Holistic I/O Activity Characterization Through Log Data Analysis of Parallel File Systems and Interconnects

Reviews

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Abstract

The computing power of high-performance computing (HPC) systems is increasing with a rapid growth in the number of compute nodes and CPU cores. Meanwhile, I/O performance is one of the bottlenecks in improving HPC system performance. Current HPC systems are equipped with parallel file systems such as GPFS and Lustre to cope with the huge demand of data-intensive applications. Although most of the HPC systems provide performance tuning tools on compute nodes, there is not enough chance to tune I/O operations on parallel file systems, including high speed interconnects among compute nodes and file systems. We propose an I/O performance optimization framework that utilizes log data of parallel file systems and interconnects in a holistic way for improving the performance of HPC system, including effective use of I/O nodes and parallel file systems. We demonstrated our framework at the K computer with two I/O benchmarks for the original and the enhanced MPI-IO implementations. The analysis by using the framework revealed the effective utilization of parallel file systems and interconnects among I/O nodes in the enhanced MPI-IO implementation, thus paving the way towards holistic I/O performance tuning framework in the current HPC systems.

Keywords: Holistic log data analysis, K computer, FEFS, Lustre, Tofu, MPI-IO

1 Introduction

HPC systems have been facing the performance gap between computing power and I/O performance. Parallel file systems such as GPFS [SH02] and Lustre [Lus] provide vast amounts of storage capacity with high I/O bandwidth to bridge the gap. Most of the I/O optimization research efforts have addressed to improve I/O performance of their implementations in an empirical way using I/O benchmarks rather than analyses of I/O activities on target parallel file systems and interconnect data transfers [BLH+13, BBR+16, TMV+16, VdSB+18, OVW+19]. With an increase in the number of compute nodes and target I/O nodes, it is quite difficult to tune an implementation only through such benchmark runs. Holistic log analysis has been proposed for investigating I/O performance bottlenecks or I/O performance tuning of applications [LWS+18, WSL+18, YJM+19]. Such analysis collects log data about file system activities in addition to I/O performance results of applications. As Yang et al. remarked in their paper [YJM+19], a storage interconnect is another contention point on HPC systems. To this end, they have extended their framework named Beacon to monitor performance counters of InfiniBand network switches.

Within this context, an interconnect is one of the important points to tune not only inter-node communications in applications but also I/O accesses towards underlying storage systems. A profiling tool named Tofu PA [IOIkM12] was provided in the K computer, which acquired statistical information called Tofu PA information regarding communication in the Tofu interconnects [AIH+12] on compute nodes used, with the purpose to tune communications among compute nodes. However, there were no tools to get the Tofu PA information of Tofu interconnects among I/O nodes and I/O activities of its parallel file systems. Similar to other HPC platforms, we conducted I/O benchmark runs to evaluate and tune performance of I/O subsystems in an empirical way in the K computer. For investigating I/O performance bottlenecks and further I/O performance improvements, a well-balanced I/O workload among compute nodes, I/O nodes, and parallel file systems is required to optimize I/O operations. Without knowing the status of I/O nodes and parallel file systems, it is quite difficult to tune I/O operations in HPC applications.

It is expected that the utilization of statistics log data of I/O subsystems such as file system servers and interconnects provides quite useful metrics for I/O performance tuning by examining statistics of I/O request operations or data packet transfers through interconnects. In this context, we have proposed a framework that monitors data transfers on Tofu interconnects on I/O nodes and I/O activities of parallel file systems with the help of log data collected in the system administration in our workshop paper [TFH+20]. To our best knowledge, this is the first work to utilize data transfer information of Tofu interconnects on I/O nodes among the HPC systems using Tofu interconnects in tuning I/O operations. The framework consists of analysis functions for several components: log data collected by *fluentd* [flu], a PostgreSQL database that keeps a large amount of executed job information (JOB-DB), and information about compute and I/O nodes (node information table).

Given a unique ID for each job (JOB-ID), the analysis function of the framework provides us data such as averaged values of essential I/O activities on OSSes used, bandwidth utilization of Tofu interconnects on I/O nodes, and heat-maps about I/O throughput of OSTs used from the log data with the help of the JOB-DB and the node information table. In this paper, we demonstrated how such analyzed data could be used for further performance improvements by examining I/O bottlenecks and unbalanced situations in I/O workload among I/O nodes used in our enhancements in collective MPI-IO implementations named "EARTH on K" [THI14, THK+18]. We have already conducted empirical benchmark evaluations in performance improvements for our enhancement work in the K computer through studies in [THI14, THK+18]. Since only the result obtained from the benchmark evaluations is I/O performance, we had difficulties in tuning the implementation. Once we have introduced the framework for the evaluations, we have noticed which subsystem is bottleneck during the

optimizations.

Compared with our previous paper [TFH+20], we have made further analysis for additional optimizations in an enhanced MPI-IO with and without two-phase I/O in order to show their impact in each underlying I/O subsystems. We have found additional explicit differences in metrics that were given by the framework in not only write operations but also read operations. In addition, we propose scoring scheme in the framework so that we can easily find optimal optimization candidates.

Rest of this paper is organized as follows. In Sec. 2, we discuss related work. A system overview of the K computer including its file I/O subsystems, in which we conducted implementation and evaluation of the proposed framework, is explained in Sec. 3. In Sec. 4, we present the proposed analysis framework. We also explain the "EARTH on K" in Sec. 5, where we briefly present its advanced functions relative to the original MPI-IO. In Sec.6, we report experimental evaluations for the proposed framework at the K computer, and we discuss the usefulness of the proposed framework through examinations about performance improvements achieved by the "EARTH on K" at the K computer. Finally, we conclude the paper in Sec. 7.

2 Related Work

I/O bottlenecks in various applications were studied in [XCD+12, SRC+12]. These studies showed numerous characteristics in terms of I/O access patterns performed by applications on HPC systems using Lustre file systems. I/O monitoring at storage system level was studied in [KZH+14,UW13,MBC+17]. For example, Kunkel et al. proposed a monitoring and analysis framework to suggest and apply performance optimizations automatically [KZH+14]. It assisted locating and diagnosing performance problems. Separately, Uselton and Write [UW13] proposed extended monitoring about metrics available from Lustre using Lustre Monitoring Tool [LMT]. They characterized I/O patterns with their own metric named File System Utilization using obtained metrics. Madireddy et al. conducted I/O system analysis using operation log data, and they demonstrated I/O characterization of each job through correlation between I/O patterns of each job and I/O subsystem activities [MBC+17]. They also discussed the influence of monitoring intervals in system performance. Multi-platform study using system logs of file systems was reported in [LWG+15]. Their cross-platform analysis with I/O behavior collection by Darshan [DAR] showed wide varieties of insights about I/O subsystem operations through comparison among the several HPC systems. Our framework also supports similar functions compared with the above studies. Compared with the above researches, our case also focuses on behavior of interconnects among I/O nodes in the target file system.

Log data collection and analysis for performance tuning were conducted in server-side analysis [LGMV14, LGMV16, XBV+16, PBLT19]. For example, Liu et al. proposed a framework to identify I/O activities automatically using trace log data from file system servers [LGMV14, LGMV16]. Separately, Xu et al. proposed their I/O profiling framework named LIOProf to track I/O activities of on Lustre file system servers including client-side statistics recorded on servers [XBV+16]. Using those metrics, they demonstrated optimization effect in collective MPI-IO implementation. A detailed study in production runs was conducted in [PBLT19] by analyzing server-side log data of parallel file systems to draw new insights about I/O characteristics. However, abovementioned studies did not focus on behavior of interconnects. Our proposed framework supports interconnect monitoring in performance bottleneck investigation to tune I/O optimization with server-side log data of a local file system although the framework has not been used in production runs at the K computer.

Interconnects are also one of the key components in HPC systems. Monitoring data transfers of interconnects tells us a hot-spot of traffic congestion for instance, and such ap-

proaches succeeded in analysis of application activities and performance impact associated with the traffic condition [ZGL16, KGP+18, CJH+19, YJM+19]. Zimmer et al. demonstrated their monitoring framework to collect detailed stats information using their daemon program named I/O Router Congestion Daemon with monitoring performance counter of Gemini interconnects in the Titan at the Oak Ridge Leadership Computing Facility [ZGL16]. Kumar et al. utilized performance counter of Gemini interconnect in the Titan too [KGP+18]. They analyzed and characterized errors and traffic congestion on Gemini interconnects. Chunduri et al. succeeded in execution time predictions of applications by analyzing traffic congestion information obtained from performance counters of Aries interconnects in the Theta at the Argonne Leadership Computing Facility [CJH+19]. They introduced a machine learning approach in their prediction. However, the above studies were not sufficient to characterize I/O activities on parallel file systems in HPC systems. Within this context, Yang el al. pointed out that storage interconnect is another contention point on HPC systems [YJM+19]. They have extended their I/O monitoring framework to monitor performance counters of InfiniBand network switches.

Recently, holistic I/O monitoring has been proposed in many research works [LWS+18, WSL+18, YJM+19]. For example, Lockwood et al. proposed a holistic I/O monitoring framework named TOKIO [LWS+18]. It consisted of several components for monitoring, analysis, and visualization for administrators and users. Separately, Wang et al. proposed a monitoring and analysis framework named IOMiner [WSL+18], in which Darshan [DAR] was introduced to collect I/O performance metrics. Application users can easily identify root cause of poor I/O performance with the framework from vast amounts of log data associated with I/O subsystems. Yang et al. proposed a monitoring framework named Beacon [YJM+19]. This framework provided a collection of monitoring tools for Metadata Servers (MDSes) and Object Storage Servers (OSSes) and analysis functions, including some visualization interface. Their extended monitoring for InfiniBand networks covered to find network contention in I/O operations. The above studies are similar to our study regarding holistic approach to characterize I/O activities.

On the other hand, our study addresses holistic I/O activity analysis through log data analysis of Tofu interconnects and parallel file systems including associated I/O nodes. The uniqueness of this framework is a holistic analysis approach using data transfer status on the Tofu interconnects among I/O nodes and associated I/O activity traces at parallel file systems.

3 K computer and Its File System Monitoring

3.1 Overview of the K computer

The K computer finished its operation for about seven years in August 2019. The system had two-layered file systems, a local file system (LFS) and eight volumes of a global file system (GFS), as shown in Figure 3.1. The LFS was a scratch high-performance storage space which was used during computations, while the GFS was used to store programs and data with high redundancy. An enhanced Lustre named Fujitsu Exabyte File System (FEFS) [SSK12] that was based on Lustre version 1.8 was equipped to build both file systems. The K computer consisted of 82,944 compute nodes and 5,184 I/O nodes, where every system rack consisted of 96 compute nodes and six I/O nodes. Every compute node and I/O node were connected through the Tofu interconnect in a six-dimensional (6D) mesh/torus network represented by X, Y, Z, A, B, and C. Tofu links of X, Z, and B were connected in a torus configuration, while those of Y, A, and C were connected in a mesh configuration. However, torus configuration of the Z-link was only available in I/O accesses through I/O nodes because I/O nodes were included only in I/O accesses. In other cases, the Z-link was used in a mesh configuration for inter-node communications by application jobs.

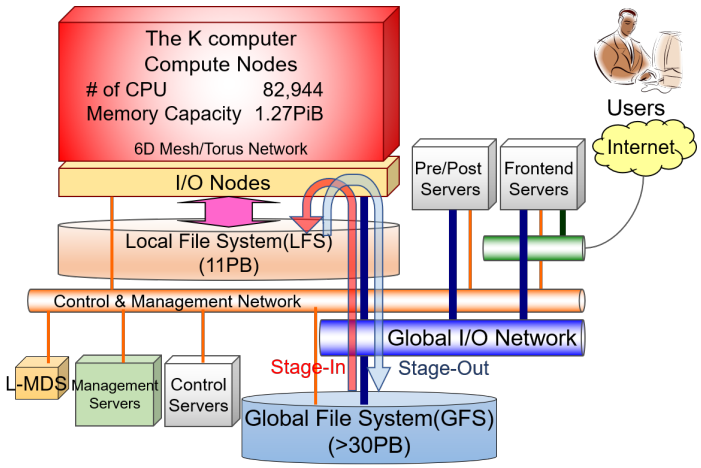


Figure 3.1: System configuration of the K computer.

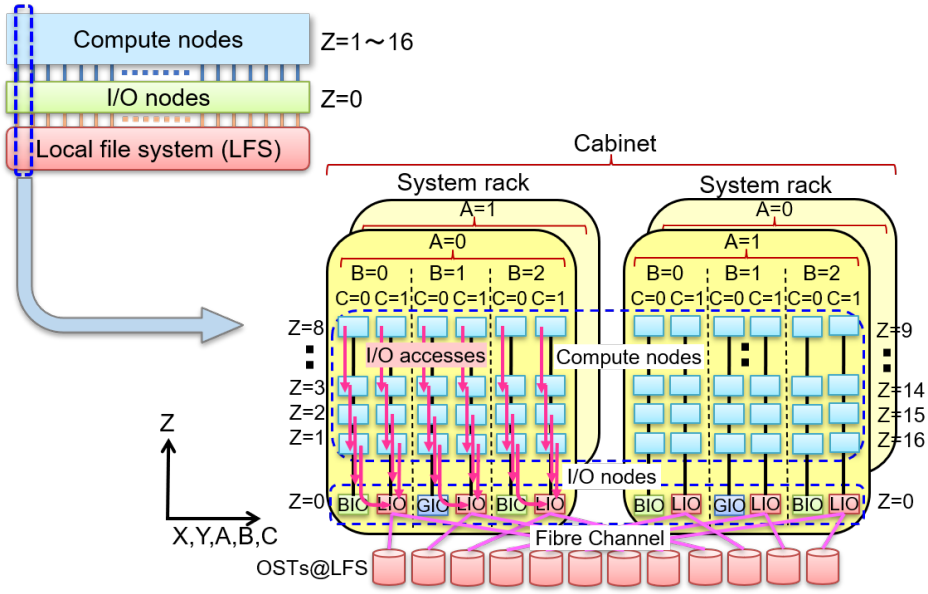


Figure 3.2: Subset of system racks of the K computer and I/O accesses from compute nodes towards the LFS.

Figure 3.2 depicts the configuration of a subset of system racks and I/O accesses from compute nodes towards the LFS. Each cabinet consists of two system racks, which have two groups separated by the A-link position (A=0 and 1) consisting of 48 compute nodes each. Every compute node was located on Z-link positions ranging from Z=1 to 8 and from Z=9 to 16 in the groups of A=0 and 1, respectively, while I/O nodes were on Z=0 in both groups. Boot-I/O nodes (BIOs) were responsible for system software start-up and Global I/O nodes (GIOs) were the gateways in accessing the GFS. The LFS was accessible from compute nodes through OSSes running on the local-I/O nodes (LIOs). Every node including I/O nodes consisted of Tofu network router (TNR) [AIH+12] where each TNR had 10 communication links ($X+$, $X-$, $Y+$, $Y-$, $Z+$, $Z-$, A, $B+$, $B-$, and C) to construct a 6D mesh/torus network.

The number of available OSTs at the LFS was uniquely configured based on the assigned compute node layout according to the I/O zoning scheme [Sum11]. I/O zoning scheme was introduced in order to mitigate I/O interference on OSTs and I/O nodes among jobs by assigning I/O nodes and OSTs on the same Z-link with compute nodes used. In Fig. 3.2, I/O

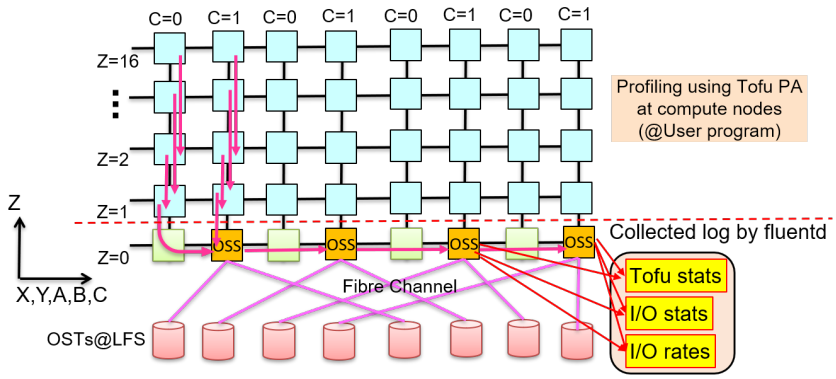


Figure 3.3: Log collection from I/O nodes.

accesses from compute nodes at the system rack are illustrated on the left side. I/O nodes on the same *Z*-links were configured to work with compute nodes that issued I/O requests, and those I/O nodes take part in data transfers during I/O accesses on the LFS. It is noted that I/O paths from compute nodes were automatically routed to the corresponding I/O nodes (either of BIO, GIO, and LIO) on the same *Z*-link, then routed to a target OSS running on an LIO.

Performance profiling tools including Tofu PA addressed to tune performance of compute nodes and communications among compute nodes. It is noted that similar profiling tools are available at our current HPC system, the supercomputer Fugaku [The] (hereinafter, Fugaku). The tools succeeded to leverage high levels of computing potential of the K computer, especially in tuning applications utilizing the large number of compute nodes in terms of data transfer status of each node in addition to CPU and memory utilization. The only way to tune I/O operations had been benchmark evaluations because there was not any I/O profiling tool for users to profile activities of I/O nodes and parallel file systems. Therefore, it was quite difficult in I/O operation tuning using only the existing profiling tools.

3.2 Log collection for monitoring the LFS

We have addressed to extract I/O activity information of the LFS in order to investigate operation status of the LFS for not only finding malfunctions but also performance tuning. In this context, we conducted to collect log data from servers associated with the LFS during the K computer operation, as shown in Figure 3.3. We have deployed *fluentd* to collect performance metrics associated with I/O operations from 5,184 I/O nodes including 2,592 LIOs which also acted as OSSes for the LFS.

The proposed analysis framework utilized the following three log data collection groups from large amounts of collected information by *fluentd*.

- `Tofu stats`: Data transfer status metrics of I/O nodes on each Tofu interconnect link (the number of transferred packets, amount of transferred data size, and others)
- `I/O stats`: Statistics of I/O requests obtained from `/proc/fs/lustre/ost/OSS/ost_io/stats` on every OSS
- `I/O rates`: Amount of size in read and write operations on every OST

Only the `I/O stats` was collected at one minute intervals, while the rest were collected at ten minute intervals. We have selected the ten minute intervals for the I/O-related monitoring as trial in a conservative manner not to affect I/O node activities for stable production runs from our empirical study. We conducted the trial monitoring in the last few months of the K computer operation. Limited storage space for the I/O related log-collection was another

reason for the ten-minutes intervals. In the last few months of the K computer operation, we already collected huge amounts of recorded information on the log-collection server from other high-priority components of the K computer for a long time.

The `Tofu stats` consisted of the following packet processing metrics of the ten Tofu links, which were obtained from the TNR of each I/O node through the Tofu PA information in each ten minute interval:

- Cycle counts until target transfer buffer was available in packet transfers
- Amount of transferred data size

It is noted that the cycle counts in the `Tofu stats` corresponded to congestion status since unavailability of transfer buffers in packet processing closely corresponds to packet transfer congestion. We conducted to retrieve those metrics from the TNR at every I/O node during the K computer operation for about a few months until the end of the K computer operation.

The `I/O stats` consisted of the same statistics with an original Lustre, where we especially focused on the three statistics, `req_qdepth`, `req_active`, and `req_waittime`. These statistics provided the status of I/O requests coming from compute nodes through I/O nodes. For instance, a large value in both `req_qdepth` and `req_waittime` indicated very busy status of OSSes or idle status of OSSes waiting for the next operation due to heavy load of an MDS before I/O accesses. Such situation was not suitable for effective I/O operations. Since `req_active` indicated the number of active threads for I/O operations, high numbers in `req_active` indicated a very good condition in terms of I/O accesses.

The `I/O rates` provided I/O throughput status at each OST over time. Collected I/O throughput information showed I/O behavior on each OST such as how much I/O bandwidth was achieved in each OST or how about I/O load balancing was for instance. Due to the reasons described above, we examined I/O activities in the two I/O benchmark runs at ten minute intervals as trial, where each I/O benchmark run took around ten minutes so that we could observe I/O activities of each I/O benchmark run. Minimization of monitoring interval time is our future work in Fugaku.

3.3 Database for executed jobs

A database to store job information named JOB-DB was built on a PostgreSQL database server to collect and refer to job information executed in the K computer. The JOB-DB kept compute nodes used, compute node layout, elapsed time, and start and finish times of job execution, which were associated with a JOB-ID, for instance. Therefore, we could refer to information about a target job from the JOB-DB by specifying a JOB-ID.

4 Analysis Framework for I/O Activities

As described in Sec. 3.2 and Sec. 3.3, we had monitoring and log collection environment for each component in the K computer operation. However, there was not any environment to have holistic I/O activity analysis for the purpose of investigation and performance tuning. Considering the complexity in I/O subsystems and I/O software stacks in a large scale of HPC systems such as the K computer, we have built an analysis framework in cooperation with the existing monitoring components described in Sec. 3.2 and Sec. 3.3. Since the framework needs to work together with several components such as the JOB-DB built on a PostgreSQL database and log data collected by *fluentd*, we have conducted to build the framework using *Python*. Figure 4.1 depicts an overview of the implemented analysis framework, which is connected with associated log data collected by *fluentd* and the JOB-DB to analyze I/O activities on I/O nodes and the LFS. Given a target JOB-ID, the framework retrieves information of the JOB-ID such as 6D mesh/torus network positions of compute nodes used and

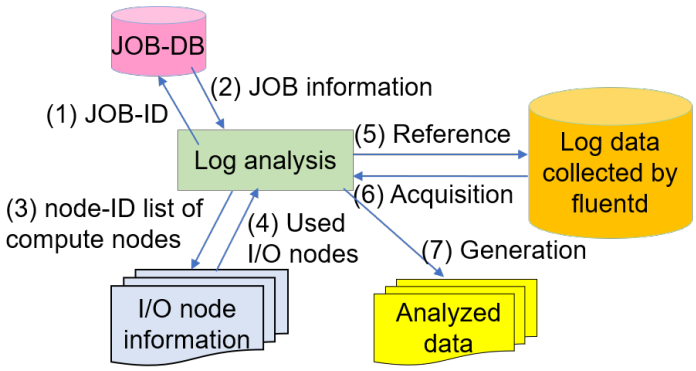


Figure 4.1: Functional overview of implemented analysis framework.

system racks used from the JOB-DB. Such information about compute nodes used and system racks is utilized to find I/O nodes used including LIOs from the I/O node table because the assigned I/O node layout is automatically configured by the shape of assigned compute nodes. Besides, start and finish times of the target job obtained from the JOB-DB are used to pick up essential information associated with the JOB-ID from a large amount of log data collected by *fluentd*.

Once the framework collects all essential information, its log analysis function figures out and gives the following information for the given JOB-ID:

- Maximum waiting time of each interconnect at each I/O node used (T_{wait}^{max}) from `Tofu stats` log collection
- Peak bandwidth utilization ratio of the interconnects relative to the theoretical bandwidth during job execution (R_{BW}) from `Tofu stats` log collection
- I/O throughput in both write and read operations on each OST used from `IO rates` log collection

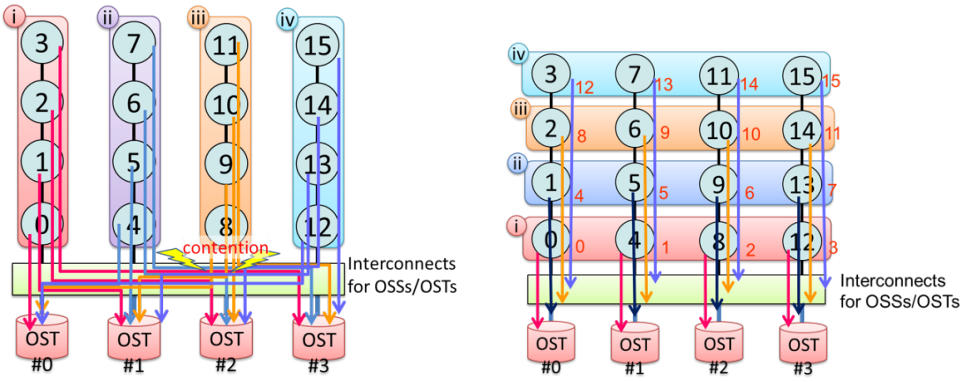
The former two performance values were calculated by using the packet transfer metrics obtained from the TNR of Tofu links used, which were obtained from `Tofu stats` log collection. The function converts the cycle counts obtained from the TNR into time values in the unit of a second for the T_{wait}^{max}. While the R_{BW} was obtained by dividing the peak bandwidth in Tofu links of the job with the theoretical bandwidth. Note that the peak bandwidth was obtained by dividing transferred packet size with elapsed time of the specified job. In the proposed framework, we used the R_{BW} to examine the effectiveness in packet transfers associated with I/O operations.

While the I/O performance values were obtained by dividing an amount of data size in read and write operations with a monitoring interval time (600 seconds in the current configuration) in each snapshot in order to know I/O throughput at each OST used. Once the analysis function is executed, data are stored in the CSV format and associated heat-map image data are stored in the PNG format.

5 Enhanced MPI-IO Implementation: EARTH on K

In order to examine effectiveness of the proposed framework, we have conducted to evaluate MPI-IO benchmark runs. In this context, we have picked up our enhanced MPI-IO implementations in addition to the original MPI-IO implementation at the K computer.

MPI-IO is an I/O interface including parallel I/O in the MPI standard [MPI]. An MPI library for the K computer supports MPI-IO functions for the FEFS using MPI-IO implementation named ROMIO [TGL99]. Two-phase I/O optimization in ROMIO improves collective



(a) Without striping-awareness (b) With striping-awareness

Figure 5.1: Aggregator layouts with and without striping awareness.

MPI-IO performance in accessing non-contiguous data layouts in each process by rearrangement to form large data access space as much as possible in each process performing I/O (aggregator). Although two-phase I/O optimization of ROMIO improves collective MPI-IO performance, the implementation on the K computer uses an old implementation of ROMIO which is not optimized for Lustre. Therefore, the original MPI-IO implementation is not suitable for the FEFS to achieve high I/O performance.

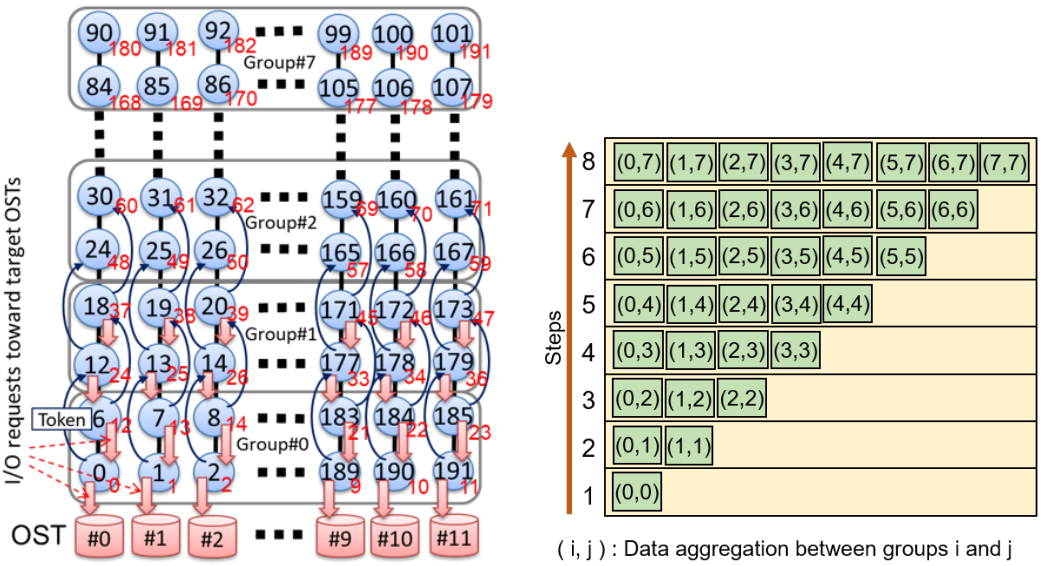
The current ROMIO with the improved two-phase I/O for Lustre [Lus08] has the potential to improve performance on the FEFS. Our enhanced MPI-IO implementation named "EARTH on K" (hereinafter, EARTH) has been developed for the K computer based on the improved two-phase I/O with topology-aware performance optimizations for collective MPI-IO at the FEFS. We have already reported performance improvements by using the EARTH in some conference papers [THI14, THK+18], there is not any evidences what kind of improvements has been achieved in underlying interconnects among I/O nodes or OST activities. In this context, we have investigated some advanced functions of this implementation with the proposed framework.

Compared with the original MPI-IO, EARTH has advanced optimizations controlled by the following three parameters represented by `agg`, `req`, and `rr`, respectively:

- `agg`: Striping-aware aggregator layout
- `req`: I/O throttling and associated stepwise data aggregation with a given number of I/O requests per step
- `rr`: Round-robin aggregator layout among compute nodes

ROMIO deploys one aggregator in each compute node, and its layout is dependent on MPI rank layout among compute nodes. In HPC systems, users have been focusing on MPI rank layout for communication performance among compute nodes. However, such optimizations are not always suited for aggregator layout with respect to interconnects among compute nodes and I/O nodes or layout of OSSes/OSTs of a Lustre file system. In such layout, contention in data transfer happens on network paths among compute nodes and a Lustre file system.

The striping-aware aggregator layout mitigates data transfer congestion by suitable aggregator layout. Figure 5.1 shows aggregator layouts with and without striping awareness in accessing four OSTs by 16 aggregators, where numbers in circles represent MPI ranks and the numbers ranging from *i* to *iv* represent the order of striping accesses. By placing aggregators in an MPI rank order as shown in Figure 5.1a, we may face contention in a path towards target OSTs. On the other hand, a striping-aware layout shown in Figure 5.1b, renumbering the



(a) I/O throttling with token relay (b) Stepwise data aggregation

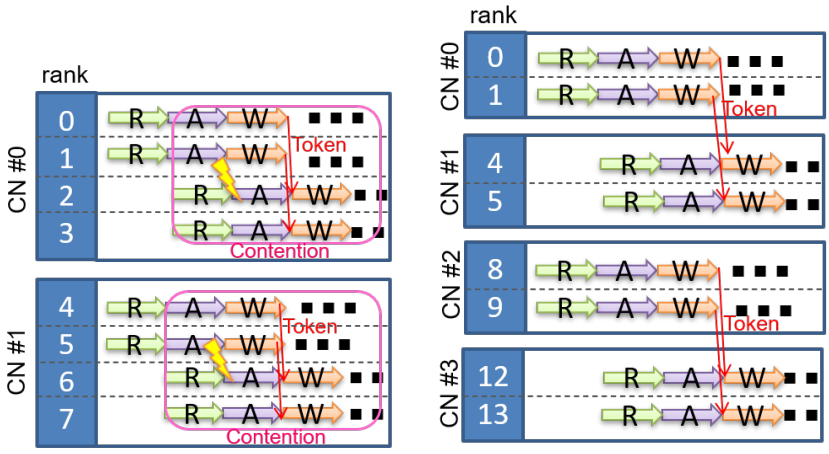
Figure 5.2: I/O request throttling with stepwise data aggregation.

order of aggregators in the red-colored numbers, eliminates data transfer congestion on every I/O path because I/O flows of every I/O path towards a target OST are evenly distributed for a striping access pattern against OSTs.

Figure 5.2a illustrates I/O throttling scheme operated by 192 aggregators accessing 12 OSTs, where we assume every process acts as an aggregator. Numbers in circles represent MPI ranks, and red-colored numbers neighboring to the circles are the aggregator layout orders configured by the striping-aware aggregator layout. Two-phase I/O consists of repetitive operations of data aggregation on every aggregator and I/O accesses by aggregators. We may have I/O request contention on OSTs if we have I/O accesses simultaneously from all aggregators. The I/O throttling scheme shown in this figure alleviates I/O request contention on OSTs by issuing I/O requests from aggregators in each group in a stepwise manner from the younger number group by relaying tokens from an aggregator that finishes I/O accesses to a corresponding aggregator in the next group. The number of groups can be tuned at runtime through `MPI_Info_set()` or an environment variable. It is also noted that EARTH also supports I/O request throttling even if we disable two-phase I/O in collective MPI-IO.

Stepwise data aggregation shown in Figure 5.2b is another optimization associated with the I/O throttling. Compared with simultaneous data aggregation by all the processes, we can eliminate congestion in data transfers among compute nodes by stepwise data aggregations issued from younger number group. In this figure, we represent data aggregation between the groups numbered by i and j as (i, j), which is equivalent to (j, i). In the first step (step=1), processes in the first group numbered as 0 initiates data transfers to aggregators on every group numbered from 0 to 7, described by $(0, k)$, where k = 0-7. However, in the first step, only the $(0, 0)$ is carried out because other groups are not ready in data aggregation. In the next step (step=2), the second group numbered as 1 initiates data aggregation of $(1, k)$, where k = 0-7, and only data aggregations of $(0, 1)$, which is equivalent to $(1, 0)$, and $(1, 1)$ complete in this step. Finally in the last step (step=8), the last group numbered as 7 initiates data aggregations of $(7, k)$, where k = 0-7. Then the remaining aggregations denoted by $(k, 7)$, where k = 0-7, complete in this step.

Figure 5.3 shows examples of blocked and round-robin aggregator layouts, where we have eight aggregators from 16 processes deployed among four compute nodes in a blocked layout. Horizontal colored arrows represented by R, A, and W stand for read, data aggregation, and



(a) Blocked layout (b) Round-robin layout

Figure 5.3: Aggregator layouts with blocked and round-robin manners, utilizing I/O throttling and stepwise data aggregation in write operations.

write phases in two-phase I/O during collective write operations, respectively. As shown in this figure, I/O throttling scheme relays tokens among aggregators. When we have a blocked aggregator layout as shown in Figure 5.3a, four processes in the two compute nodes (*CN#0* and *CN#1*) work as aggregators, which are from 0 to 7 in MPI ranks. As a result, we may have contention within the same compute node in performing each phase of two-phase I/O. It is also noted that such layout leads to high I/O workload in each node compared with other compute nodes without aggregators. Meanwhile, the round-robin aggregator layout in Figure 5.3b can distribute I/O workload evenly among compute nodes, and this layout also prevents aggregators from I/O access contention within the same compute node by reducing the number of aggregators in the same compute node.

Although the above enhancements outperformed the original version in an empirical study using I/O benchmark runs [THI14, THK+18], there was not any investigations about the performance impact of those optimizations in I/O nodes or underlying file systems. One of the main reasons is the lack of tools to characterize optimization effects in data transfers among I/O nodes and I/O accesses against the LFS at the K computer. By using the proposed framework, we examined their advanced features at the K computer in the following section.

6 Experimental Evaluation

We conducted to examine functionalities of the proposed framework at the K computer through two I/O benchmark runs, IOR [IOR] and HPIO [CCkL+06], about the original MPI-IO implementation and EARTH. Although the K computer was already dismantled, we believe that results and experiences obtained from the evaluations provide useful hints for current HPC systems including Fugaku. Although IOR supports two file creation modes, accessing file per rank and shared access to a single file, we utilized the shared access mode with collective MPI-IO. Meanwhile, HPIO supports I/O accesses for non-contiguous data layout, and we performed collective MPI-IO for the data layout. For both benchmark runs, we initiated 12,288 processes on 3,072 compute nodes forming a logical 3D layout of $8 \times 12 \times 32$ in order to eliminate I/O interference from other jobs. According to the 3D layout of assigned compute nodes, 192 OSTs were assigned for parallel I/O, and we set 192 as a stripe count to use all available OSTs. We set 256 MiB and 64 MiB in stripe size in the IOR run and the HPIO run, respectively.

In both benchmark runs, every processes worked as aggregators with ascending order

layout in MPI ranks from zero in the original MPI-IO under default configuration. On the one hand, 6,144 processes were chosen to be aggregators in the EARTH case in order to examine performance impact of aggregator layout among compute nodes according to optimization configuration of the EARTH. In this paper, `original` stands for the original MPI-IO, while a combination of the three optimization parameters, `agg`, `rr`, and `req`, indicates MPI-IO of the EARTH. Concerning the EARTH use case, `agg=1` stands for striping-aware aggregator layout and `rr=1` denotes round-robin aggregator layout among compute nodes. A zero value in each case stands for deactivation in the corresponding layout optimization. The last parameter `req` with a number describes the number of I/O requests going to each OST per step in I/O throttling and stepwise data aggregation except that `req=0` denotes deactivation of I/O throttling and stepwise aggregation.

In the IOR benchmark run, we conducted collective MPI-IO without two-phase I/O. In this paper, we describe collective MPI-IO with and without two-phase I/O by giving "T:" and "N:" at the beginning of the parameter configuration notation such as `T:original` and `N:original`, respectively.

6.1 Benchmark configuration

We conducted to evaluate collective MPI-IO in the two benchmark runs, IOR and HPIO with the proposed framework. In both cases, we enabled two-phase I/O implemented in ROMIO.

6.1.1 IOR

The following command was executed in write operations to generate a shared file of 3 TiB (= 256 MiB × 12,288) per iteration:

```
$ ior -i 5 -a MPIIO -c -U hints_info -k -m -vvv -w -t 256m -b 256m \
-o ${TARGET_DIR}/test-IOR.dat -d 0.1
```

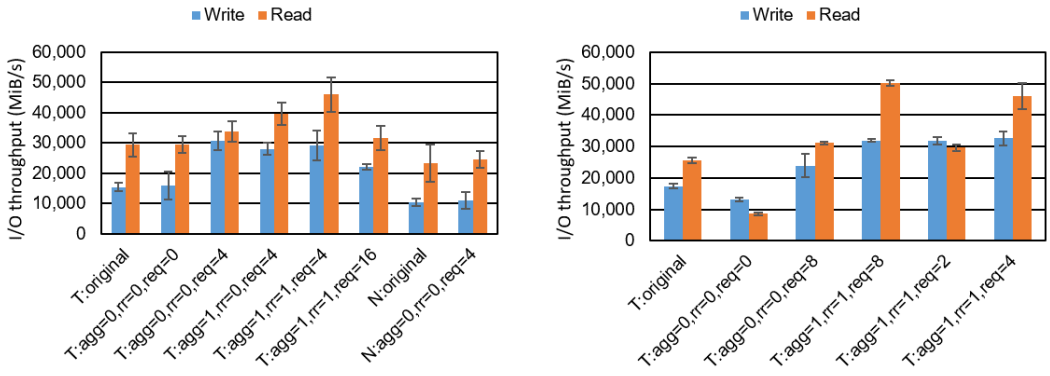
We performed read operations with the same command changing "-w" by "-r", followed by write operations with the above command in every optimization parameter configuration. "`hints_info`", is a file describing some hints associated with I/O operations such as the number of processes per node and so forth. A target file (`test-IOR.dat`) was generated in the directory (`${TARGET_DIR}`) with 192 stripe count. We carried out collective MPI-IO with and without two-phase I/O by enabling or disabling "`romio_cb_write`" and "`romio_cb_read`" through the "`hints_info`."

6.1.2 HPIO

We executed the following command for write operations to generate a shared file of about 2.1 TiB (≈ (5,992 B + 256 B) × 12,288 × 30,729 - 256 B) per iteration, followed by read operations in non-contiguous access pattern on a target file with specifying the number of processes per node (`-H cb_config_list=*:4`) and parameter to tune the number of aggregators to be 6,144 (=192 × 32):

```
$ hpio -n 12288 -n 0010 -r 6 -B -s 5992 -c 30729 -p 256 -m 01 -O 11 -f 0 \
  -S 0 -a 0 -g 2 -H cb_config_list=*:4 -H romio_lustre_co_ratio=32 \
  -d ${TARGET_DIR} -w 1
```

Note that the option, "`cb_config_list`" was available only for the EARTH case, and thus all processes worked as aggregators in the original case as we explained. The target file was generated in the directory `${TARGET_DIR}` with 192 stripe count. We conducted the collective MPI-IO only with two-phase I/O because collective MPI-IO without two-phase I/O was time-consuming under the non-contiguous access pattern and it was difficult to perform in a limited machine time.



(a) IOR benchmark (b) HPIO benchmark

Figure 6.1: Benchmark results of the original MPI-IO and EARTH with several optimization configurations by using (a) IOR and (b) HPIO.

6.2 Benchmark results

Figure 6.1 shows averaged I/O throughput values with standard deviations for the IOR and HPIO benchmarks.

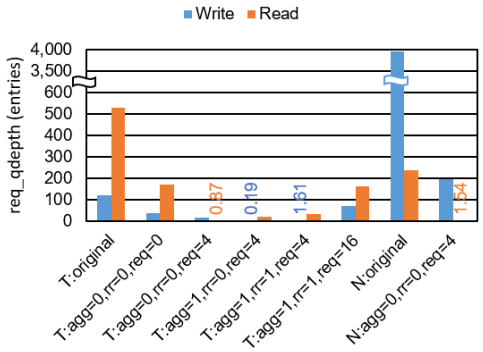
The original MPI-IO operations with and without two-phase I/O represented by `T:original` and `N:original` showed poor performance in both read and write operations in the IOR runs. The same situation was observed for the `T:original` case in the HPIO runs. EARTH with full optimization in aggregator layout, I/O request throttling, and stepwise data aggregation outperformed other cases by setting four requests per step (`T:agg=1,rr=1,req=4`) in the IOR runs and eight requests per step (`T:agg=1,rr=1,req=8`) in the HPIO runs. However, performance was degraded by changing the number of requests per step or deactivating aggregator layout optimization. In addition, the EARTH case using only I/O throttling without two-phase I/O (`N:agg=0,rr=0,req=4`) could not improve I/O performance compared to the original case (`N:original`) in the IOR runs.

Although we learned optimization effects through such empirical benchmark runs in our previous research papers [THI14, THK+18], it was not clear about the performance impact of the optimization configuration on I/O nodes, Tofu links among I/O nodes, and the LFS. We report investigations of each component using the proposed framework in the following subsections.

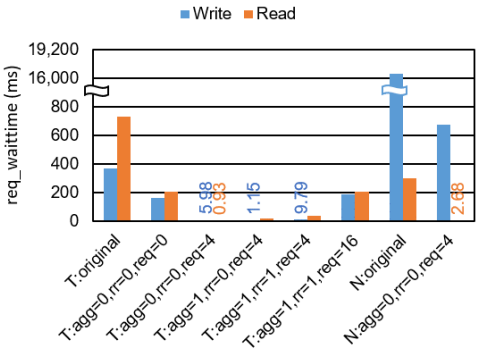
6.3 I/O request status at file system servers

Figure 6.2 shows the mean values of `req_qdepth`, `req_waittime`, and `req_active` from `I/O stats` log collection during I/O operations at the IOR benchmark run. As shown in Figure 6.2a, the two original cases with or without two-phase I/O, `T:original` and `N:original`, had the largest number of requests in a request queue in each I/O operations with or without two-phase I/O. Figure 6.2b shows that those cases also took the longest time to proceed requests in each I/O operations with or without two-phase I/O. Additionally, Figure 6.2c shows the highest number of I/O threads in the original case with two-phase I/O. Note that the maximum number of threads at each OSS of the LFS was 32 at the K computer. Through these results, we determined that the two original cases, `T:original` and `N:original`, were not suited for I/O request processing at OSSes.

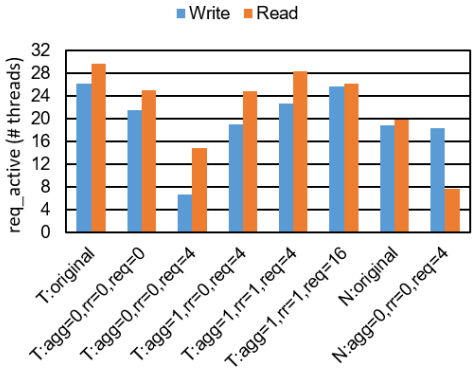
While the EARTH use case with good I/O performance (`T:agg=1,rr=1,req=4`) showed small number of requests in the queue, as shown in Figure 6.2a. Figure 6.2b also shows the fact that this case took quite short times to process I/O requests. Additionally, Figure 6.2c shows many I/O threads were active in this case.



(a) `req_qdepth`: The vertical axis is expanded from 600 to 3,500



(b) `req_waittime`: The vertical axis is expanded from 800 ms to 16 s



(c) `req_active`

Figure 6.2: Mean stats values obtained from OSSes using our analysis framework during the IOR benchmark run, where numbers represent very small values.

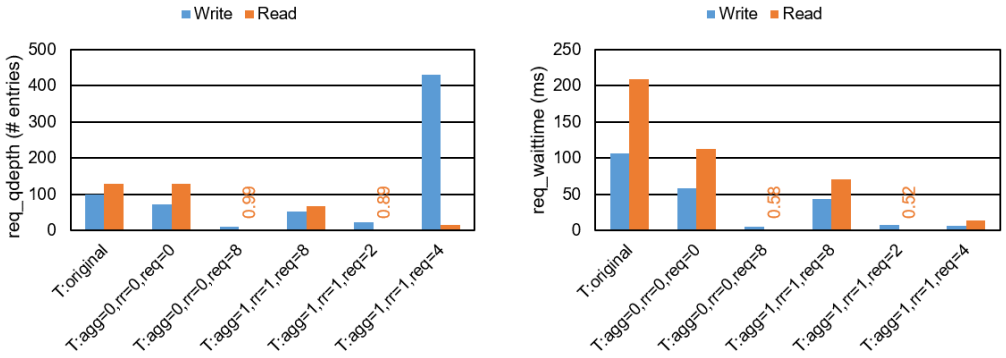
Figure 6.3 shows the same statistics obtained in the HPIO benchmark run. Similar to the IOR run, the original use case was not good compared with the EARTH use case with good optimization configuration indicated by `T:agg=1,rr=1,req=8`.

6.4 Bandwidth utilization and waiting times in data transfers on Tofu interconnects of I/O nodes

Figure 6.4 shows mean values of (a) R_{BW} and (b) T_{wait}^{max} on Tofu links of I/O nodes used. Concerning bandwidth utilization shown in Figure 6.4a, the original MPI-IO use case showed the lowest utilization, while the full set of EARTH optimizations such as `T:agg=1,rr=1,req=4` led to higher levels of bandwidth utilization relative to other cases. While the use cases without two-phase I/O, `N:original` and `N:agg=0,rr=0,req=4`, showed larger number of requests in queue, especially in write operations. By considering effectiveness in data transfers among I/O nodes via Tofu interconnects, a higher utilization was preferable. Within this context, the above optimized case was suitable for I/O optimization.

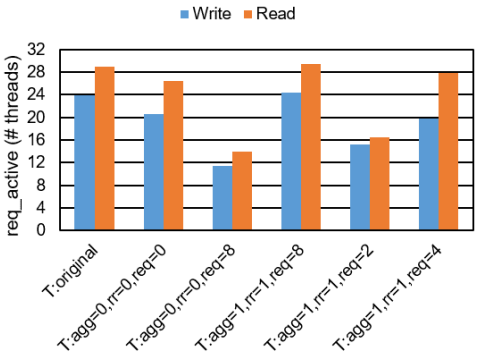
Figure 6.4b shows that the enhanced implementation without aggregator layout optimization indicated by `T:agg=0,rr=0,req=4` took the longest times. It is also noted that this case also performed the lowest bandwidth utilization in write operations, as shown in Figure 6.4a. It is notable that the lack of aggregator layout optimization in the EARTH case led to a negative impact in data transfers on Tofu interconnects among I/O nodes.

In a similar way, Figure 6.5 shows bandwidth utilization ratios and waiting times in data transfers on Tofu links of I/O nodes used at the HPIO benchmark run. The EARTH



(a) `req_qdepth`

(b) `req_waittime`



(c) `req_active`

Figure 6.3: Mean stats values obtained from OSSes using our analysis framework during the HPIO benchmark run, where numbers represent very small values.

use case with the best configuration (`T:agg=1,rr=1,req=8`) also outperformed other cases in Figure 6.5a. This case also minimized waiting times in both read and write operations among the EARTH use cases in Figure 6.5b.

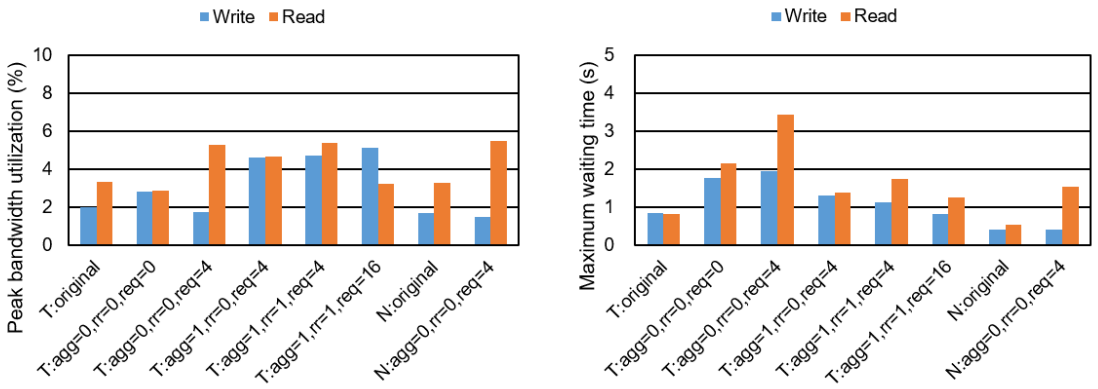
6.5 Load balancing in I/O throughput at OSTs

Figure 6.6 shows write throughput heat-maps ranging from 0 to 160 MiB/s among the 192 OSTs used during the IOR benchmark runs. Horizontal and vertical axes ranging from 0 to 15 and from 0 to 11, indicate subjected relative 2D positions of OSTs used from the logical 3D layout of the K computer.

In the original MPI-IO use case in Figure 6.6a, we can see performance gaps among the left and right sides separated by the dotted line. Figure 6.6b also shows performance gaps among OSTs used because of imbalanced aggregator layout although the EARTH was used. Both cases were not suitable configurations because total I/O performance was limited by the slowest OSTs in parallel I/O. Meanwhile, the most optimized case in Figure 6.6c shows a well-balanced situation in write throughput among OSTs used. Within the context of parallel I/O characteristics, this case was suitable to achieve I/O performance for the benchmark run.

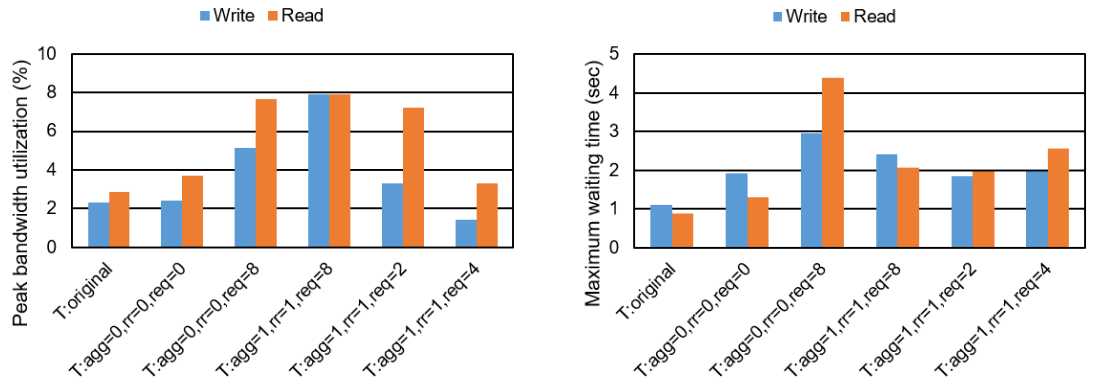
On the other hand, Figure 6.6d and Figure 6.6e show poor I/O throughput in collective write operations in the original and the EARTH use cases without two-phase I/O, respectively. These poor performance situations were due to contention in I/O task assignment to I/O threads by huge number of concurrent I/O accesses from all 12,288 processes as we observed in Figure 6.2a and Figure 6.2b.

Figure 6.7 shows read throughput heat-maps ranging from 0 to 160 MiB/s among the 192 OSTs used at the IOR benchmark runs. Imbalanced bandwidth situations in the original



(a) R_{BW} (b) T_{wait}^{max}

Figure 6.4: Mean values for (a) R_{BW} and (b) T_{wait}^{max} on the Tofu interconnects among I/O nodes used during the IOR benchmark run.

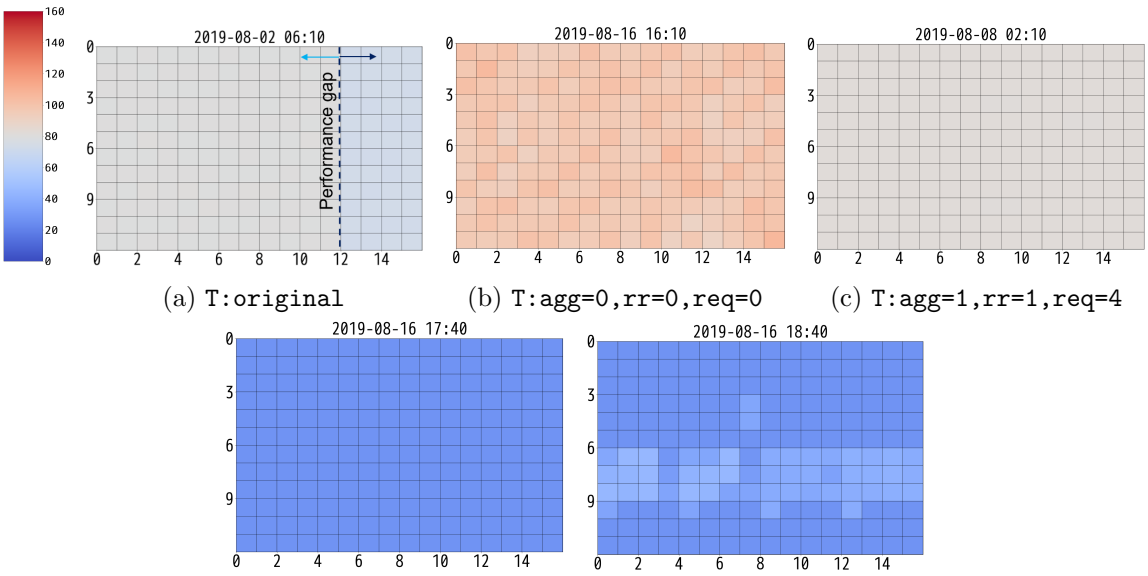


(a) R_{BW} (b) T_{wait}^{max}

Figure 6.5: Mean values for (a) R_{BW} and (b) T_{wait}^{max} on the Tofu interconnects among I/O nodes used during the HPIO benchmark run.

MPI-IO use case and the EARTH use case without any optimizations were observed in Figure 6.7a and Figure 6.7b, respectively. Meanwhile, well-balanced situations were achieved in the EARTH use case with an optimal optimization configuration, which led to high performance collective I/O, as shown in Figure 6.7c.

Write and read throughput heat-maps ranging from 0 to 160 MiB/s at the HPIO run are also shown in Figure 6.8 and Figure 6.9, respectively. In Figure 6.9, the EARTH use case with insufficient configuration (`T:agg=0,rr=0,req=8`) showed lower performance compared with the original MPI-IO use case. Meanwhile, a full set of the three optimizations in the EARTH use case (`T:agg=1,rr=1,req=8`) achieved the highest I/O throughput at every OST used. Read throughput heat-maps in Figure 6.9 show the highest I/O throughput in the insufficient optimization configuration (`T:agg=0,rr=0,req=8`), followed by the original MPI-IO use case and the full optimization configuration case. However, the insufficient configuration case performed the longest waiting time in the Tofu interconnects among the I/O nodes used, as shown in Figure 6.5b, and thus high I/O bandwidth could not be achieved in this configuration.



(a) `T:original` (b) `T:agg=0,rr=0,req=0` (c) `T:agg=1,rr=1,req=4`

(d) `N:original` (e) `N:agg=0,rr=0,req=4`

Figure 6.6: Write throughput heat-maps ranging from 0 to 160 MiB/s about the 192 OSTs used during the IOR benchmark run.

Optimization	I/O stats			Tofu stats		I/O rates	Overall
configuration	req_qdepth	req_waittime	req_active	R_{BW}	T_{wait}^{max}	OST_{mean}	score
T:original	7	7	1	7	2	5	4.83
T:agg=0,rr=0,req=0	5	4	4	6	7	1	4.50
T:agg=0,rr=0,req=4	1	1	8	4	8	7	4.83
T:agg=1,rr=0,req=4	2	2	5	2	5	6	3.67
T:agg=1,rr=1,req=4	3	3	3	1	6	4	3.33
T:agg=1,rr=1,req=16	6	5	2	3	4	2	3.67
N:original	8	8	6	8	1	8	6.50
N:agg=0,rr=0,req=4	4	6	7	5	3	3	4.67

Table 6.1: Scores of the IOR benchmark run, where lesser is better in each score number.

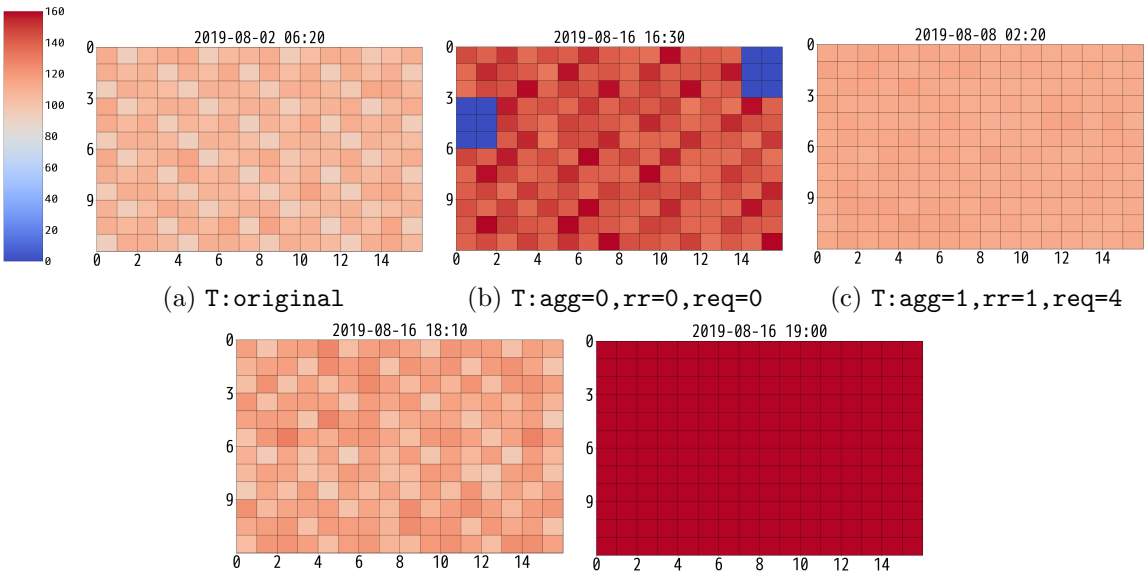
6.6 Overall evaluation

We conducted the overall evaluation based on the abovementioned results in each target metric. From the results in write and read operations in each benchmark run, we obtained mean values of the following metrics:

- Three metrics of `I/O stats`: (`req_qdepth`, `req_waittime`, and `req_active`)
- Two metrics of `Tofu stats`: (R_{BW} and T_{wait}^{max})
- Mean OST I/O bandwidth from `I/O rates` (OST_{mean})

It is preferable to have low values in the two of the three metrics in `I/O stats`, `req_qdepth` and `req_waittime`. While having high value is preferable in the `req_active`. Concerning the two metrics in the `Tofu stats`, high value is desirable in R_{BW}, while low value is suitable in T_{wait}^{max}. High value is preferable in OST_{mean} from `I/O rates`. We gave them ranks from 1 in the order from the best one among the evaluated optimizations in each metric according to the above context. Finally we obtained a stats score as a mean value of the ranks.

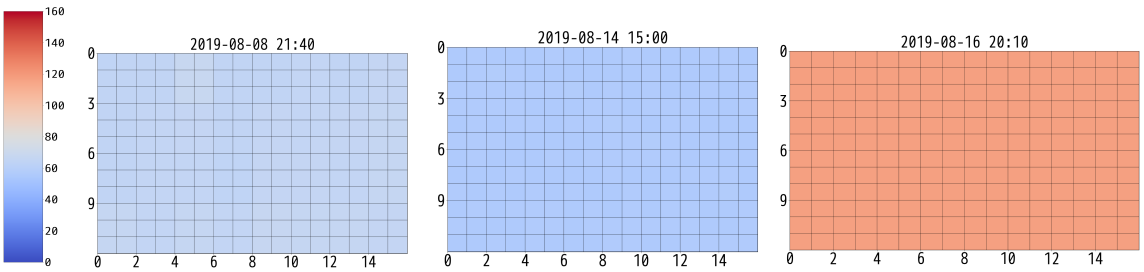
Table 6.1 summarizes the scores of the IOR benchmark run. We can see that the case of `T:agg=1,rr=1,req=4` shows the best overall score (3.33) among the evaluated optimization parameter sets. Although we already examined that this case was the best in the IOR run, we observed another insight that the bast case achieved such balanced situation among I/O subsystems from the score.



(a) `T:original` (b) `T:agg=0,rr=0,req=0` (c) `T:agg=1,rr=1,req=4`

(d) `N:original` (e) `N:agg=0,rr=0,req=4`

Figure 6.7: Read throughput heat-maps ranging from 0 to 160 MiB/s about the 192 OSTs used during the IOR benchmark run.



(a) `T:original` (b) `T:agg=0,rr=0,req=8` (c) `T:agg=1,rr=1,req=8`

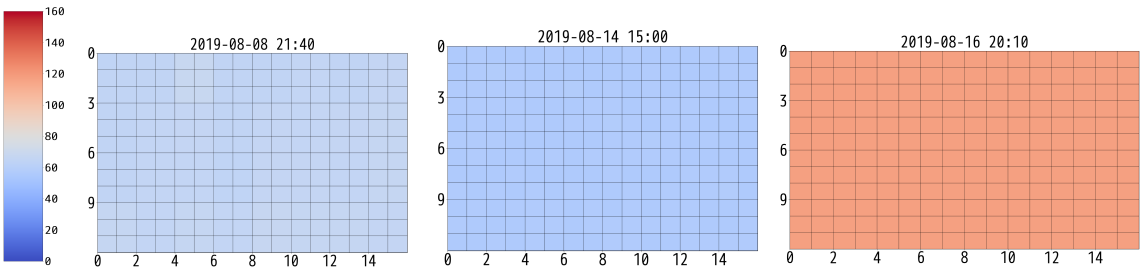
Figure 6.8: Write throughput heat-maps ranging from 0 to 160 MiB/s about the 192 OSTs used at the HPIO benchmark run.

Meanwhile, the scores of the HPIO benchmark run are summarized in Table 6.2. From this table, we can see that the case of `T:agg=1,rr=1,req=8` achieves the best score (2.67) among the evaluated optimization parameter configurations. The best case showed balanced situation among the I/O subsystems as well as the IOR benchmark run. We can easily observe the best optimization configuration with the balanced situation using the scoring scheme.

7 Conclusions

We built a holistic log data analysis framework to characterize I/O activities at the LFS and data transfers through the Tofu interconnects of I/O nodes in I/O optimization at the K computer. The proposed framework utilized the bandwidth status of the Tofu links among I/O nodes used and performance metrics of log data generated at the LFS and I/O nodes. The holistic analysis of data transfer activities on the Tofu links among I/O nodes and I/O activities on the LFS provided useful information in I/O performance tuning.

The two I/O benchmark runs showed notable differences in I/O activities at the LFS and data transfers through the Tofu links among I/O nodes between the original MPI-IO and the enhanced one named EARTH. The EARTH with the optimal optimization configuration showed a high number of active threads on OSSes with short waiting times in I/O request



(a) `T:original` (b) `T:agg=0,rr=0,req=8` (c) `T:agg=1,rr=1,req=8`

Figure 6.9: Read throughput heat-maps ranging from 0 to 160 MiB/s about the 192 OSTs used at the HPIO benchmark run.

Optimization	I/O stats			Tofu stats		I/O rates	Overall
configuration	req_qdepth	req_waittime	req_active	R_{BW}	T^{max}_{wait}	OST_{mean}	score
T:original	5	6	2	5	1	5	4.00
T:agg=0,rr=0,req=0	4	5	4	4	2	6	4.17
T:agg=0,rr=0,req=8	1	1	6	2	6	1	2.83
T:agg=1,rr=1,req=8	3	4	1	1	4	3	2.67
T:agg=1,rr=1,req=2	2	2	5	3	3	4	3.17
T:agg=1,rr=1,req=4	6	3	3	6	5	2	4.17

Table 6.2: Scores of the HPIO benchmark run, where lesser is better in each score number.

operations in comparison with the original MPI-IO. The EARTH case also showed high scores in bandwidth utilization of the Tofu links and waiting times for data transfers on the Tofu links in addition to high I/O bandwidth on OSTs. Such obtained profiling information provided insights to understand why the EARTH gained I/O performance relative to the original MPI-IO. We had an unknown issue in performance gaps among different optimization configurations of the EARTH. The framework also informed us how much the impact in I/O activities at the LFS and bandwidth utilization of the Tofu links of I/O nodes among several optimization configurations of the EARTH not only individual examinations in the three log data collections but also overall scoring scheme. By using the framework, we obtained the same answer about the optimal optimization configuration in the two I/O benchmark runs compared with the I/O bandwidth values obtained only from benchmark runs. Compared with traditional evaluation only using I/O benchmarks, our framework can provide more insights about the I/O activities in each I/O subsystem such as high speed interconnects and activities on the target file systems.

Our future work is building a similar framework in Fugaku, with more sophisticated organization of the database to cover all essential metrics from collected log data with a fine-grained monitoring interval. Although the system configuration of Fugaku is different from the K computer, the enhanced Tofu interconnects called TofuD [AKO+18] in Fugaku supports the same metrics used in the proposed framework. This means that we can monitor Tofu data transfer packet status through TNRs of TofuD. Unfortunately, we did not have any chance to investigate real application jobs with the proposed framework in the K computer because the implementation and the evaluation were done as trial only for the last few months before the K computer termination. Such evaluation would be our future work if we have chance to deploy the similar framework in Fugaku. The proposed analysis framework with some enhancements for Fugaku is expected to be useful for I/O performance tuning by monitoring I/O workloads of I/O nodes and file systems and data transfers on TofuD interconnects. According to some confidential issues with vendors, we cannot describe anything about the framework in Fugaku.

We did not have any enhanced works about the proposed framework in other HPC platforms unfortunately. However, we consider that the framework can be easily enhanced in other

HPC platforms since the framework was built by open source environment such as *Python*. Although the proposed framework was partially lack of generality by using logs of Tofu and FEFS, which were specific subsystems in Fujitsu's machine, we can enhance it by having an abstract layer on top of an underlying system-dependent layer. Other interconnects such as Gemini [ARK10, PVB+13] or Aries [Arib, Aria] from Cray also provide the similar hardware counters, and they have been used in log analysis studies [CJH+19, AAB+18, ZGL16, PVB+13]. Such abstract layer will cover all the system-dependent layer to provide metrics about data transfers on interconnects. Besides, metrics extracted from FEFS were ones available in Lustre because FEFS was an enhanced file system based on Lustre. Therefore it would be easy to utilize the same metrics in other HPC platforms equipped with Lustre file systems. Within this context, enhancements on other HPC platforms would be another challenge.

Acknowledgment

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Reviews

This section is optional for reviewers and shows their assessment that lead to the acceptance of the original manuscript. Reviewers may or may not update their review for a major update of the paper, the exact trail is available in GitHub repository of this article. The reviews are part of the article and validate the acceptance. Please check the details on the JHPS webpage.

Reviewer: Lingfang Zeng, Date: 2021-04-16

Overall summary and proposal for acceptance What makes the reviewer deeply influenced in this manuscript is that the experiment is very rich. The main shortcomings of the manuscript are: (1) lack of discussion on the optimization scheme and technical details (which also leads to the lack of support/explanation in the Section "Experimental Evaluation": what are the specific measures / improvements to achieve the performance optimization?) (2) The technical schemes and experimental platform are out of date and lack of novelty. (3) The unique software and hardware scheme makes the technical schemes of this draft unrepeatable, which is not in line with the purpose of JHPS. It is suggested that the draft be rejected. Others: (1) Page 4, Section 3 "K computer and Its File System Monitoring" – The system was retired (about two years). In the era of Exascale Supercomputers and intelligent computing, always new architecture and technology can attract readers. (2) Page 8, Section 5 "Enhanced MPI-IO Implementation: EARTH on K", "Its advanced functions are summarized in the following three key optimization parameters described by agg, req, and rr, respectively:" – This is the main contribution of this draft, but the details are too few. Although the reviewer understands the relevant technical details, the readers may not be sure. On the whole, the contribution of this draft is too little, lack of novelty. (3) Page 10, Section 6 "Experimental Evaluation", Subsection 6.1 "Benchmark configuration" – K computer has been running for many years. It has run many typical applications and must have collected a lot of real log information. Therefore, I suggest using real application log and system log information instead of being generated by benchmark.

Scope Yes. Its topic fits the JHPS.

Significance Minor.

Readability Yes.

Presentation It's clear and easy to understand.

References Yes.

Correctness There are some sound.

Reviewer: Suren Byna, Date: 2021-05-09

Overall summary In contrast to existing I/O performance analysis efforts, this paper collects interconnection information and detailed parallel file system information on I/O nodes. This additional information allows authors to analyze I/O performance using OSS stats files and interconnect bandwidth.

Some of my concerns were related to the overhead for tracing and storing the detailed information, the impact of other concurrent jobs on the system affecting the bandwidth, and a comparison with existing logs.

It seems that the Tofu and I/O stats have been extracted periodically and stored in a separate database. It was unclear to me if that periodic access cost anything? How large was the stats database?

In the analysis shown (OSS stats, bandwidth utilization, and load balance of I/O to OSTs), were there other jobs running concurrently along with the IOR and HPIO jobs that are being studied? What was the impact of them?

Since the results shown here are mainly for a decommissioned system, is the stats collection and storing continuing on current production systems? What was the impact of this study? While various plots were shown for the same configurations across the evaluation section, how do they (bandwidth utilization, waiting time in data transfer, OSS stats, etc.) correlate with the I/O throughput?

The last point regarding comparison with existing logs, such as Darshan and Darshan's extended tracing (DXT), could we get the information needed for the analysis shown in this paper? If not, what information is unavailable? It would be good to describe and compare.

Scope Yes. Its topic fits the JHPS.

Significance Minor.

Readability Yes.

Presentation It's easy to read the paper; I'd suggest some reorganizing in the introduction to motivate the problem before jumping into the Tofu PA log collection and information.

References Yes.

Correctness The exploration and evaluation are correct.

Reviewer: Anthony Kougkas, Date: 2021-05-16

Overall summary The paper presents a holistic log data analysis framework to characterize I/O activities at the LFS and data transfers through the Tofu interconnects of I/O nodes in I/O optimization at the K computer. Further, the paper presents a comparison between vanilla MPI-IO and EARTH, an optimized one, and how the obtained profiling information gave insights to understand why the EARTH demonstrated higher I/O performance relative to the original MPI-IO. The analysis framework allowed the authors to uncover how much I/O activities at the LFS and bandwidth utilization of the Tofu links of I/O nodes impacted the performance of EARTH. Extensive results were presented and analyzed.

I enjoyed reading about this work. The paper is informative on issues stemmed by poor monitoring and analysis of I/O activities in a large computing environment. This reviewer found the paper focusing on the K computer a bit restricting in drawing conclusions in general. A lot of the proposed framework is specific to the architecture (e.g., LIO, GIO, BIO are all particulars of the K computer) and I am not convinced that the audience can extract generally useful methodologies on I/O tracking. However, the paper reads well, has a decent motivation section, and the extensive results presented are only positive. I am recommending a minor revision with the following three suggestions: a) the authors should invest some time bringing the manuscript in published quality through detailed proofreading. b) add a subsection (or a clear paragraph somewhere early in the paper) discussing in detail the intellectual contributions. c) add a discussions and considerations section (before the evaluation maybe) where the authors can connect their methodology in a more general architecture (i.e., how could we achieve the same depth of collected information for another HPC machine? What

parts of this work are specific to K computer and what are not? Is the framework developed open sourced? What are the caveats of the proposed analysis?)

Strengths

- The paper addresses issues in an area (i.e., I/O activity monitoring) that needs more investigation by the community.
- The paper has done a great work presenting the methodology the authors followed and described the architecture of K computer in great detail making it easy to follow.
- The paper went to great lengths to present detailed performance analysis of MPI-IO and EARTH.

Weaknesses

- The paper is more of an experience paper. There is nothing general in the findings but solely focuses on the K computer. Even though this was a production machine, it does not represent all HPC architectures. There is little (or no) discussion as to how the reader can replicate their work for a general architecture.
- The paper needs a good proofreading, possibly multiple passes. While it is not poorly written, there are many areas where grammar and syntax can be polished

Reviewer: George Markomanolis, Date: 20210-05-17

Overall summary The authors present their work, an I/O performance optimization framework that uses log data of parallel file systems and interconnects in a holistic way. They discuss the Tofu PA profiling tool on the K computer for the Tofu interconnects. They present how all the framework works and its usefulness for specific cases. One main disadvantage of this paper is that this is a work for a decommissioned system, the K supercomputer. The collection of statistics every 1 or 10 minutes depending on the type of the stats can not correlate with every I/O intensive application. The installed ROMIO version on the K computer is not optimized for the Lustre, thus a newer version was used and the comparison between these two is not fair. There are presented some results from their approach and their metrics are explained. They do achieve better I/O performance with their tuning. The manuscript is more experimental, sometimes tuning parameters becomes more known case but the holistic approach on such system is not a common topic. I would like to see more explanations about the duration of the logs collection as collecting every a few minutes is a really specific I/O pattern. I assume it is not possible to have more diverse applications as the K computer is not available anymore. I would also like some discussion regarding overhead from your tool.

Scope Yes. It fits.

Significance Minor.

Readability Yes but it could be improved

Presentation It is good but a proofreading would help.

References Yes.

Correctness Yes, although the fact that the research is not reproducible because of the decommissioned system is always an issue.