OS: `CentOS Linux release 7.3.1611 (Core)`
  - Kernel: `Linux vm01-es7k01 3.10.0-514.21.2.el7.x86_64.lustre #1 SMP Wed Jun 21 03:34:21 PDT 2017 x86_64 x86_64 x86_64 GNU/Linux`
  - Lustre: `DDN Lustre 2.7.x + Patches`

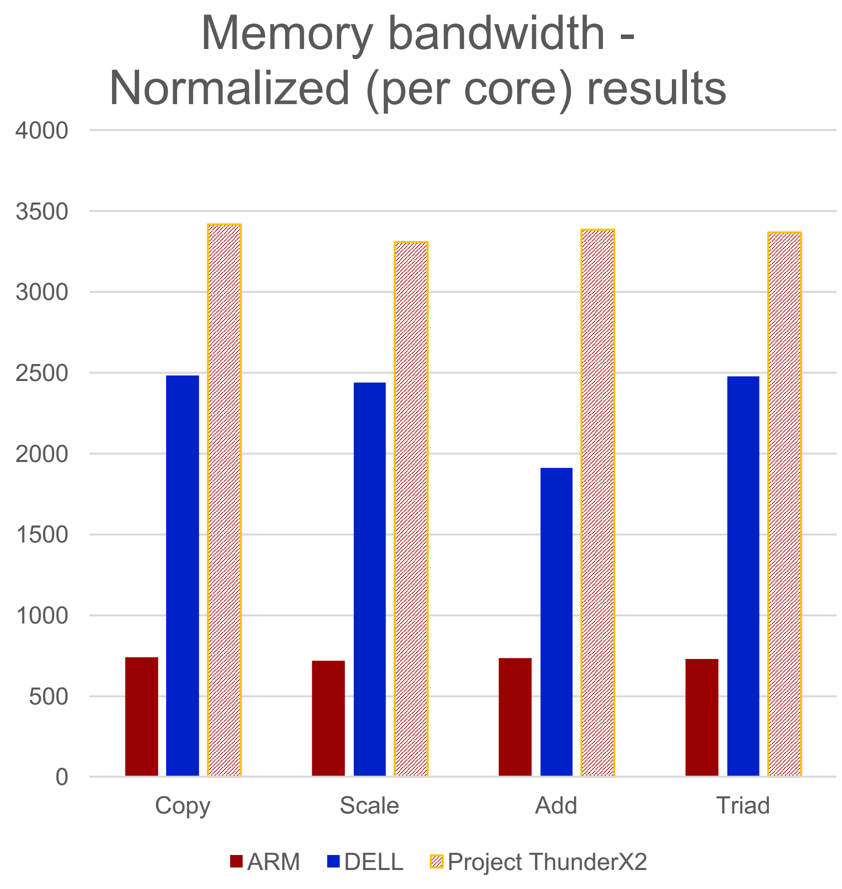
10

Stand alone ARM servers

Baseline Performance

Single ARM Server – first glimpse Memory Bandwidth (stream)






```
ARM# gcc-6 –O3 -march=ARMv8.1-a -fopenmp -mcmodel=large \ -DSTREAM_ARRAY_SIZE=2600000000 -Wall stream.c -o stream_h
DELL# gcc -Ofast -fopenmp stream.c -Wall -m64 -mcmodel=medium -DSTREAM_ARRAY_SIZE=1100000000 -o stream_h
```

IB RDMA Network test with IB_SEND_RW Sanity tests

```
root@s167:~# ib_send_bw -a -b -c UC -z 192.168.0.185
root@s165:~# ib_send_bw -a -b -c UC -z
************************************
*.Waiting for client to connect... *
************************************
---------------------------------------------------------------------------------------
                    Send Bidirectional BW Test
Dual-port       : OFF          Device         : mlx4_0
Number of qps   : 1            Transport type : IB
Connection type : UC           Using SRQ      : OFF
TX depth        : 128
RX depth        : 1000
CQ Moderation   : 100
Mtu             : 2048[B]
Link type       : IB
Max inline data : 0[B]
rdma_cm QPs     : OFF
Data ex. method : rdma_cm
---------------------------------------------------------------------------------------
local address: LID 0x25 QPN 0x0255 PSN 0xfe41b5
remote address: LID 0x26 QPN 0x47d1 PSN 0x8db89f
---------------------------------------------------------------------------------------
#bytes     #iterations    BW peak[MB/sec]    BW average[MB/sec]   MsgRate[Mpps]
2          1000             9.01               7.98                       4.185542
1000             16.95             16.42                4.303677
1000             33.17             32.75                4.292886
1000             66.34             65.39                4.285470
32         1000             132.68             130.73                     4.283882
64         1000             265.36             262.16                     4.295241

<SNIP>

131072     1000             8250.48            8244.47                    0.065956
262144     1000             8263.43            8256.41                    0.033026
524288     1000             8252.15            8246.37                    0.016493
1048576    1000             8256.10            8248.31                    0.008248
2097152    1000             8254.87            8251.13                    0.004126
4194304    1000             8256.12            8251.63                    0.002063
8388608    1000             8138.98            8138.19                    0.001017
---------------------------------------------------------------------------------------
```

ARM Server – point to point IB BW MPI OSU BW and BIBW

Unidirectional BW

```
root@s165:/mnt/lustre# mpirun_rsh -hostfile
/mnt/lustre/bin/mach -n 2 /mnt/lustre/mvapich/bin/osu_bw
# OSU MPI Bandwidth Test v5.3.2
# Size        Bandwidth (MB/s)
1                       0.22
2                       0.84
4                       2.14
8                       4.28
16                      8.56
32                     17.05
64                     33.76
128                    65.66
256                   115.18
512                   245.05
1024                  399.22
2048                  735.48
4096                 1090.75
8192                 1235.69
16384                2838.55
32768                4864.02
65536                4688.12
131072               5270.83
262144               5333.59
524288               5297.62
1048576              5387.66
2097152              5400.73
4194304              5415.79
```

Bidirectional BW

```
root@s165:/mnt/lustre# mpirun_rsh -hostfile /mnt/lustre/bin/mach
-n 2 /mnt/lustre/mvapich/bin/osu_bibw
# OSU MPI Bi-Directional Bandwidth Test v5.3.2
# Size        Bandwidth (MB/s)
1                       0.28
2                       1.25
4                       2.51
8                       4.97
16                      4.02
[illegible]            19.13
[illegible]            38.35
[illegible]            72.64
[illegible]           142.76
[illegible]           269.86
[illegible]           519.32
[illegible]           872.59
[illegible]          1261.87
8192                 1449.39
16384                2608.61
32768                4686.06
65536                7477.37
131072               8310.94
262144               8436.23
524288               8539.24
1048576              8597.96
2097152              8624.46
4194304              8472.55
```

Single ARM server – storage backend

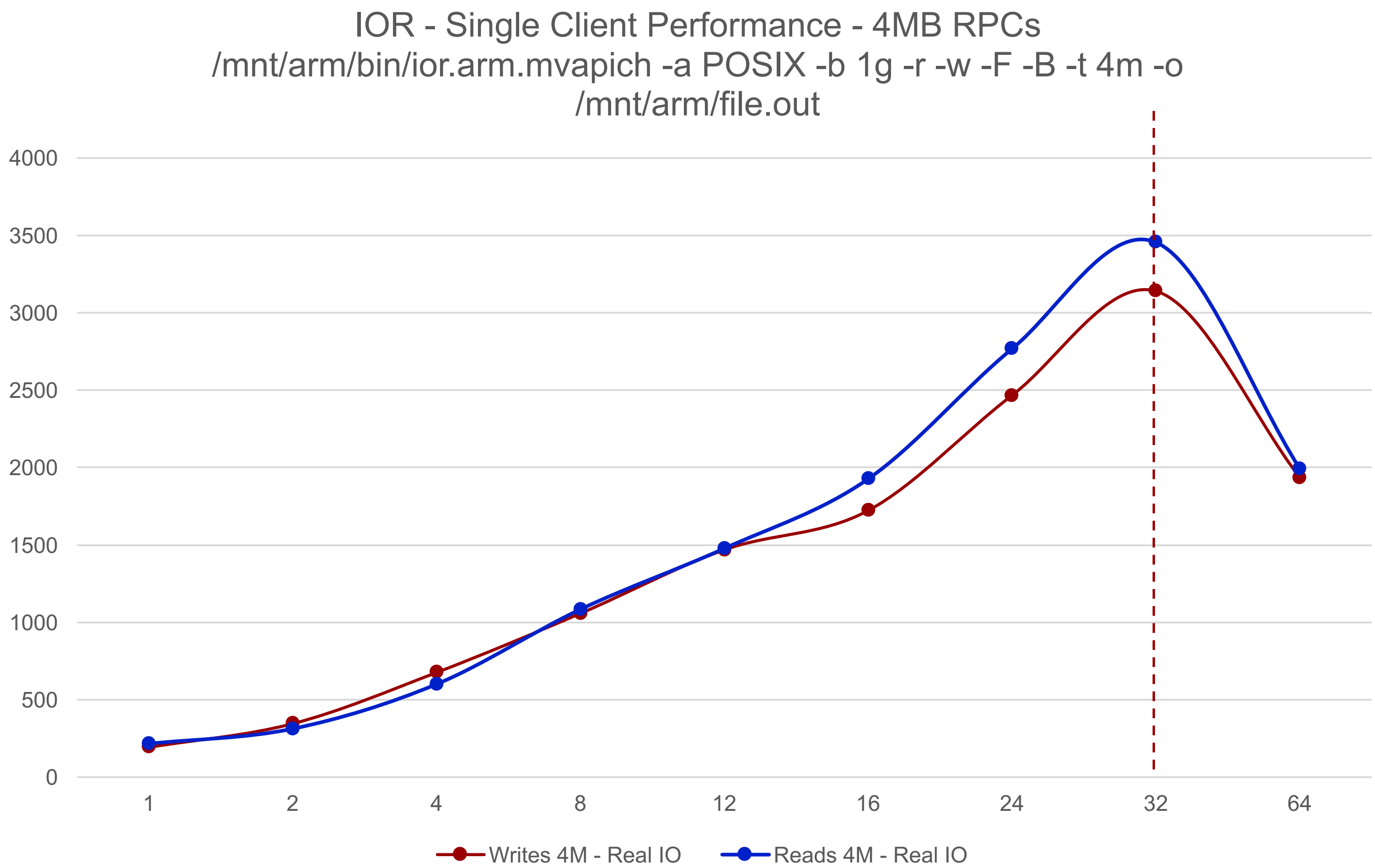
Simple test to evaluate storage backend – FIO

- 1 x ARM server connected to SFA7700X via IB-SRP (FDR)

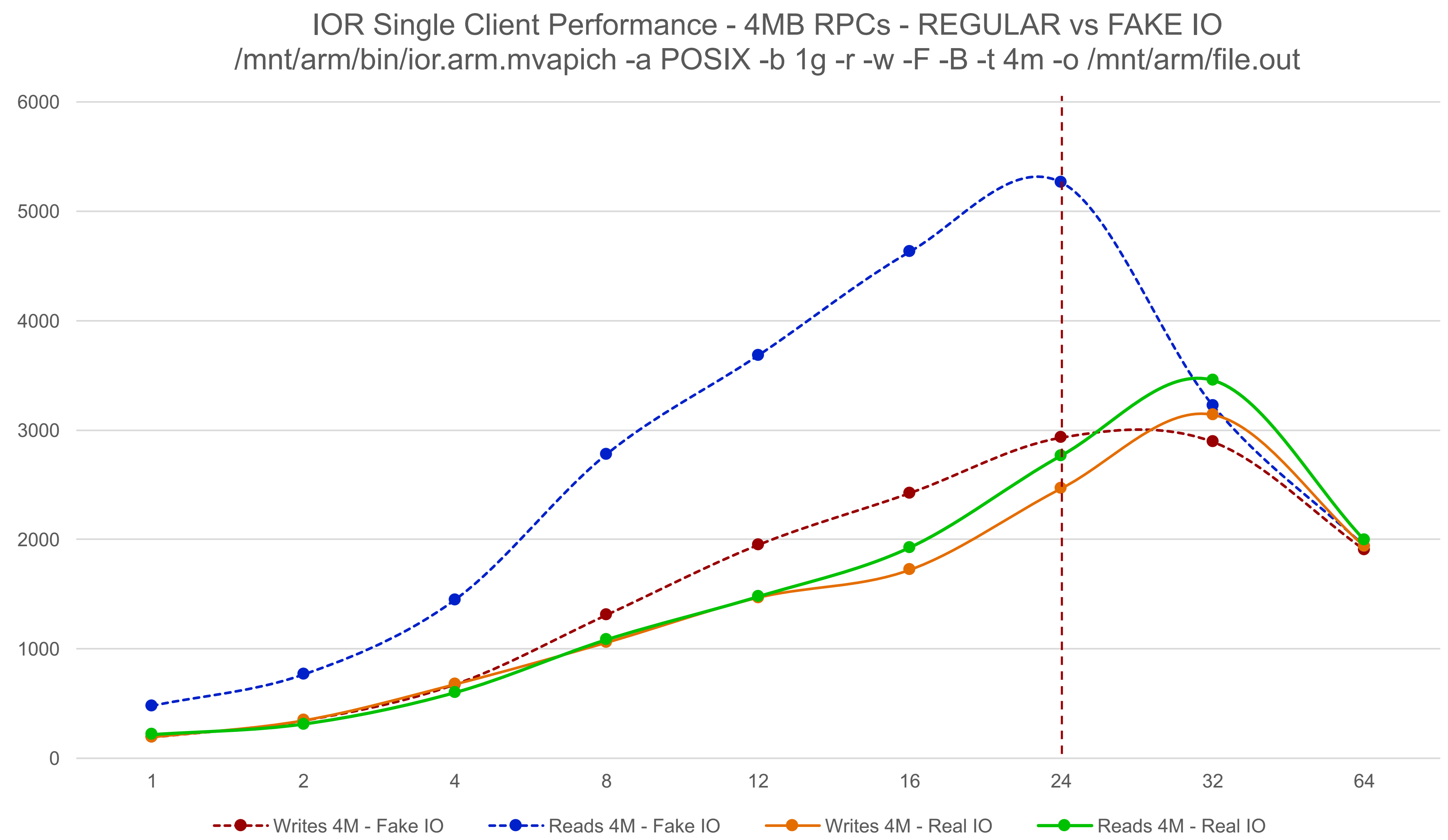
```
root@s165:/sys/block# fio --name=foo --rw=read --bs=1m --runtime=30 --time_based --ioengine=libaio --iodepth=64 --direct=1 --numjobs=8 --
group_reporting --filename=/dev/sdb --filename=/dev/sdc
foo: (g=0): rw=read, bs=(R) 1024KiB-1024KiB, (W) 1024KiB-1024KiB, (T) 1024KiB-1024KiB, ioengine=libaio, iodepth=64
...
fio-3.0
Starting 8 processes
Jobs: 8 (f=16): [R(8)][100.0%][r=5260MiB/s,w=0KiB/s][r=5260,w=0 IOPS][eta 00m:00s]
foo: (groupid=0, jobs=8): err= 0: pid=37191: Tue Sep 26 18:51:52 2017
  read: IOPS=5426, BW=5427MiB/s (5690MB/s)(159GiB/30074msec)
   slat (usec): min=191, max=101843, avg=1202.10, stdev=5434.79
   clat (usec): min=342, max=562238, avg=92961.48, stdev=54905.53
    lat (usec): min=807, max=562616, avg=94164.77, stdev=55509.54
   clat percentiles (msec):
    |  1.00th=[    7],  5.00th=[   17], 10.00th=[   31], 20.00th=[   48],
    | 30.00th=[   63], 40.00th=[   75], 50.00th=[   86], 60.00th=[   96],
    | 70.00th=[  112], 80.00th=[  136], 90.00th=[  165], 95.00th=[  190],
    | 99.00th=[  251], 99.50th=[  284], 99.90th=[  510], 99.95th=[  527],
    | 99.99th=[  550]
  bw (  KiB/s): min=153600, max=983040, per=12.50%, avg=694524.80, stdev=105260.97, samples=480
  iops        : min=  150, max=  960, avg=678.12, stdev=102.78, samples=480
 lat (usec)   : 500=0.01%, 750=0.01%, 1000=0.01%
 lat (msec)   : 2=0.06%, 4=0.31%, 10=1.87%, 20=3.92%, 50=15.35%
 lat (msec)   : 100=41.89%, 250=35.57%, 500=0.90%, 750=0.11%
 cpu          : usr=0.34%, sys=31.73%, ctx=19114, majf=0, minf=21757

<SNIP>

Run status group 0 (all jobs):
  READ: bw=5427MiB/s (5690MB/s), 5427MiB/s-5427MiB/s (5690MB/s-5690MB/s), io=159GiB (171GB), run=30074-30074msec

Disk stats (read/write):
 sdb: ios=55827/0, merge=55472/0, ticks=2579464/0, in_queue=2582500, util=94.10%
 sdc: ios=53850/0, merge=57636/0, ticks=2780888/0, in_queue=2793204, util=95.68%
```

Part 1 – ARM Server

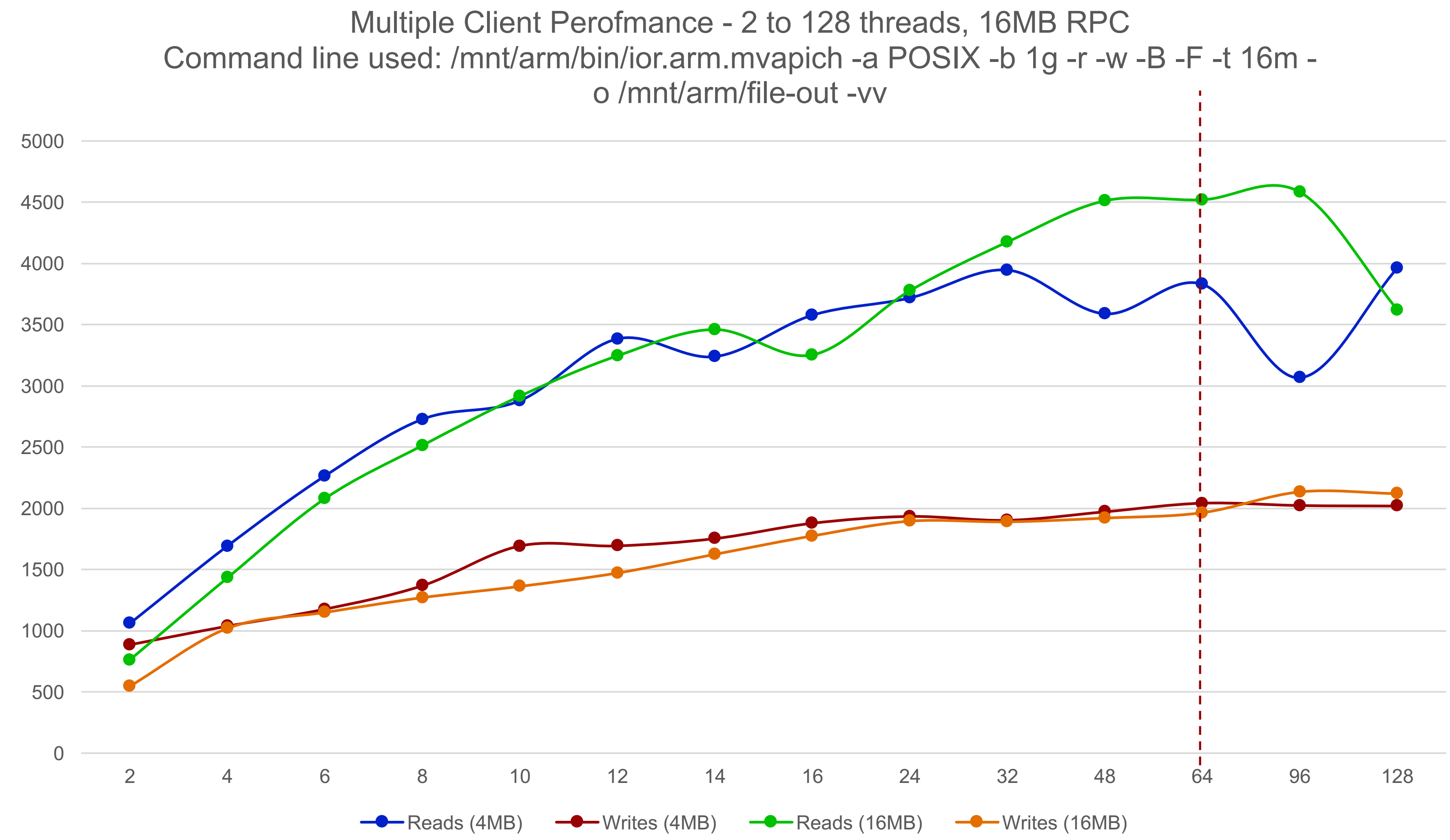
IOR Single Client Performance – Multiple Threads



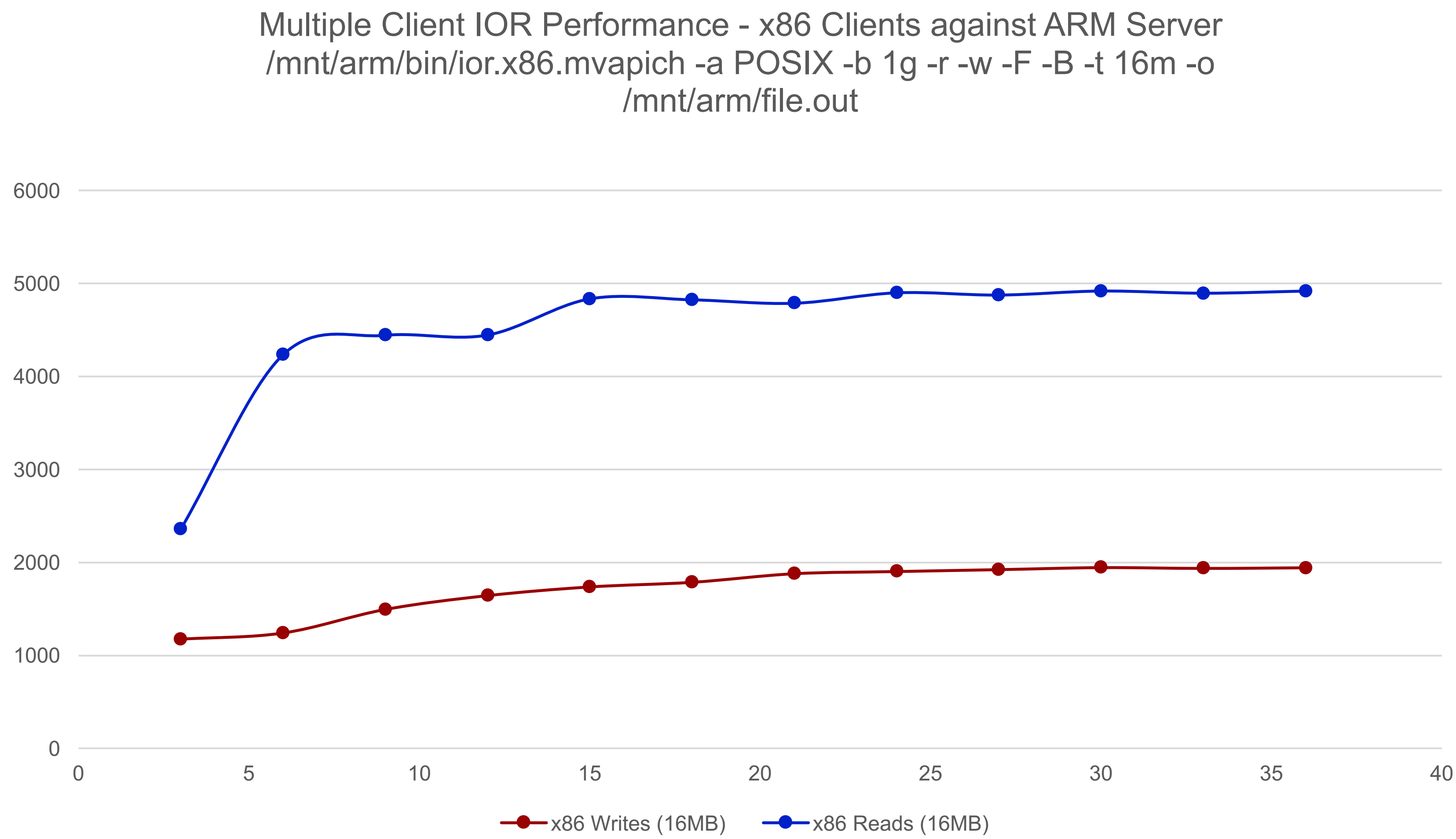
IOR Single Client Performance – Multiple Threads



IOR Results – end to end multiple clients (Real I/O)



X86 clients against Lustre ARM server IOR Sequential Performance



ARM and x86 Clients comparison IOR, multiple clients - Sequential

Sniplet from brw_stats during a set of runs (2 to 128 threads)

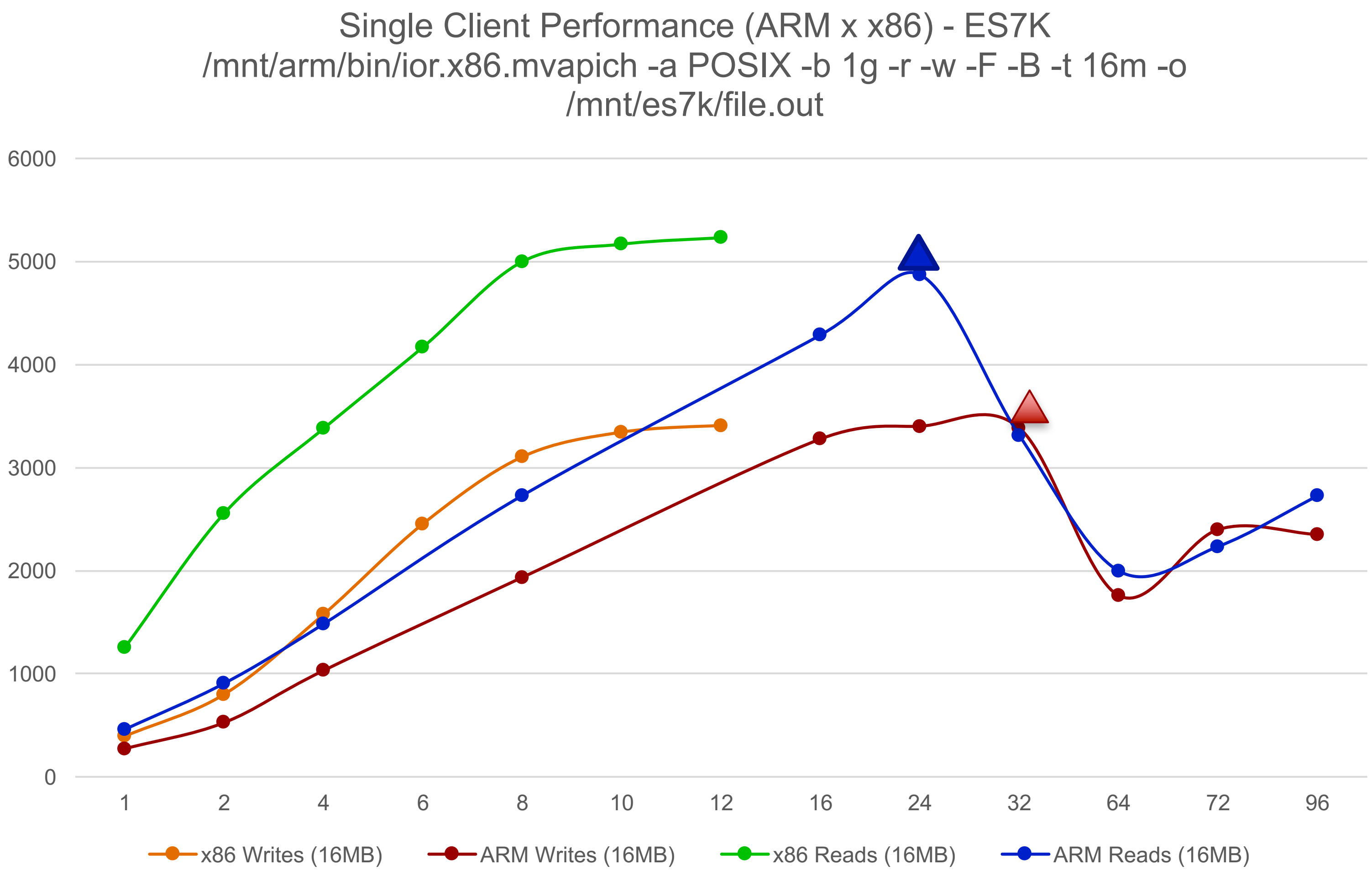
```
Ltest-OST0000
<snip>
read        |      write
disk I/O size          ios    % cum % |  ios          % cum %
4K:                                127    0    0    |     1    0    0
8K:                                146    0    1    |     0    0    0
16K:                               403    2    4    |     0    0    0
32K:                               681    4    8    |     0    0    0
64K:                              1590   10   19    |     0    0    0
128K:                             1565   10   29    |     0    0    0
256K:                              631    4   33    |     0    0    0
512K:                               89    0   34    |     0    0    0
1M:                               9905   65  100    | 169184   99  100
```

Very much the same for all other OSTs ltest-OST000[0-6]

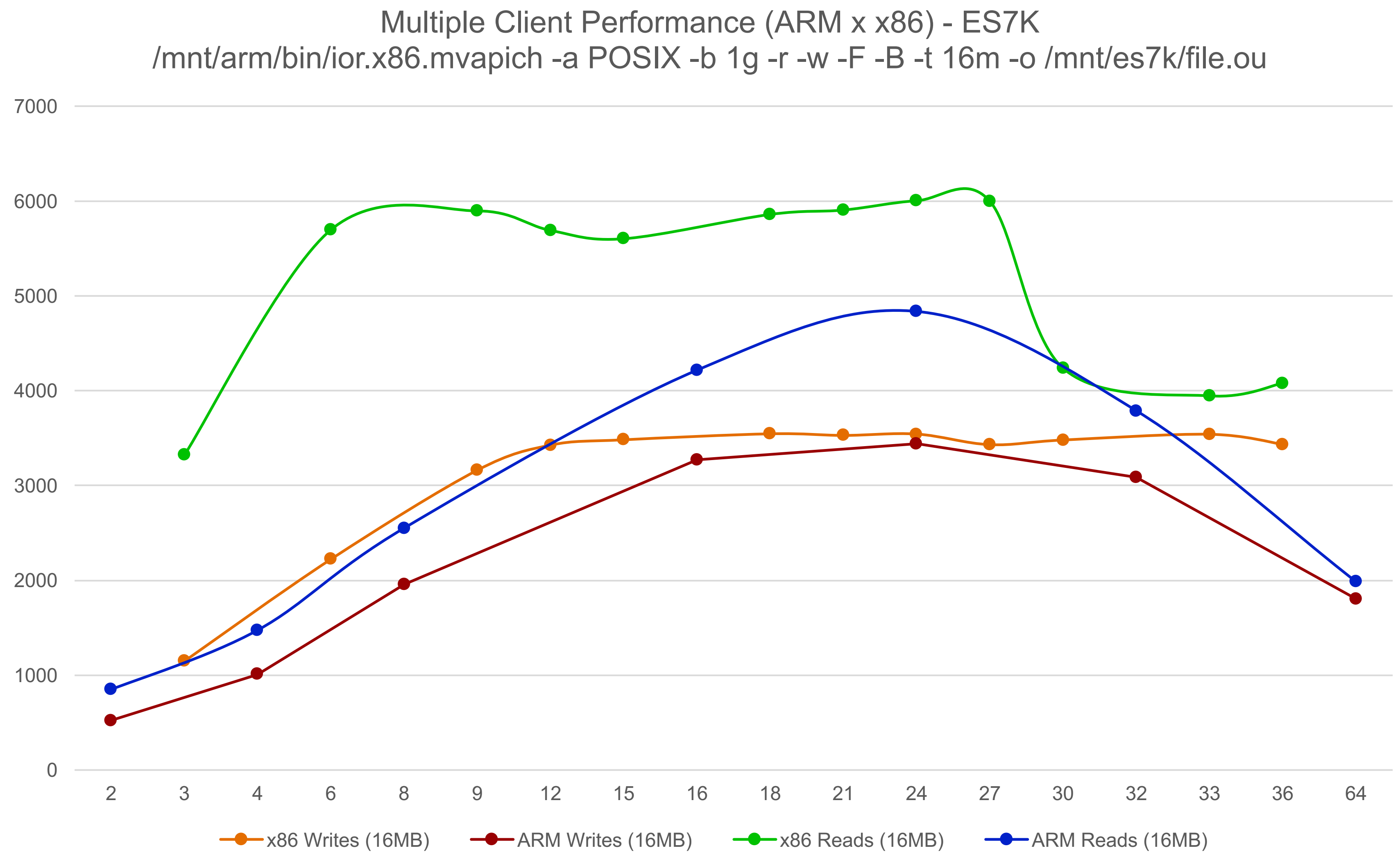
```
Ltest-OST0001
<snip>
read        |      write
disk I/O size          ios    % cum % |  ios          % cum %
4K:                                 44    0    0    |     1    0    0
8K:                                 44    0    0    |     0    0    0
16K:                               119    0    1    |     0    0    0
32K:                               245    1    3    |     0    0    0
64K:                               461    3    7    |     0    0    0
128K:                              452    3   10    |     0    0    0
256K:                              148    1   12    |     0    0    0
512K:                               30    0   12    |     0    0    0
1M:                              10940   87  100    | 168096   99  100
```

Part II – ARM Clients

Single Client Performance comparison



Multiple Client performance comparison



25

Preliminary Conclusions

ARM Server - RAW vs Lustre

- **RAW performance indicates the ARM systems could potentially sustain high bandwidth**
  - We achieved about 7GB/sec reading/writing into and from a Flash based storage that is capable of doing 10GB/sec I/O.
  - The bottleneck is the IB-FDR used with IB-SRP as connection
  - Concurrent Infiniband traffic also performs well. Tests executed demonstrated about 6GB/sec unidirectional BW and about 9GB/sec bi-directional on both IB_RDMA calls (*ib_send_bw)* and also on MPI layer.
  - Memory bandwith per core is much lower than other x86 architecture that probably will affect Lustre IO too.

”Noise” - Unpredictability on the Server side

- **We observed noise and unpredictable server behavior when scaling up the IO workload thus increasing the number of OSS service threads.**
  - Such behavior is related to the highly scalable number of cores on two NUMA domains.
  - Changing LNET partitions plays a little but yet visible effect on server performance.
  - Lustre PIO _should_ help since the effects we are seeing on ARM servers are similar to KNL nodes (high core count, low frequency) – Avoiding serialization should help.
- **The best numbers are observed when using 24 to 32 cores**
  - More than 32 cores causes noisy and the results become unpredictable. This effect is known, specially on high count core SoC architecture.
  - No L3 cache line and all coherent helps to minimize the effect
  - 4 LNET partitions seems to be optimal for the tested CPU

Server Performance

- **Reads seems reasonable, writes needs improvement**
  - Lustre back-end **write** performance is limited to 3-3.5GB/sec
    - It's about 50% of RAW I/O performance
    - Client concurrency slow down to 2-2.5GB/sec
      - Increasing the default number of OSS service threads didn't take much effect (default 360).
  - Lustre back-end **read** performance seems to be max out to 5-5.5GB/sec
    - Compared to other Lustre back-end, Read performance seems good.
    - Ext4 can provide maximum of 6-6.5GB/sec (for this test environment).

Minimizing NUMA effects

Change LNET partition table
- Initially set to 8 partitions, brought the inflexion point lower
- 4 partitions was the setting that provides better and more reliable performance

```
root@s165:~# cat /proc/sys/lnet/cpu_partition_table
0     : 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
1     : 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47
2     : 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71
3     : 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95

root@s165:~# cat /etc/modprobe.d/lustre.conf
options lnet networks=o2ib(ib0)options
libcfs cpu_npartitions=4options
libcfs cpu_pattern=""
```

ARM Lustre Clients

- **Overall Performance equivalent to OLD Xeons, but likely to be half of the current ones.**
  - 24 core ARM matches the 12 core Haswells (reads and writes)
  - Ability to write faster on an optimized DDN ES7K also helps to blame ARM server for lower numbers
- **Similar type of NUMA issues found on client, but harder to understand and tune.**
  - Benefits of LNET partitions and other NUMA tuning still not clear
  - Applications can probably have better behavior using *numactl*

Lustre

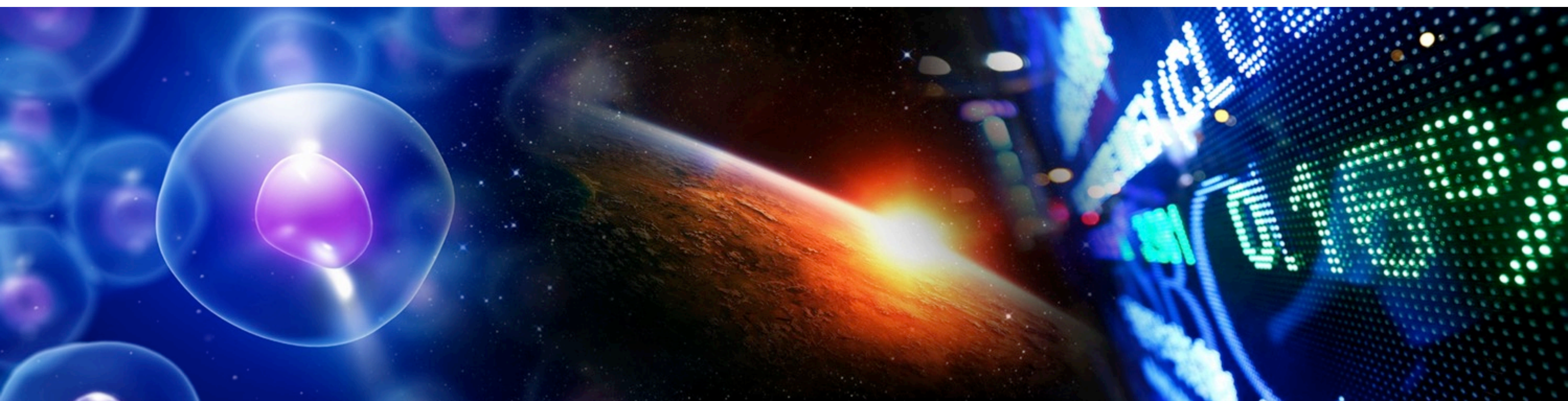
- **Build procedure required three patches**
  - LU-9950 and LU-9951
    - Build process, not really a Lustre code change
    - Patches on JIRA
  - LU-9564 backported (in order to build server on Ubuntu/debian)
  - Not very complicate, but require some cleanup in the process (built on Ubuntu - caused some library incompatibilities)
- **The process overall is easy and straight forward**

What next?

- **Study still in very preliminary stage**
- **More research on the server side**
  - We are interesting on alternatives for the current offerings
  - Evaluate SoC features for better utilization (crypto, RAID engine, virtualization)
  - Profile IO and general workloads
- **Need to test 40GbE**
  - Native chips and embedded Switch on SoC is supposedly to deliver better I/O balance (opposed to utilization of single IB card)
- **Experiment in larger scale**
  - Looking for large environments willing to cooperate
- **Lustre side**
  - P0: Run tests with PIO and compare results
  - Profile writes

Thank you

Carlos Thomaz
Thanks for the help from Frank Leers, Gu Zheng and rest of the team.



Extra slides

Building Lustre

Submitted patches in JIRA

- https://review.whamcloud.com/#/c/27323/
- https://jira.hpdd.intel.com/browse/LU-9950
- https://jira.hpdd.intel.com/browse/LU-9951

Prepare kernel source

```
root@s164:~ git clone http://kernel.ubuntu.com/git-repos/ubuntu/ubuntu-xenial.git/ ubuntu-kernel
root@s164:~/ubuntu-kernel# uname -r 4.4.0-93-generic
root@s164:~/ubuntu-kernel# git tag | grep 4.4.0-93 Ubuntu-4.4.0-93.116
root@s164:~/ubuntu-kernel# git checkout Ubuntu-4.4.0-93.116
```

Configure Kernel source

```
root@s164:~/ubuntu-kernel# touch .scmversion
root@s164:~/ubuntu-kernel# cp /boot/config-`uname -r` .config
root@s164:~/ubuntu-kernel# cp /usr/src/linux-headers-`uname -r`/Module.symvers
```

Building Lustre

Patch Makefile

```
root@s164:~/ubuntu-kernel# git diff
diff --git a/Makefile b/Makefile
index f1fee0c..5f235dc 100644
--- a/Makefile
+++ b/Makefile
@@ -1,7 +1,8 @@
 VERSION = 4
 PATCHLEVEL = 4
-SUBLEVEL = 79
-EXTRAVERSION =
+SUBLEVEL = 0
+EXTRAVERSION = -93-generic
+
 NAME = Blurry Fish Butt

 # *DOCUMENTATION*
root@s164:~/ubuntu-kernel# make modules_prepare
```

Patch Lustre

- LU-9950, LU-9951, *review.whamcloud.com/#/c/27323/*

Build Lustre

```
bash autogen.sh && ./configure --enable-server --enable-ldiskfs --with-zfs=no --with-o2ib=/usr/src/ofa_kernel/default/  \
--with-linux=/root/ubuntu-kernel/ --enable-module && make debs
```

Installing e2fsprogs

▶ Build and replace e2fsprogs

```
git clone git://git.hpdd.intel.com/tools/e2fsprogs.git
cd e2fsprogs git checkout v1.42.13.wc6 -b v1.42.13.wc6
wget -P ../ http://archive.ubuntu.com/ubuntu/pool/main/e/e2fsprogs/e2fsprogs_1.42.13-1ubuntu1.debian.tar.xz
tar --exclude "debian/changelog" -xf ../e2fsprogs_1.42.13-1ubuntu1.debian.tar.xz
sed -i 's/ext2_types-wrapper.h$//g' lib/ext2fs/Makefile.in
dpkg-buildpackage -b -us -uc

dpkg -i libcomerr2_1.42.13-1_arm64.deb libss2_1.42.13-1_arm64.deb e2fsck-static_1.42.13-1_arm64.deb e2fslibs_1.42.13-1_arm64.deb
e2fsprogs_1.42.13-1_arm64.deb
```