

# LDMS Darshan Connector: For Run Time Diagnosis of HPC Application I/O Performance

Sara Walton<sup>1</sup>, Omar Aaziz<sup>1</sup>, Ana Luisa V. Solórzano<sup>2</sup>, Ben Schwaller<sup>1</sup>, and Devesh Tiwari<sup>2</sup>

<sup>1</sup>Sandia National Laboratories, Albuquerque, USA

<sup>2</sup>Northeastern University, Boston, USA

**Abstract**—Periodic capture of comprehensive, usable I/O data for scientific applications requires an easy-to-use technique to record information throughout the execution without causing substantial performance effects. In this paper, we introduce a unique framework that provides low latency monitoring of I/O event data during run time. We implement a system-level infrastructure that continuously collects I/O application data from an existing I/O characterization tool to enable insights into the I/O application behavior and the components affecting it through analyses and visualizations. In this effort, we evaluate our framework by analyzing sampled I/O data captured from two HPC benchmark applications to understand the I/O behavior during the execution life of the applications. The result shows the utility of capturing I/O application performance and behavior.

## I. INTRODUCTION

As more scientific I/O applications are developed and used, the need for improved fidelity and throughput of these applications is more pressing than ever. Much design efforts and investments are being put into improving not only I/O applications but also the system components. Being able to identify, predict and analyze I/O behaviors are critical to ensuring parallel storage systems are utilized efficiently [1].

Variations in I/O can be caused by the system usage and behavior such as the file system (e.g. buffering, file transfer, interrupt handling), network congestion, data set size and storage, system resource contentions, or by the access patterns of the application itself [2]. This variation makes it difficult to determine the root cause of I/O related problems and have a thorough understanding of throughput for system-specific behaviors and I/O performance in similar applications across a system.

Generally, the I/O performance is analyzed post-run by application developers, researchers and users in the form of regression testing or other I/O characterization tools that capture the applications behavior. An example of one of these tools is *Darshan*, which monitors and captures I/O information on access patterns from HPC applications [3]. Efforts to identify the origin of I/O performance usually come from the analysed data collected by these I/O characterization tools. Correlations are then made with the environment in which they were ran or other analyses from various application runs. However, this approach does not provide the ability to know **when** a significant variation of I/O performance occurs during runtime and, if the developer or user wishes to, identify any

correlations between the file system, network congestion or resource contentions and the I/O performance.

Execution logs that provide *absolute timestamps* (e.g. time-series) enable users and developers to perform temporal performance analysis, and better understand how these changing components affect the I/O performance variation as well as provide further insight into the application I/O pattern. Therefore, we introduce our *Darshan LDMS Integration* approach that incorporates the *absolute timestamps* to provide a runtime timeseries set of application I/O data. This paper covers the following contributions:

- Describes the approach used to expose absolute timestamp data from an existing I/O characterization tool;
- Provide a high level overview of the implementation process and other tools used to collect application I/O data during run time;
- Demonstrates use cases of the *Darshan-LDMS Connector* for two applications with distinct I/O behavior on a production HPC system;
- Utilizes Darshan LDMS data to identify and better understand any root cause(s) of application I/O performance variation run time;
- Presents how this new approach can be integrated with other tools to benefits users to collect and assist in the detection of application I/O performance variances across multiple applications.

## II. BACKGROUND

### A. *Darshan*

Darshan is a lightweight I/O characterization tool that captures I/O access pattern information from HPC applications. [3]. This tool is used to tune applications for increased scientific productivity or performance and is suitable for full time deployment for workload characterization of large systems [4]. It provides detailed statistics about various level file accesses made by MPI and non-MPI applications which can be enabled or disabled as desired. These levels include POSIX, STDIO, LUSTRE and MDHIM for non-MPI applications and MPI-IO, HDF5 and some PnetCDF for MPI applications [5]. This functionality provides users with a summary of I/O behavior and patterns from an application post-run. It does not provide insights into run time I/O behavior and patterns or concurrent system conditions. This limits the ability to use

this data to identify the root cause(s) of I/O variability and when this occurs.

### B. LDMS

The Lightweight Distributed Metric Service (LDMS) is a low-overhead production monitoring system that can run on HPC machines with thousands of nodes collecting and transporting HPC data via *samplers* and *plugins*. A *sampler* is a daemon that collects the data while the *plugin* determines the kind of data sampled, aggregated, or stored, which takes a set configuration to initialize and configure plugins. The system state insights are achieved by LDMS's synchronous and *absolute timestamp* view of system conditions through multi-hop aggregator support with multiple levels. This support is in a tree structure where the *samplers* (e.g leaves) determine the kind of data sampled, the intermediate aggregators are used for data transport, and the last level aggregators are used for storage. There are a variety of plugins that can be used to collect several metrics. Additional functionalities exist in LDMS, such as the *Streams API*, that allow for the aggregation of event-based application data. This framework utilizes *LDMS Streams API* to collect Darshan's I/O event data from applications during execution time and store the *timestamped* data in a database.

### C. DSOS

The Distributed Scalable Object Store (DSOS) is a database designed to manage large volumes of HPC data [6] efficiently. LDMS uses it to support high data injection rates to enhance query performance and flexible storage management. DSOS has a command line interface for data interaction and various APIs for languages such as Python, C, and C++. A DSOS cluster consists of multiple instances of DSOS daemons, *dsosd*, that run on multiple storage servers on a single cluster. The DSOS Client API can perform parallel queries to all *dsosd* in a DSOS cluster. The results of the queried data are then returned in parallel and sorted based on the index selected by the user. This database and its Python API are used in this framework for storing and querying the I/O event data.

### D. HPC Web Services

The HPC Web Services is an analysis and visualization infrastructure for LDMS [7], that integrates an open-source web application, Grafana [8], with a custom back-end web framework (Django) which calls python modules for analysis and visualization of HPC data. Grafana is an open-source visualization tool tailored towards time-series data from various database sources. Grafana provides charts, graphs, tables, etc. for viewing and analyzing queried data in real time. Using a custom DSOS-Grafana API, the python analysis modules to be used can be specified in a Grafana query. Once specified, that python analysis transforms any data queried from the dashboard before returning the data to Grafana. Grafana enables a wide variety of visualization options for the data and allows users to save and share those visualizations to others. This framework will leverage the HPC Web Services for run time analyses and visualizations of the I/O event data.

## III. DARSHAN LDMS INTEGRATION

Darshan collects I/O application data for post-run analysis, and LDMS has a low overhead sampling capability supported by fast storage and a modern web interface. We chose to enhance both Darshan and LDMS by adding a sampling capability that acts as a connector between these two applications to support I/O runtime data sampling and visualization. Here is a high-level overview of the design and implementation of the *Darshan LDMS Integration* and the components used to create this infrastructure:

- The I/O characterization tool, Darshan, to collect application I/O behavior and patterns.
- LDMS to provide and transport live run time data feed about application I/O events. [9]
- DSOS to store and query large amounts of data generated on a production HPC system. [6]
- HPC Web Services to present run time I/O data to enable the user to create new meaningful analyses [7].

LDMS is used to efficiently collect and transport scalable *synchronous* and *event-based* data with low-overhead. Two key functionalities the *Darshan LDMS Integration* will leverage in order to create the *Darshan-LDMS Connector* are the LDMS publish-subscribe bus and LDMS transport [10]. In this work, we enhanced LDMS to support application I/O data injection and store it to DSOS, then modified Darshan to expose the *absolute timestamp* to publish run time I/O events for each rank to *LDMS Streams*. This integration will be described in detail later on in paper.

*DSOS* will enable the ability to query the timestamped application I/O data through a variety of APIs while Grafana will provide a front-end interface for visualizing the stored data that has been queried and analyzed using Python based modules on the back-end. With these tools, users can view, edit and share analyses of the data as well as create new meaningful analyses.

## IV. INTEGRATION TOOLS

### A. Darshan

Darshan is divided into two main parts: 1) *darshan-runtime* which contains the instrumentation of the characterization tool and produces a single log file at the end of each execution summarizing the I/O access patterns used by the application [11]. 2) *darshan-util* which is intended for analyzing log files produced by *darshan-runtime* [11]. The *Darshan LDMS Integration* focuses on the *darshan-runtime* [5] as this is where the source code of I/O event data is recorded by Darshan.

Darshan tracks the start, duration and end time of an application run via the C function *clock\_gettime()* and converts the result into seconds and passes the result to a struct that is then used to report the summary log files [12]. Therefore, in order to retrieve the *absolute timestamp* and include it into the I/O event data during run time, a time struct pointer was added to the function call that used *clock\_gettime()* in *darshan-runtime*. This pointer was passed through all of Darshan's modules and the *absolute timestamp* was collected. This was the preferred

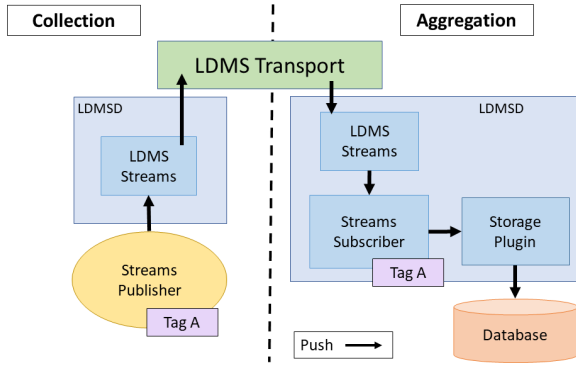


Fig. 1: Overview of the LDMS event data collection. Application data is *pushed* by publishing data to the *LDMS Streams* which is then *pushed* through the LDMS transport to the *LDMS Streams* LDMS aggregator (right) where the data is *pushed* to the streams subscriber (Tag A) and stored to a database.

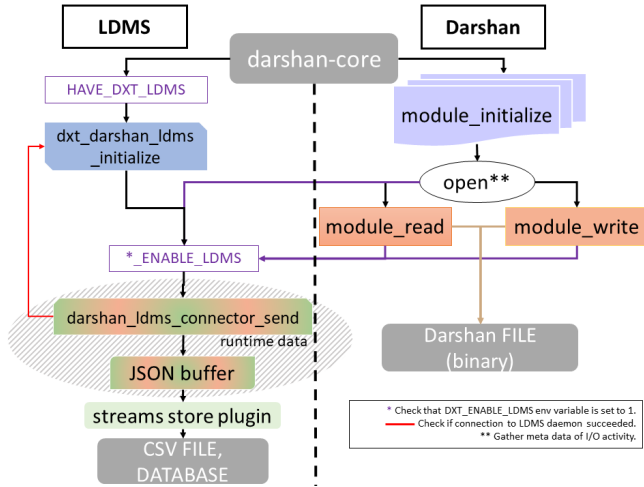


Fig. 2: Overview of the *Darshan-LDMS Connector* design and how it collects I/O data for each read, write, open and close events per rank from Darshan. The LDMS library must be linked against the Darshan build in order to utilize the *LDMS Streams* functionality and store plugins.

method as it required minimal changes to Darshan’s source code and no additional overhead and latency between the function call and recording of the *absolute timestamp*.

### B. LDMS Streams

The word *LDMSD* refers to an LDMS daemon that provides the capability of data collection, transport and storage and their *plugins* determine the functionality of these capabilities [9]. Daemons on the compute nodes run sampler plugins and transport is achieved through multi-hop *aggregation*. LDMS had two levels of aggregator daemons [9] which can utilize storage plugins to store any sets of data into various formats so long as it’s specified beforehand.

The *Darshan LDMS Integration* leverages the LDMS transport to support the injection and transport of application I/O data which requires a *push-based* method to reduce the amount of memory consumed and data loss on the node as well as reduce the latency between the time in which the event occurs and when it is recorded. A *pull-based* method would require a buffering to hold an unknown number of events between pulls. Also, the transported data format needs to support *variable-length* events because the I/O data will most likely vary in size.

We created an I/O targeted LDMS streams store that utilizes the LDMS publish-subscribe bus capability, *LDMS Streams*, to publish I/O event data. *LDMS Streams* is intended for publishing and subscribing to an *LDMS streams* tag. This tag needs to be specified in LDMS daemons and *plugins* in order to publish event data to *LDMS Streams* and receive this published *LDMS Streams* data that match the tag. This process and the *push-based* method can be seen in Figure 1. Event data can be specified as either *string* or *JSON* format. The *LDMS Streams* API was modified to support long application connections and message injections. *LDMS Streams* uses best effort without a reconnect or resend for delivery and does not cache it’s data so the published data can only be received after subscription. The *LDMS Streams* allows the ability for any data source to be injected into the LDMS transport.

### C. Darshan Connector

The most recent version of Darshan allows for full tracing of application I/O workloads using their DXT instrumentation module which can be enabled and disabled as desired at runtime. DXT provides high-fidelity traces for an application’s I/O workload vs Darshan’s traditional I/O summary data and currently traces POSIX and MPI-IO layers [5]. Our design leverages the additional I/O tracing Darshan’s DXT module plugin provides through the new *Darshan-LDMS Connector* capability.

The *Darshan-LDMS Connector* functionality collects both DXT data and Darshan’s original I/O data and optionally publishes a message in JSON format to the *LDMS Streams* interface as seen in Figure 3. The *absolute timestamp* is also included in this message with the given name “timestamp”. The LDMS transport then transports the I/O event data to a *DSOS* database where Grafana can access and query this data. the *Darshan-LDMS Connector* currently uses a single unique *LDMS Stream* tag for this data source. For the file level access types that DXT does not trace or that have different name-value pairs, a value of “N/A” or “-1” is given in the JSON message. For example, Darshan’s POSIX module (IEEE standard that establishes a set of guidelines for compatibility and portability between operating systems) traces the number of bytes read and written per operation (e.g. “max\_byte”) and number of times access alternated between reads and writes (e.g. “switches”). The I/O operations shown in Figure 3 are “open” and “close” which are not applicable to these traces. Therefore, “max\_byte” and “switches” are

**JSON Message**

```
{ "uid":99066,"exe":"<absolute-path>/mpi-io-
test","job_id":226903,"rank":3,"ProducerName":"nid00046","file":"<absolute-path>/mpi-io-
test.tmp.dat","record_id":1601543006480890062,"module":"POSIX","type":"MET","max_byte":-
1,"switches":-1,"flushes":-1,"cnt":1,"op":"open","seg":[{"data_set":"N/A","pt_sel":-1,"irreg_hslab":-
1,"reg_hslab":-1,"ndims":-1,"npoints":-1,"off":-1,"len":-1,"dur":0.002069,"timestamp":1653416252.990068}]}

{"uid":99066,"exe":"N/A","job_id":226901,"rank":2,"ProducerName":"nid00046","file":"N/A","record_id":16
01543006480890062,"module":"POSIX","type":"MOD","max_byte":-1,"switches":-1,"flushes":-
1,"cnt":1,"op":"close","seg":[{"data_set":"N/A","pt_sel":-1,"irreg_hslab":-1,"reg_hslab":-1,"ndims":-
1,"npoints":-1,"off":-1,"len":-1,"dur":0.002296,"timestamp":1653416253.006978}]}
```

**CSV Header**

```
#module,uid,ProducerName,switches,file,rank,flushes,record_id,exe,max_byte,type,job_id,op,cnt,seg:off,seg:
pt_sel,seg:dur,seg:len,seg:ndims,seg:reg_hslab,seg:irreg_hslab,seg:data_set,seg:npoints,seg:timestamp
```

Fig. 3: Output of a MPI-IO Darshan test run in the JSON format (top image), and the CSV file header (bottom). The name:value pairs in light blue indicate meta data stored, while the light purple indicates the file level access data not applicable to POSIX. The "seg" is a list containing multiple name:value pairs.

not present in Darshan and their corresponding JSON message names are set to "-1" by the *Darshan-LDMS Connector*.

Darshan has a large number of metrics it uses for I/O tracing and post-processing calculations. The current stages of this framework collects a subset of these metrics to publish to *LDMS Streams*, as presented in Figure 3. These metrics will provide the ability to create new I/O behavior analyses and visualizations to get further insights of the application I/O behavior, and reveal correlations between I/O performance variability and system behavior. Table I depicts the names and definitions of each metric in the JSON file. Depending on the "type" input, the absolute directory of the Darshan file output and executable will be recorded and published to *LDMS Streams*. If "type" is set to "MET" (e.g. "meta"), the absolute directories will be recorded. Otherwise, it will receive the value "N/A" if set to "MOD" (e.g. "module"). The "type" will be set to "MET" for open I/O events, which are the Darshan I/O records that have permanent values during the application execution, such as the rank, file and node name. The "type" is set to "MOD" for all other I/O events to reduce the message size and latency when sending the data through an HPC production system pipeline.

#### D. Storage: DSOS Database

DSOS is built on the Scalable Object Store (SOS) database [6] and was intended to address the domain-specific needs of large-scale HPC monitoring. It was chosen as the preferred monitoring database at Sandia because it allows for interaction via a command line interface which allows for fast query testing and data examination. DSOS also provides scalable data ingest and the ability to query large volumes of data which is required for the large amounts of data to be ingested and stored. To sort though the published *LDMS Streams* data, combinations of the job ID, rank and timestamp are used to create joint indices where each index provided a different query performance. An example of this is using `job_rank_time` which will order the data by job, rank then

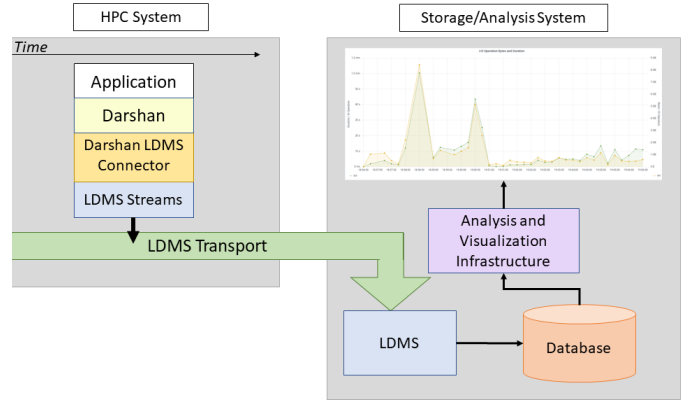


Fig. 4: Overview of the *Darshan LDMS Integration* where the *Darshan-LDMS Connector* is used to intercept the I/O behavior Darshan is collecting utilizes the various tools to publish, store, analyze and view runtime I/O behavior.

timestamp and then search the data by a specific rank within a specific job over time.

#### E. Analysis and Visualization: HPC Web Services

The HPC Web Services [7] is an infrastructure that consists of the analysis and visualization components of this approach. The front-end for the service website is Grafana [8] and the back-end consists of Python analysis modules. The HPC Web Services also provide instant analysis where data can be analyzed and viewed in real time as opposed to the traditional method of querying the results of analyzed data from a separate database.

Grafana is an open-source visualization application that provides various charts, graphs and alerts for supported data sources. It can support multiple data formats but is best suited for timeseries data. It has storage plugins for many database technologies in order to query and render data from multiple data sources. The *Darshan LDMS Integration* implemented a storage plugin for the DSOS database in order to query this data and visualize it on the Grafana web interface [8]. An overview of the this integration can be seen in Figure 4.

Python analysis modules are used to produce meaningful visualizations on the queried data from the DSOS database. With these modules, queried data is converted into a pandas dataframe to allow for easier application of complex calculations, transformations and aggregations on the data. The type of analysis module is specified in the Grafana web interface. These python modules that *Darshan LDMS Integration* will demonstrate how runtime I/O data will provide further insights and understanding into application I/O behavior, patterns, performance variability and any correlations these have with the system behavior.

## V. EXPERIMENTAL METHODOLOGY

This section presents our experimental methodology to evaluate our framework using two applications: HACC-IO, and the

uuid	User ID of the job run
exe	Absolute directory of the application executable
module	Name of the Darshan module data being collected
ProducerName	Name of the compute node the application is running on
switches	Number of times access alternated between read and write
file	Absolute directory of the filename where the operations are performed
rank	Rank of the processes at I/O
flushes	Number of "flush" operations. It is the HDF5 file flush operations for H5F, and the dataset flush operations for H5
record_id	Darshan file record ID of the file the dataset belongs to
max_byte	Highest offset byte read and written per operation
type	The type of JSON data being published: MOD for gathering module data or MET for gathering static meta data
job_id	The Job ID of the application run
op	Type of operation being performed (i.e. read, write, open, close)
cnt	The count of the operations performed per module per rank. Resets to 0 after each "close" operation
seg	A list containing metrics names per operation per rank
seg:pt_sel	HDF5 number of different access selections
seg:dur	Duration of each operation performed for the given rank (i.e. a rank takes "X" time to perform a r/w/o/c operation)
seg:len	Number of bytes read/written per operation per rank
seg:ndims	HDF5 number of dimensions in dataset's dataspace
seg:reg_hslab	HDF5 number of regular hyperslabs
seg:irreg_hslab	HDF5 number of irregular hyperslabs
seg:data_set	HDF5 dataset name
seg:npoints	HDF5 number of points in dataset's dataspace
seg:timestamp	End time of given operation per rank (in epoch time)

TABLE I: Metrics defined in the JSON file published to the *Darshan LDMS Integration*.

Darshan MPI-IO benchmark. We performed the experiments in a Cray HPC cluster using NFS and Lustre file systems.

#### A. Applications

- HACC-IO is the I/O proxy for the large scientific application: Hardware Accelerated Cosmology Code (HACC), an N-body framework that simulates the evolution of mass in the universe with short and long-range interactions [13]. The long-range solvers implement an underlying 3D FFT. HACC-IO is an MPI code that simulates the POSIX, MPI collective, and MPI independent I/O patterns of fault tolerance HACC checkpoints. It takes a number of particles per rank as input, writes out the simulated checkpoint information into a file, and then read it for validation. We ran HACC-IO with several configurations to simulate different workloads on the NFS and Lustre file systems. Table IIb shows the different run configurations.
- MPI-IO-TEST benchmark is a Darshan utility that exists in the code distribution to test the MPI I/O performance on HPC machines. It can produce iterations of messages with different block sizes sent from various MPI ranks. It can also simulate collective and independent MPI I/O methods. We experimented with NFS vs. Lustre and collective vs. independent MPI I/O. We ran the benchmark with four configurations on 22 nodes and set the number of iterations to 10 and the block size to 16MB. Table IIa shows the different configuration used.

#### B. Evaluation System

We experiment using several I/O loads on the Voltrino Cray XC40 system at Sandia National Laboratories. The system

has 24 diskless nodes with Dual Intel Xeon Haswell E5-2698 v3 @ 2.30GHz 16 cores, 32 threads/socket, 64 GB DDR3-1866MHz memory, and connected with a Cray Aries DragonFly interconnect. The machine connect to two file systems: the network file system (NFS) and the Lustre file system (LFS).

#### C. Enviroment

The HPC cluster, Voltrino, was used to run LDMS samplers on the compute nodes and one LDMS aggregator on the head node. LDMS uses the UGNI interface to transfer Darshan streams data, and other performance metrics from the compute nodes to the head node. The aggregator on the head node transmits the data to another LDMS aggregator on another cluster, Shirley, for analysis and storage. Shirley hosts the HPC web services consisting of the Grafana application and DSOS database.

We ran the applications with our enhanced Darshan library that wraps the I/O functions dynamically, for each MPI rank, to sample I/O data and send it using streams to the LDMS local node sampler daemon. We set the `LD_Preload` environment variable to point to the Darshan library shared objects which contain the sampling wrappers before we run the applications.

## VI. RESULTS

This section covers what significance of the approach to collect runtime application I/O data using *Darshan LDMS Integration*. We present performance analysis that shows how the new metrics helped provide more insight results into I/O behavior and how this information represented in Grafana.

### A. Experiments and Overhead

Each application was tested on the Lustre and NFS file system with various configurations for each application run. All application experiments were repeated 5 times for the *Darshan-LDMS Connector* and Darshan only (i.e. no LDMS implementation) which summed to a total of 40 job submissions. The layout for these runs are shown in Table II.

MPI-IO-TEST				
File System	NFS		Lustre	
Nodes	22		22	
Block Size	16*1024*1024		16*1024*1024	
Iterations	10		10	
Collective	Yes	No	Yes	No
Avg. Messages	50390	6397	25770	15676
Rate (msgs/sec)	37	7	95	38
Average Runtime(s)				
Darshan	1376.67	880.46	249.97	428.18
dC	1355.35	858.68	270.98	414.35
% Overhead	-1.55%	-2.47%	8.41%	-3.23%
Standard Deviation(s)				
Darshan	48.18	29.43	2.85	31.49
dC	96.63	76.58	1.07	8.17
% Variance	-5.25%	-8.10%	9.22%	2.39%

(a) MPI-IO

HACC-IO				
File System	NFS		Lustre	
Nodes	16		16	
Particles/Rank	5000000	10000000	5000000	10000000
Avg. Messages	1663	1774	1995	1711
Rate (msgs/sec)	2	1	3	2
Average Runtime(s)				
Darshan	882.46	1353.87	417.14	1616.87
dC	775.24	1365.24	467.24	1027.44
% Overhead	-12.15%	0.84%	12.01%	-36.45%
Standard Deviation(s)				
Darshan	37.08	87.24	25.03	154.53
dC	53.68	46.97	142.77	256.62
% Variance	-14.65%	4.08%	-17.25%	-47.36%

(b) HACC-IO

TABLE II: Overview of each experiment configuration, target file system, average elapsed time(s) and standard deviation(s) from 5 runs, calculated overhead of LDMS and variance of the runs.

The average of the 5 execution times (e.g., Average Runtime (s)) for Darshan and the *Darshan-LDMS Connector* (e.g., dC) was then taken and used to calculate the percent overhead of LDMS. Because of the system availability, the runtimes with Darshan were only performed and recorded 1-2 weeks before the experiments with the *Darshan-LDMS Connector*. As seen from Table IIa, the overhead of LDMS on Darshans' MPI-IO-TEST benchmark for three experiments shows a decrease in overall runtime with the *Darshan-LDMS Connector*. Since this is not feasible, the runtime improvement seen with the *Darshan-LDMS Connector* is most likely due to the NFS and Lustre file systems performance variation where (and when) these experiments were performed. We have not been able

to test on a different cluster or have had the opportunity to interleave the Darshan, and *Darshan-LDMS Connector* runs to mitigate any file system performance changes.

The HACC-IO application, seen in Table IIb was similar to the MPI-IO-TEST benchmark regarding a shorter runtime with the *Darshan-LDMS Connector* for both file systems. Again, this is most likely due to the Lustre and NFS file systems as described earlier. The other two experiments, NFS with 10 million particles and Lustre with 5 million particles, show an overhead of 0.84% and 12.01%, respectively. The experiment with 0.84% overhead indicates no significant effect on the applications runtime. In contrast, the experiment with 12.01% overhead shows a longer runtime with the *Darshan-LDMS Connector* which is most likely due to performance variation in both file systems which we will investigate in the near future. The calculated variance for each of the experiments are statistically significant to assume that the overhead of LDMS is likely due to factors outside of LDMS and therefore are inconclusive. Therefore, we can not make any assumptions about the significant increases in overhead (e.g. MPI-IO collective using luster).

We observed a significant increase in total runtime from the *Darshan-LDMS Connector* for short I/O applications with an approximate rate of 500,000 messages sent per second. This large volume of data being collected and sent causes an increase in runtime because of the json message formatting.

Darshan collects all I/O events of an application run and the *Darshan-LDMS Connector* is implemented such that when Darshan detects an I/O event, the *Darshan-LDMS Connector* will collect and format that current set of I/O metrics into a json message. In order to send a json message, all integers must be converted to strings and this conversion comes at a performance cost. Therefore, the more I/O intensive an application is and the shorter the runtime, the overhead will increase significantly and cause the runtime performance to drop. Since there is currently no other way to send I/O data as a json message to the LDMS Streams interface without converting the integers to strings, we must pay a performance cost. If this issue persists when the variance is not statistically significant, we plan to further develop the *Darshan LDMS Integration* framework to allow users to collect every  $n$ -th I/O event detected by Darshan. This functionality will allow users to analyze a percentage of their applications I/O behavior during runtime without having to sacrifice runtime performance.

### B. Analysis and Grafana Output

Figure 5 shows the number of I/O requests per node for close and open operations for two jobs using the same input for the HACC-IO application on Lustre for 10 million particles per rank. This variation is under investigation to understand the root cause of such behavior such as the data loss.

Figure 6 shows the duration of the reads and writes per rank for each execution (job\_id metric) of the MPI-IO benchmark without using collective operations. We notice a similar behavior for the I/O operations duration for all



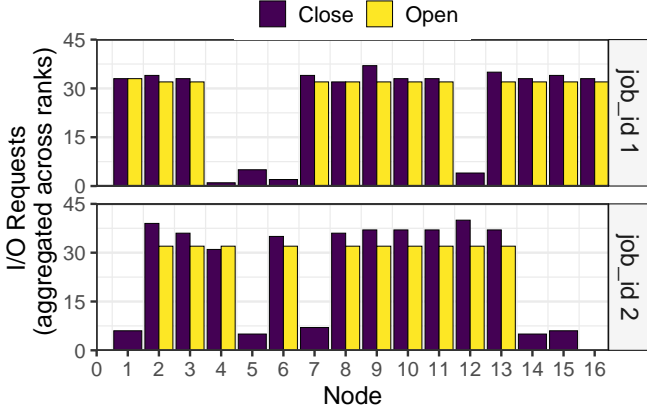


Fig. 5: The amount of I/O operations for HACC-IO using the same input.

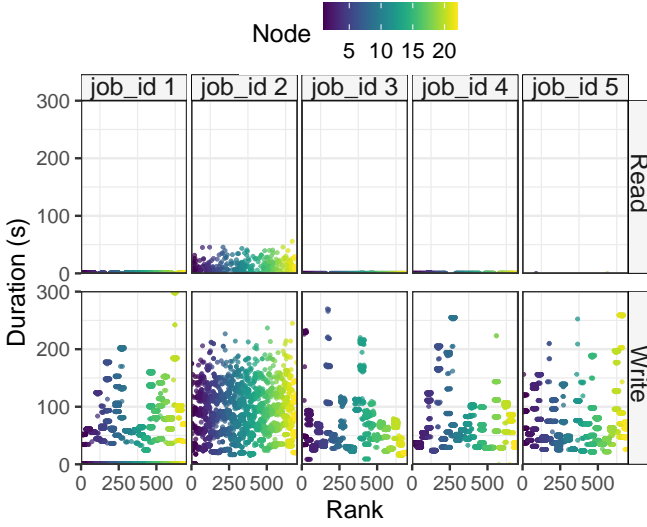


Fig. 6: Jobs for the MPI-IO benchmark without collective operations presented variability in the number and duration of I/O operations.

jobs except the second one (`job_id 2`). It presents a mean duration of 6.75 seconds for reads and 78s for writes, while the other jobs had a mean duration of 0.05s for reads and 54s for writes. With the collected logs, we can perform a spatial performance analysis to understand the variability in the I/O behavior per system component, in this case, per nodes and ranks.

Using the absolute timestamps collected we can temporally view wherein the application execution the variability of a job occurred and better understand the I/O behavior. Figure 7 presents the duration and occurrence of I/O operations throughout the MPI-IO benchmark for `job_id 2`. We can identify the application I/O pattern of performing writes during ten phases, and then read at the end, corresponding to the HACC-IO simulation purpose to write the checkpoint file

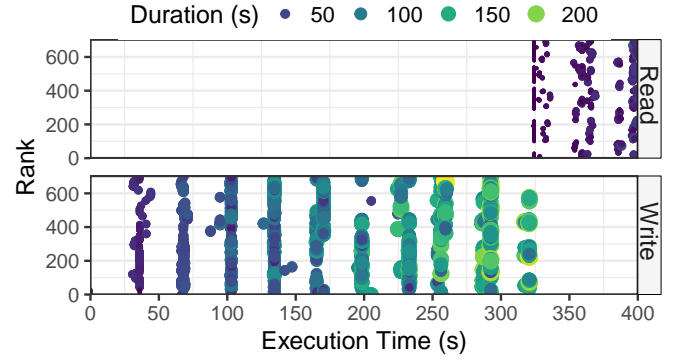


Fig. 7: Distribution of read and write operations throughout the execution time for the `job_id 2`, can reveal the application I/O pattern, and wherein the application there were faster and slower operations.

system and then read for validation. Also, this application run faster writes at the beginning and slower at the end, with the slowest writing after 250 seconds.

The same job is also represented in Figure 8 using the Grafana interface. This figure presents the number of I/O writes (blues) and reads (green) and the number of bytes sent aggregated across ranks. This timeseries shows the read and write behaviors throughout execution time which provides further insights into I/O occurrences and size. For example, we can identify the two instances in which a write above 20GB occurs and the single instance in which a read above 10GB occurs. A developer or user can then use this information to create new and meaningful analyses about their applications I/O operations and patterns. Grafana offers an interactive front-end view where users can easily filter to visualize specific time and metrics intervals. Such representation using the absolute timestamps facilitates the correlation of I/O performance congestion, for example, with system behavior monitoring, which can also be represented as a Grafana dashboard.

Without the *Darshan-LDMS Connector*, it would not be possible to create the meaningful analyses and visualizations shown in Figures 6-8. In contrast, Figure 5 shows the aggregate I/O behavior which can be created with Darshan alone. This figure does not provide the timeseries data and thus in-depth insights into I/O behavior like the *Darshan LDMS Integration* does.

## VII. RELATED WORK

Extensive research has already been proposed in literature to improve I/O performance and behavior. The PASSION Runtime Library for parallel I/O proposed by Syracuse University [14] that optimizes I/O intensive applications through Data Prefetching and Data Sieving, the IOPin: Runtime Profiling of Parallel I/O in HPC Systems proposes a dynamic instrumentation to show the interactions between a parallel I/O application and the file system [15], Design and Implementation of a Parallel I/O Runtime System for Irregular Applications [16] that

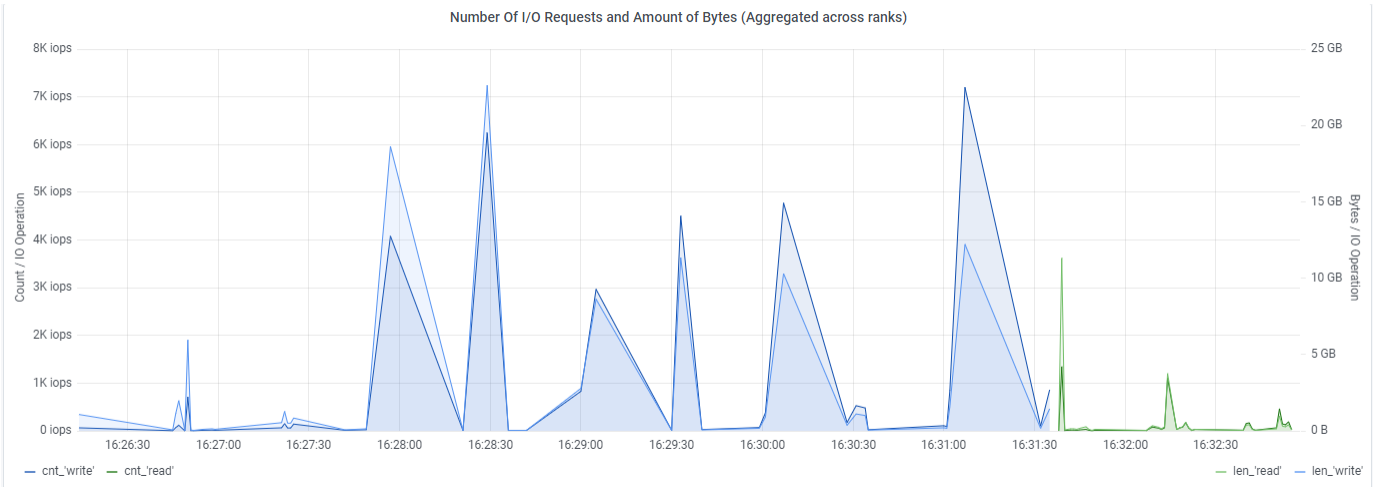


Fig. 8: Graphana visualization of the `job_id 2` writes (blue) and reads (green) operations and number of bytes per operation, using the absolute timestamp metric collected with *Darshan LDMS Integration*.

proposes two different collective I/O techniques for improving I/O performance.

Darshan was the preferred I/O characterization tool because the Darshan’s eXtended Tracing (DXT) [5] instrumentation module provides high-fidelity traces for an application’s I/O workload vs Darshan’s traditional I/O summary data [5]. It also collects timestamped data which made it possible to expose the *absolute timestamp* for collecting runtime timeseries data. Other open-source I/O tools that we have come across or are aware of do not have this extensive I/O tracing capability which is leveraged in this work. Other open source I/O profiling tools exist such as the linux command, `iostat` [17], which collects system I/O device statistics and generates reports about the I/O loads between physical disks and `ioprof` [18] which provides insights into I/O workloads. However, these I/O tools do not provide detailed insights into file I/O system.

This work differs from these approaches because we *leverage and enhance* existing applications and tools to design an infrastructure that creates runtime analyses and visualizations from detailed traces of application I/O events during execution time. The *Darshan LDMS Integration* integrates LDMS’s *timestamped* data collection and storage capabilities [10] with Darshan [4] to collect runtime application I/O data. Further, a database is implemented to allow for efficient queries of large volumes of data as well as python analysis modules and an open-source web application for runtime analyses and visualizations.

## VIII. FUTURE WORK

This paper covered the *Darshan LDMS Integration* design and implementation of the *Darshan-LDMS Connector* which collected I/O data from an I/O characterization tool to create a new timeseries that allows for further insights into I/O behavior and patterns. Five key components were used to develop this design which were the I/O event data (Darshan), data collection (LDMS Streams), storage (DSOS), analysis

(Python modules) and visualization (Grafana). These results of this design proved to enhance both LDMS and Darshan tools as well as create new insights and provide a better understanding to application I/O performance and behavior.

The next steps are to further expand the *Darshan-LDMS Connector* and it’s capabilities by including more I/O event data and demonstrating advanced insights into correlations between I/O performance and system behavior. However, an issue with increased overhead does arise when collecting data from short but intensive I/O applications. To address this issue, we will include an option for users to decide the rate of I/O events that the *Darshan-LDMS Connector* will collect and format into a json message. Having this option will allow users who are running intensive I/O applications to still be able to analysis runtime timeseries data of their application without concern of the runtime performance.

The *Darshan LDMS Integration* will be available as an optional “module” plugin to the Darshan tool so their users can collect timeseries data without increasing memory impact on compute nodes and better understand their applications I/O performance across HPC systems and clusters.

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