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XkitS：A computational storage framework for high energy physics based on EOS storage system

Yaosong Cheng, Minxing Zhang, Haibo Li, Yujiang Bi, **Yaodong Cheng**

Computing center, IHEP, CAS

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中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

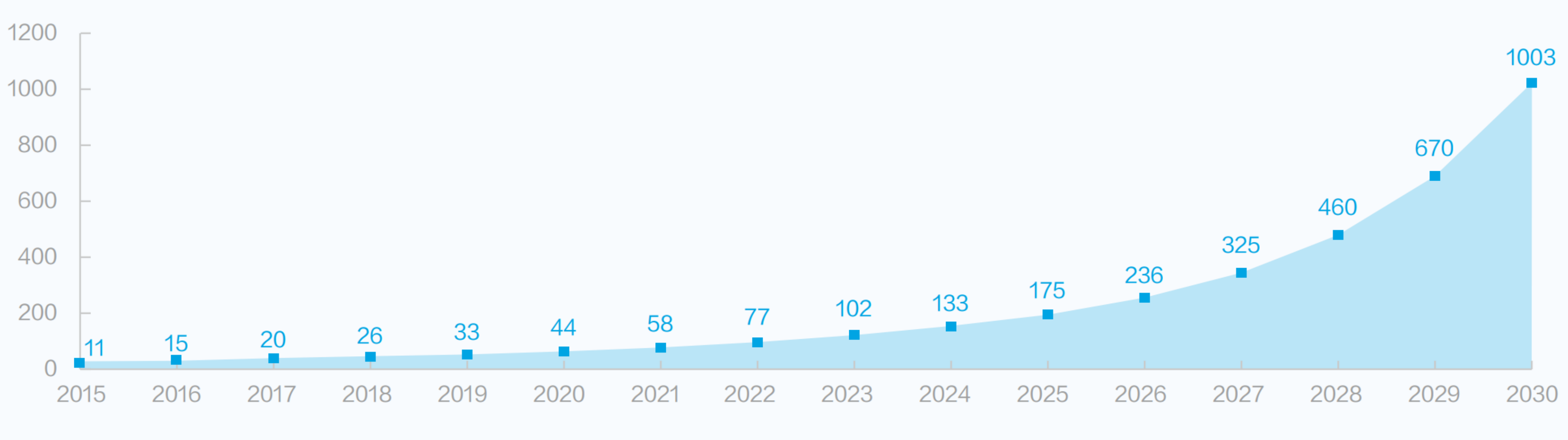
Outline

- Background and motivation
- Architecture design and implementation
- Deployment and usage
- Some use cases
- Conclusion

Background - Data exploration

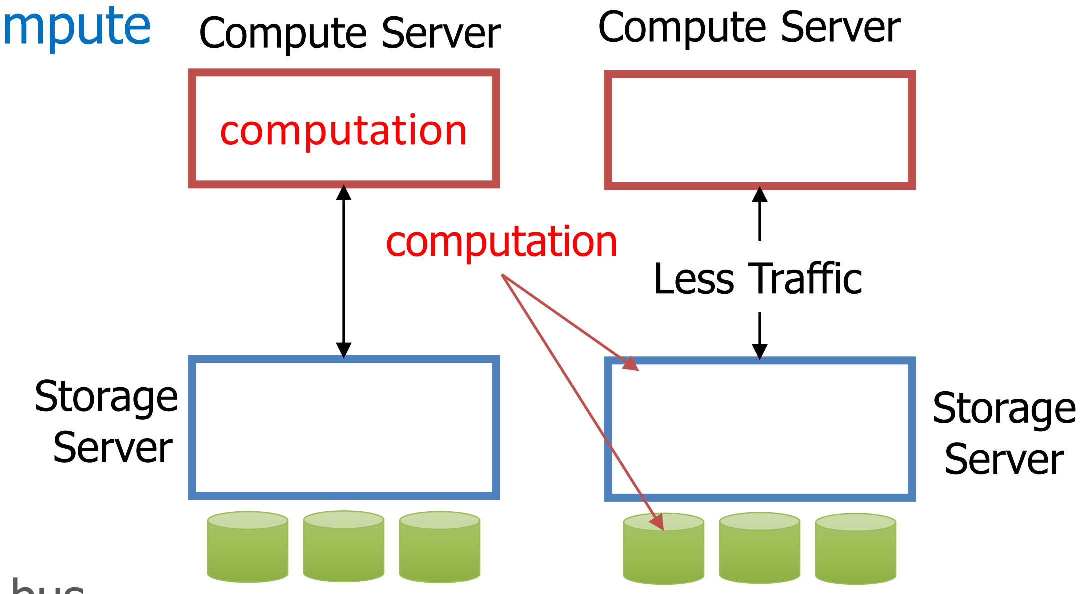
- The data generated worldwide will reach yottabyte (YB) every year by 2030
  - Driven by large scientific experiments, IoT, smart vehicle, biomedical, new energy, AIGC, …
  - It is difficult to move data due to too large volume
- If the data move is reduced, it will
  - Save energy
  - Save network bandwidth
  - Reduce the load of host CPU

Process data close/near/in storage



Computational Storage

- Move compute to the data instead of data to the compute
- Value
  - Less data transferred on the network
  - Faster response times (low latency)
  - Improved security; Energy Efficiency
- Architecture Approaches
  - CSD: Move compute into the drive
  - CSA: Move compute into the storage array
  - CSP: Compute platform on the PCI-E/NVMe/NVMeoF bus
- Implementation approaches
  - FPGA, GPU, ASICs with embeded ARM, etc
- Standards
  - SNIA TWG (Storage Networking Industry Association Computational Technical Work Group)
  - **Computational Storage Architecture and Programming Model v1.0** published August 2022



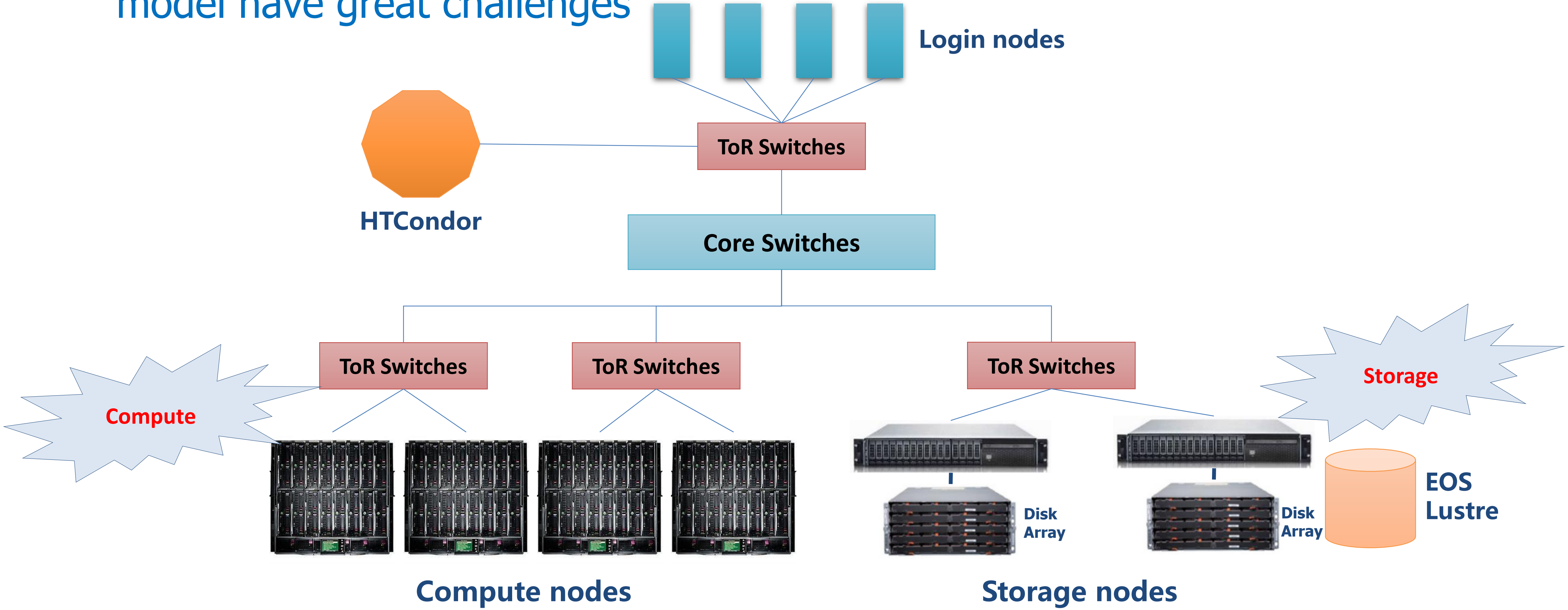
51 Participating Companies - 261 Member Representatives

Some cases of computational storage

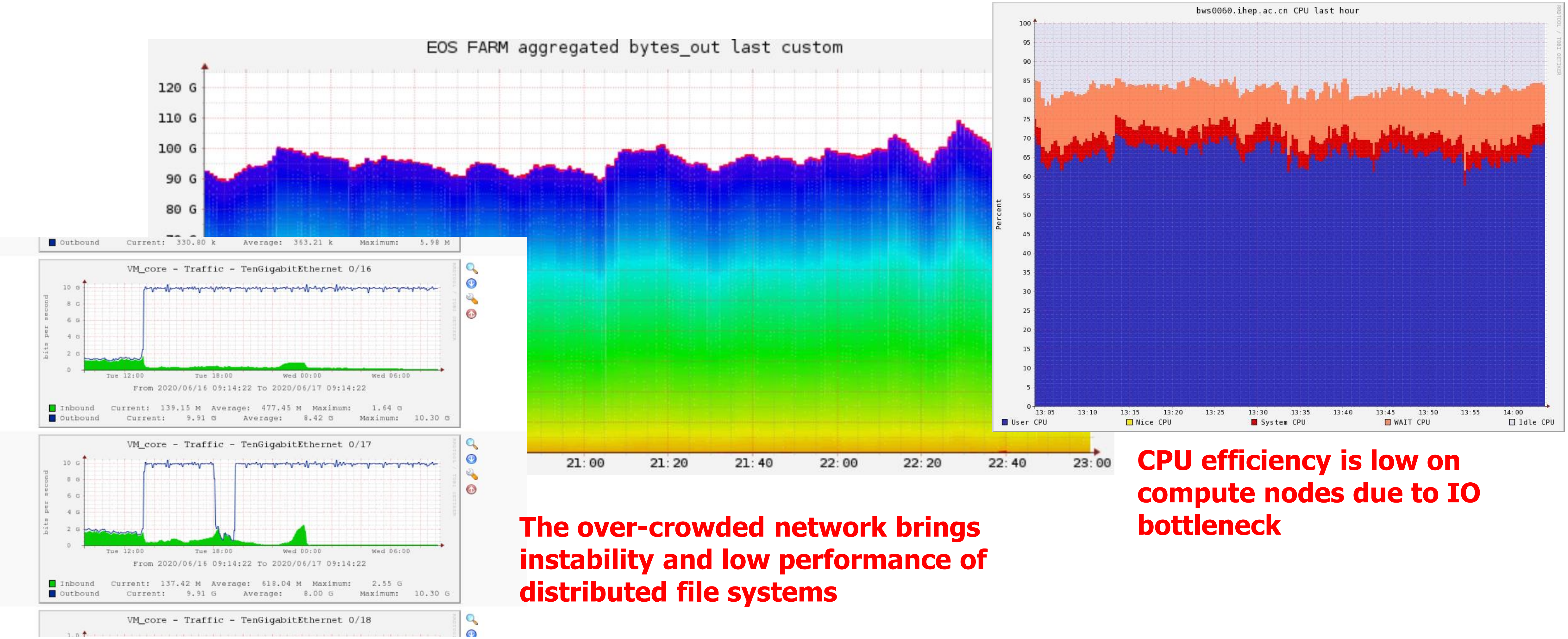
- SmartSSD
  - Put FPGA into SSD, supporting compression, AI inferencing, …
- Database acceleration
  - Scans and aggregations close to data. POLARDB [FAST’20]
- File system offload
  - Functions such as indexing and metadata operations in SmartSSD
  - KevinFS [USENIX OSDI’21] (https://github.com/dgist-datalab/kevin)
- Computation offload from compute node
  - push down structured queries from compute node to storage server
  - SkyhookDM [FAST’20] (https://iris-hep.org/projects/skyhookdm.html)
- Neural network acceleration
  - HolisticGNN [Fast’22], RecSSD [ASPLOS’21], RM-SSD [HPCA’22]

Why do we need Computational Storage

- Our current network-centric architecture and compute-storage separation model have great challenges



Problems



CPU efficiency is low on compute nodes due to IO bottleneck

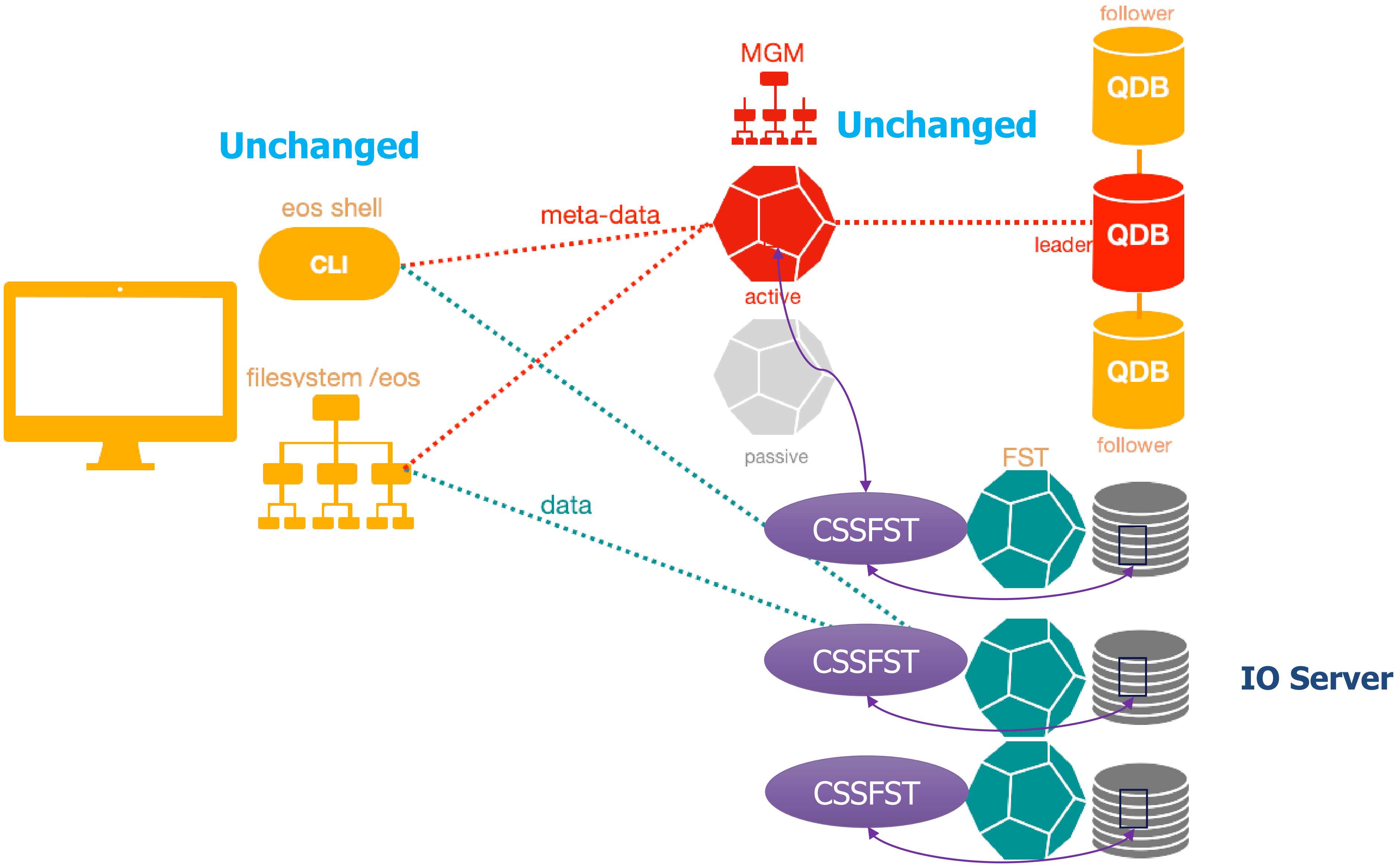
The over-crowded network brings instability and low performance of distributed file systems

Overloading of switch ports leads to package loss

Solution considerations

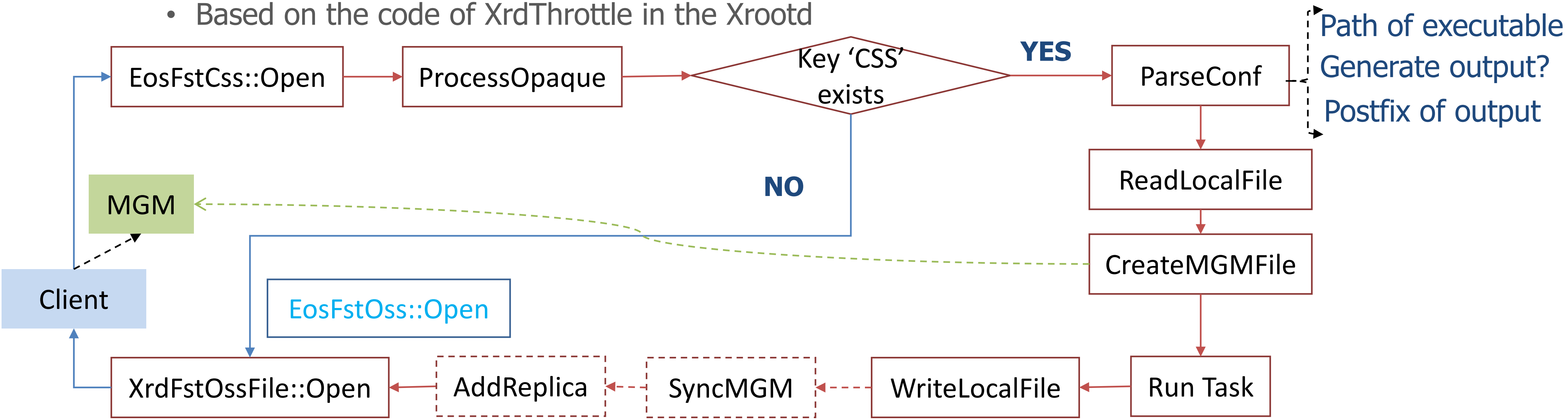
- Different computational storage solutions
  - **CSD:** many products available in the market, such as SmartSSD by Samsung, WD NGD, etc. High performance, but with Small capacity, high price.
  - **CSA:** Not yet find available products
  - **CSP:** Use computing resources on storage node as a processor. Easy to expand storage capacity but still exchange data between CSP and storage devices using PCIe.
- Computational storage solution based on EOS (developed by CERN)
  - The CPU or other resources (GPU, FPGA, etc) in storage server work as CSP
  - The name of task to be executed on storage server is appended into the file path *Open("root://eos01/eos/data.txt") → Open("root://eos01/eos/data.txt?css=sort")*
  - The task running on FST node r/w file locally
  - Name the solution **XkitS**: an eXtendable kit for computational Storage

Architecture



Implementation

- Write a plugin **EosFstCss** for FST, which doesn't modify any code of FST
  - Based on the code of XrdThrottle in the Xrootd



- If the task doesn't generate output file, such as 'sort' function, SyncMGM and AddReplica are not necessary, and stdout&stderr will be written into the local file, then READ operation will get them
- The naming of the local output file is based on EOS rule, ie. fid/10000
- The code is hosted on IHEP GitLab, and has been tested with EOS4.8 and EOS5.1

  https://code.ihep.ac.cn/storage/eoscss/cssfst.git

Deployment in FST

- Install cssfst rpm package in FST server
- Modify xrd.cf.fst configuration file

  ~~*xrootd.fslib -2 libXrdEosFst.so*~~

  xrootd.fslib -2 libEosFstCss.so -2 libXrdEosFst.so

- Edit /etc/eoscss.conf and customize computational storage functions

```
{ "sort" :    {
   "name" : "sort",
   "path" : "/usr/local/libexec/cssfst/sort.sh",
    "out"   : false },
  "km2a_decode" : {
   "name" : "km2a-decode",
   "path" : "/usr/local/libexec/cssfst/km2a-decode.sh",
   "out"   : true,
   "postfix" : "root"},
  "zstd": {
  "name": "zstd",
  "path" : "/usr/local/libexec/cssfst/zstd.sh",
  "out"   : true,
  "postfix" : "zst‟  } }
```

- The executable shell is written and deployed by administrator, which can use container (docker, singularity, …)
- All the executable shell should given one input file and one output file, and return “EXEC_SUCCESS” or EXEC_FAILED

```
#cat sort.sh
/usr/bin/sort -n $1 > $2
if [ $? -eq 0 ];then
 echo "EXEC_SUCCESS"
exit 0
echo "EXEC_FAILED"
exit 1
```

```
#cat km2a-decode.sh
container=/usr/local/libexec/cssfst/km2adecode.sif
apptainer exec --bind $dirn $container
/root/km2a/km2a-decode/decode_sort $1 $2
if [ $? -eq 0 ];then
echo "EXEC_SUCCESS"
exit 0
echo "EXEC_FAILED"
exit 1
```

How to add a new CSS function

- Don’t need to modify any code of the plugin or EOS
- Don’t need to restart any service of EOS
- 1st： Write your own program which runs on FST server using computing resources such as GPU, CPU, FPGA, etc. Even the program could be a user-defined container
  - Eg. partical_classify.exe
- 2nd: Wrap your program in a shell MUST with one input file and output file. If the program doesn’t produce any output file, “stdout” or “stderr” can be redirected into the output file
- 3rd: Edit /etc/eoscss.conf and add a new JSON item, eg. ‘partical_classify’

```
“partical_classify" :    {
  "name" : "sort",
  "path" : "/usr/local/libexec/cssfst/partical_classify.sh",
   "out"  : false },
```

→ wrapper of partical_classify.exe

DONE!!!

- 4th: use client tool to run the function adding it to file patheg. css=partical_classify

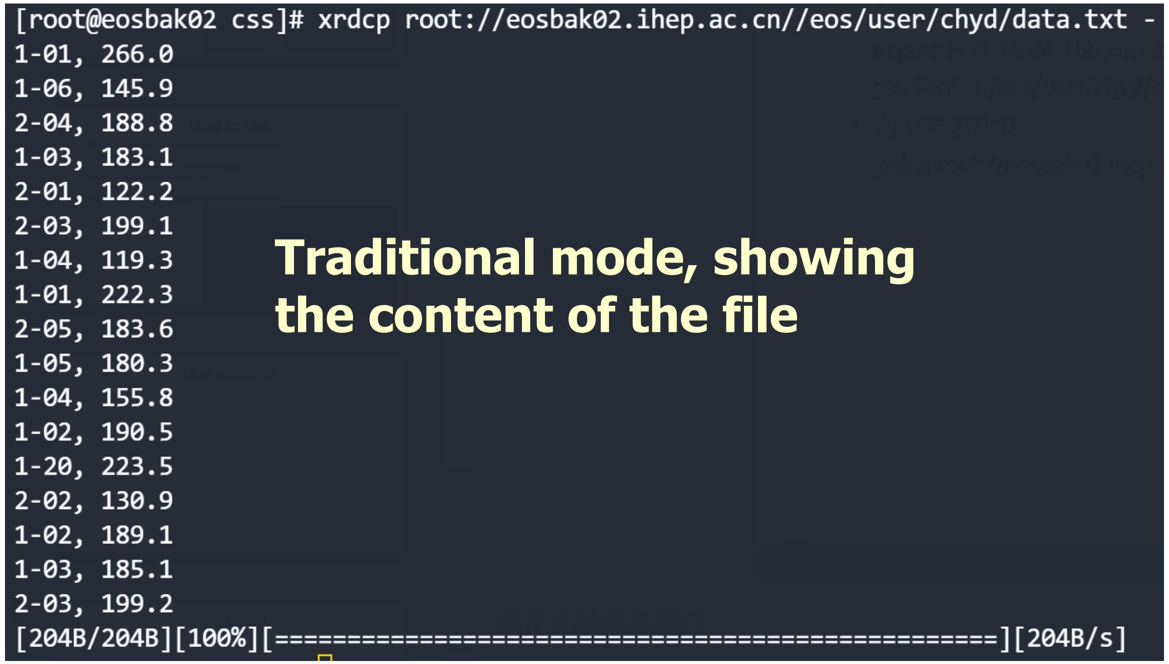
How to use

- Two methods to use it, xrdcp or a dedicated client cssclient
- 1) use xrdcp, appending CSS function name into file path

  xrdcp root://eosbak02.ihep.ac.cn//eos/user/chyd/data.txt?css=sort -
- 2) use cssclient tool, which is a wrapper of XrdPosixXrootd (Open, Read)

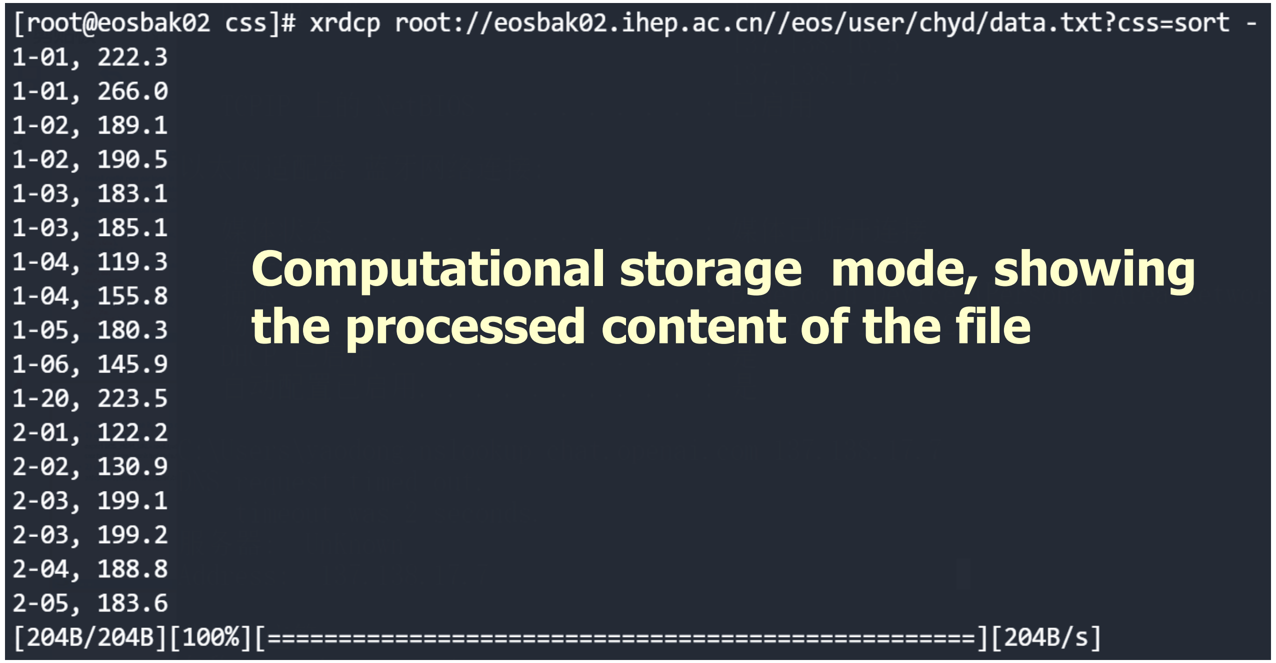
  export EOS_MGM_URL=root://eosbak02.ihep.ac.cn/

  cssclient -f /eos/user/chyd/data.txt -c sort



```
[root@eosbak02 css]# xrdcp root://eosbak02.ihep.ac.cn//eos/user/chyd/data.txt -
1-01, 266.0
1-06, 145.9
2-04, 188.8
1-03, 183.1
2-01, 122.2
2-03, 199.1
1-04, 119.3
1-01, 222.3
2-05, 183.6
1-05, 180.3
1-04, 155.8
1-02, 190.5
1-20, 223.5
2-02, 130.9
1-02, 189.1
1-03, 185.1
2-03, 199.2
[204B/204B][100%][==================================================][204B/s]
```

Traditional mode, showing the content of the file

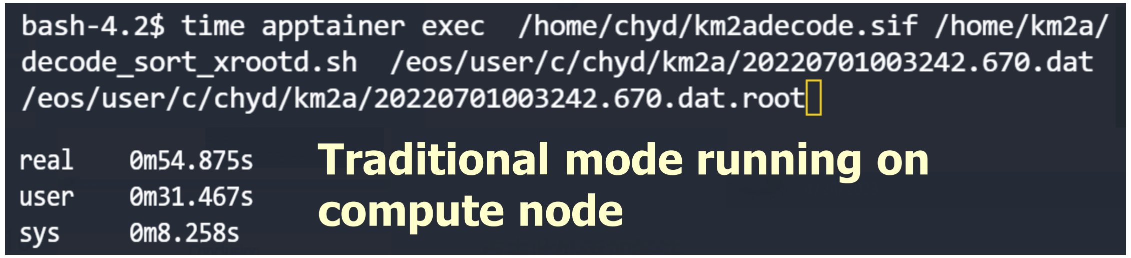


```
[root@eosbak02 css]# xrdcp root://eosbak02.ihep.ac.cn//eos/user/chyd/data.txt?css=sort -
1-01, 222.3
1-01, 266.0
1-02, 189.1
1-02, 190.5
1-03, 183.1
1-03, 185.1
1-04, 119.3
1-04, 155.8
1-05, 180.3
1-06, 145.9
1-20, 223.5
2-01, 122.2
2-02, 130.9
2-03, 199.1
2-03, 199.2
2-04, 188.8
2-05, 183.6
[204B/204B][100%][==================================================][204B/s]
```

Computational storage mode, showing the processed content of the file

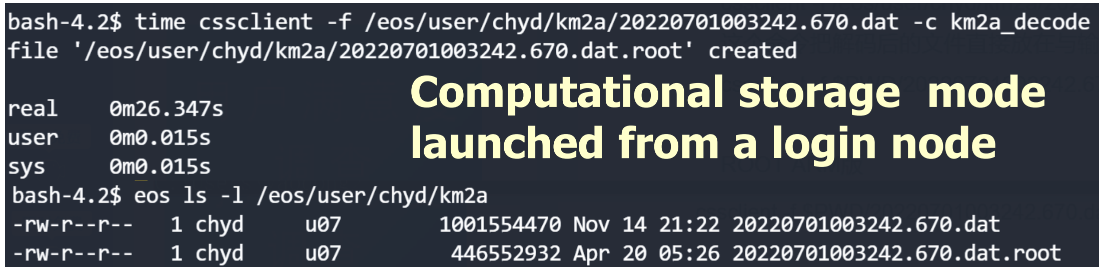
One example of LHAASO decode

- LHAASO is a large-scale cosmic ray detector array located in southwest China at an altitude of 4410 meters, ~2000 KM away from Beijing
  - It generates 12PB of data annually, which is transferred to Beijing
  - Decode is process to convert raw detector binary data into ROOT file, which needs to read and write much data but consumes very little CPU power
- Traditional computing mode: a compute node reads raw data (.dat) from one FST server and then write output data (.root) into another EOS server
- Computational storage mode: any XRootd client can launch the decode function on FST server through XRootd Client or cssclient, which read and write data locally



```
bash-4.2$ time apptainer exec  /home/chyd/km2adecode.sif /home/km2a/
decode_sort_xrootd.sh  /eos/user/c/chyd/km2a/20220701003242.670.dat
/eos/user/c/chyd/km2a/20220701003242.670.dat.root

real    0m54.875s
user    0m31.467s
sys     0m8.258s
```

Traditional mode running on compute node



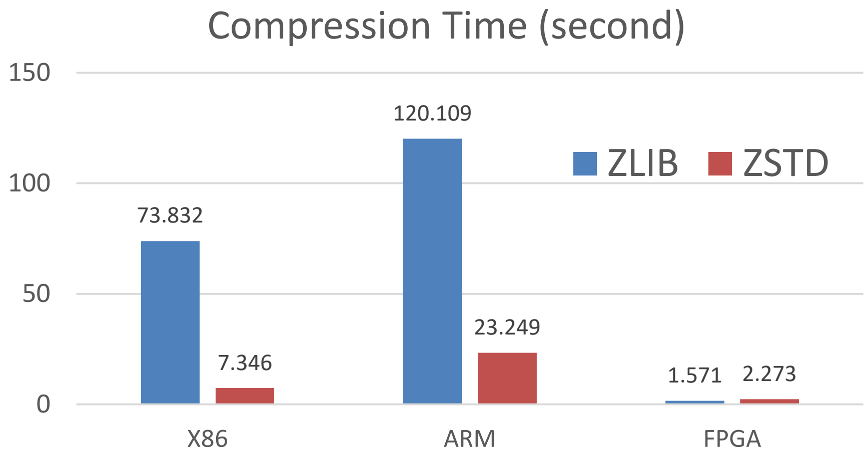
```
bash-4.2$ time cssclient -f /eos/user/chyd/km2a/20220701003242.670.dat -c km2a_decode
file '/eos/user/chyd/km2a/20220701003242.670.dat.root' created

real    0m26.347s
user    0m0.015s
sys     0m0.015s
bash-4.2$ eos ls -l /eos/user/chyd/km2a
-rw-r--r--   1 chyd     u07        1001554470 Nov 14 21:22 20220701003242.670.dat
-rw-r--r--   1 chyd     u07         446552932 Apr 20 05:26 20220701003242.670.dat.root
```

Computational storage mode launched from a login node

The same program processes one same file, but the CSSFST only took one half the time of traditional mode

More cases

- In addition to CPU power in EOS server, some heterogenous computing resources such as GPU, CPU/SoC, FPGA can also be used as computational storage accelerator
- Case 1: We implemented Intelligent compression for synchrotron radiation source image [chep’21] based on neural network algorithm, but it is very slow. So we use GPU and FPGA to accelerate the process, more than 340X faster than original method



	Original	GPU+FPGA	JPEG2000	PNG	ZSTD
Compression rate	2.08	1.78	1.26	1.43	1.13
Time(s)	1281.4	3.7	0.8	0.6	0.6

- Case 2: We have designed a low-power server that integrates an FPGA and an ARM chip on a single motherboard. First, we ported EOS to the AARCH64 architecture [chep’21] and then developed a compression algorithm based on FPGA, more than 100X faster than ARM CPU, 50X faster than X86 CPU with ZLIB.

Conclusion

- Computational storage is an approach to exploit the computing resources in EOS server
- The tool XkitS is scalability, configurability, ease of deployment and use
- The heterogenous computing power such as GPU, CPU/SoC, FPGA can be added in storage server to accelerate the data processing
- There are some known issues, such as the difficulty to reduce data movement in RAIN (erasure code) mode, task scheduling between storage servers, etc.
- Hopefully collaborate with the community to enhance computational storage functionality, making it one of the optional features of EOS

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Thank you for your attention

chyd@ihep.ac.cn