ATLAS DataFlow Infrastructure: recent results from ATLAS cosmic and first-beam data-taking

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Abstract. The ATLAS DataFlow infrastructure is responsible for the collection and conveyance of event data from the detector front-end electronics to the mass storage. Several optimized and multi-threaded applications fulfill this purpose operating over a multi-stage Gigabit Ethernet network which is the backbone of the ATLAS Trigger and Data Acquisition System. The system must be able to efficiently transport event-data with high reliability, while providing aggregated bandwidths larger than 5 GByte/s and coping with many thousands network connections. Nevertheless, routing and streaming capabilities and monitoring and data accounting functionalities are also fundamental requirements.

During 2008, a few months of ATLAS cosmic data-taking and the first experience with the LHC beams provided an unprecedented test-bed for the evaluation of the performance of the ATLAS DataFlow, in terms of functionality, robustness and stability. Besides, operating the system far from its design specifications helped in exercising its flexibility and contributed in understanding its limitations. Moreover, the integration with the detector and the interfacing with the off-line data processing and management have been able to take advantage of this extended data taking-period as well.

In this paper we report on the usage of the DataFlow infrastructure during the ATLAS data-taking. These results, backed-up by complementary performance tests, validate the architecture of the ATLAS DataFlow and prove that the system is robust, flexible and scalable enough to cope with the final requirements of the ATLAS experiment.

1. Introduction
ATLAS [2] is one of the four experiments installed at the LHC, CERN, Geneva, Switzerland. In preparation for the first LHC beams, and following the LHC accident, the ATLAS experiment went through a phase of continuous cosmic data-taking. This period started on August 1st 2008 and lasted 3 months. In the present paper we report about the usage of the ATLAS Trigger and Data Acquisition, in particular concerning the data-flow components, during the 2008 ATLAS data-taking phase.

2. ATLAS Trigger and Data Acquisition (TDAQ)
The ATLAS Trigger and Data Acquisition (TDAQ) [3] system is responsible for the selection and the conveyance of interesting physic data, reducing the initial LHC frequency of 40 MHz

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to a rate of stored events of $\sim 200$ Hz. In its final configuration, the TDAQ system will include $O(20k)$ applications running on roughly 2000 nodes interconnected by a multi-stage Gigabit Ethernet network.

The ATLAS TDAQ is organized in a three-level selection scheme (Fig. 1), including a hardware-based first-level trigger and a software-based second and third level triggers. In particular, the second-level trigger operates over limited regions of the detector, the so-called Region-of-Interest (RoI). The last selection step, the Event Filter, deals instead with completely built events. The TDAQ system is based on in-house designed multi-threaded software, mostly written in C++ and Java and running on a Linux operating system.

3. DataFlow Infrastructure

The DataFlow infrastructure is the TDAQ sub-system responsible for the collection and the conveyance of event data from the detector front-end electronics to the mass storage. This purpose is fulfilled by several dedicated applications, which can be classified based on the two different networking domains that form the TDAQ networking infrastructure [4].

In the first domain, the so-called Data-Collection network, the system is based on a push-pull architecture. The Read-Out System (ROS) in fact buffers and serves over the network the data fragments received via $\sim 1600$ fibers from the front-end. The ROS is composed by roughly 150 PCs housing custom PCI boards. The ROS clients are the Event Builder (EB) and the second level trigger (LVL2). In the final running conditions, the LVL2 farm [5], which will include up to 500 nodes, will analyse partial event data fetched from the ROS PCs, reducing the initial trigger rate of 75 (100) kHz to $\sim 3.5$ kHz. The ROS PCs will experience a LVL2 request rate as big as 12 kHz and an aggregated throughput of $O(3$ GB/s). Upon the LVL2 acceptance, the events are fully built by the Event Builder [6]. Given the predicted average event size of 1.5 MB, the EB, which includes $\sim 100$ building applications, must sustain a total throughput of $\sim 5$ GB/s.

The EB moreover decouples the Data-Collection network from the Event Filter network, the second networking domain of the DataFlow infrastructure. The building applications in fact buffer the fully built events and serve them to the third triggering level, the Event Filter.
Table 1. Available TDAQ resources during the 2008 ATLAS cosmic data-taking period. (\*\*)The presently installed processor racks have a double network connection which allows to use them either as LVL2 or EF. (\*\*\*)The EB farm can run up to 94 independent building applications.

| Installed nodes (2008) | Final farm size |
|------------------------|-----------------|
| Read-Out System        | 149             |
| LVL2                   | 850* 500        |
| Event Builder          | 63** 63         |
| Event Filter           | 850* 1600       |
| SFO                    | 5 6             |

(EF). On each EF node a DataFlow application (EFD) is responsible for the data handling and distribution to the selection processes. Since the EF farm will include up to 1600 computing nodes, the connection between the EB and EF is organized in sub-farms, containing subsets of the building applications and processing racks. Such a configuration allows for flexibility and redundancy in the usage of the available resources. The last elements of ATLAS TDAQ system are the data-logging nodes, called Sub-Farm Outputs (SFO), where the accepted events are temporarily stored on local disks while waiting for the transmission to the mass storage. The SFO farm [7] must be able to handle a I/O rate of 300 MB/s and to buffer up to 24 hours of data-taking results, in order to decouple the on-line system from the off-line mass storage.

As shown in Table 1, by the summer 2008 a large amount of TDAQ resources were already deployed in order to support the initial data-taking. In particular the full ROS, EB and SFO farms were available.

3.1. Routing and Streaming
The ATLAS DataFlow infrastructure also provides routing and streaming capabilities as well as support for optimized handling of calibration data. In the ATLAS TDAQ framework, streaming is defined as the on-line classification of raw events based either on their physics content or processing results. The event classification is normally performed by the trigger software, while the SFOs are responsible for the actual streaming of the data into different data files. The other DataFlow applications are anyway stream-aware in order to implement a correct routing of the events. Routing in fact enables the optimization of the event paths in the on-line system, allowing resource savings.

3.1.1. Partial Event Building A major feature provided by the DataFlow infrastructure, combining the routing and streaming capabilities, is the so-called “Partial Event Building” (PEB). For detector calibrations often only a subset of the full event data is needed. Being able to collect and transport only such a subset allows to sustain higher calibration rates and to reduce the on-line and off-line bandwidth and storage volume requirements. In the ATLAS TDAQ system, dedicated LVL2 calibration algorithms select events interesting for detector calibrations, defining the needed data subsets. The EB, being based on a pull protocol, is then able to build a partial event, which is forwarded to the data-logging nodes, skipping further processing steps.
4. Cosmic data-taking

In preparation for the first LHC beam in September 2008, the ATLAS experiment started a continuous cosmic data-taking session on August 1st. The data-taking period lasted, beyond the first LHC beams, till the end of October.

This long operation period provided an invaluable feedback to the DataFlow infrastructure in terms of functionality, stability and efficiency. In fact roughly 550 millions of events have been collected and handed over the off-line facilities by the ATLAS DataFlow infrastructure (Figure 2). As shown in Figure 3, DataFlow infrastructure errors only affected 0.4% of the collected data volume. Most of these errors (63%) are actually due to a single, major, system-wide accident. The remaining fraction of DataFlow-tagged errors have been mostly caused by crashes and timeouts of the trigger processors. For these cases, in fact, the data-flow applications demonstrated to be robust enough to preserve the event data and either restart the trigger analysis or forward the data to the off-line facilities for later analysis.

Besides exercising the system operation, the cosmic data-taking, due to its peculiar requirements, also contributed to a better understanding of the data-flow component integration and configuration. In fact, despite the typical cosmic LVL1 trigger rate of $\sim$200 Hz, the data-flow had to handle event sizes ranging from $O(100 \text{ kB})$ to $\sim$15 MB. The event size is in fact strongly influenced by the contributing sub-detectors and especially by their configuration in terms of data-compression and zero-suppression. Therefore, from the performance and throughput point
Figure 4. Throughput (in MB/s) of the SFO farm during the 2008 data-taking period. Screen-shot of the networking monitoring tool.

of view, only the SFO farm has been regularly used at the design working point and even beyond. The full farm is in fact able to sustain an aggregated I/O rate of 550 MB/s (Figure 4): roughly 1 PB of data, distributed over 650 thousand files, have been handled by the farm during the data-taking period.

The remaining data-flow components, instead, have been loaded well below their expected working points. Complementary, high-rate, performance tests have been carried out in order to back-up the data-taking utilization results (Section 5). On the other hand, the collection and conveyance of very large events required the development of dedicated system configurations and the improvement of the component robustness against truncated or corrupted data.

Finally, during the cosmic data-taking we also had the first widespread usage of routing and streaming capabilities. Figure 5 shows the typical set of data streams during a cosmic run: physics data are subdivided mostly on the basis of the LVL1 trigger type. Moreover, calibration and problematic events are kept separated, allowing a easier and faster handling of the different data-types by the offline facilities.

The partial event-building was also part of the cosmic trigger menu: Figure 6 shows the event-size distribution, as seen by the Event Builder. The small peak at about 200 kB represents

Figure 5. Online histogram produced by the SFOs showing the relative populations and the overlaps of the different data streams.
Figure 6. Online SFI histogram produced during an ATLAS cosmic run. The plot shows the event size distribution as seen by the Event Builder. The large peak at 5.1 MB represents fully build physics events, while the small peak around 200 kB stands for partially built calibration events.

partially built calibration events, which are 25 times smaller the corresponding full event (~5.1 MB).

5. DataFlow Performance
Regular TDAQ tests are performed in order to assess the system performance and scalability, beyond the cosmic data-taking working point, and to evaluate new software releases. The current limited hardware resources do not permit to reach the high-luminosity running conditions. However, the system size already allow to significantly probe the scalability of the DataFlow hardware and software infrastructure.

Recently the trigger menu dedicated to the initial LHC luminosity of $10^{31} \text{cm}^{-2}\text{s}^{-1}$ has been tested loading a representative simulated data sample into the ROS PCs. The system has been able reach a LVL1 trigger rate of 60 kHz, even if the trigger menu is optimized for 10 kHz only, therefore including loose thresholds and cuts. The rate was limited by the ROS processing power: in fact some PCs were experiencing request rates up to ~30 kHz (Figure 7), where in the final running conditions at most 12 kHz are foreseen. The EB was driven by the LVL2 at a rate of 4.2 kHz corresponding to throughput of 3 GB/s due to the small event size of the data sample (800 kB).

The results of the trigger menu tests are backed-up, in the Event Filter area, by independent tests of the EB-EF scaling properties. The EB, when not sending data to the Event Filter processors is able to almost double the throughput required in the design working point (Figure 8). In fact, each building application can saturate a Gbit link, with an effective data rate of 3000 MHz.

Figure 7. Distribution of the ROS request rate per sub-detector. Simulated data were loaded into the ROSs, which were serving event fragments to the LVL2 and the Event Builder.
rate at the application layer of 114 MB/s, almost independently of the underlying network protocols. When the output to the Event Filter is enabled, the additional data handling load only introduces a performance penalty of ~10%, which corresponds to a maximum throughput of 105 MB/s per building applications. On the other hand, the currently installed Event Filter network bandwidth is smaller than the Event Builder one. Therefore the EB farm cannot be saturated and the maximum aggregated throughput into the EF is limited to 6 GB/s, which is anyway larger than the design working point value.

6. Conclusions
Most of the ATLAS TDAQ DataFlow sub-systems completed the deployment and commissioning phase in preparation for the ATLAS 2008 cosmic data-taking. This data-taking period provided a benchmark for the integration of the different DataFlow components, their monitoring capabilities, stability and efficiency. Major features, beyond the basic data conveyance, like partial event building, have been widely used during the data-taking. Moreover, the data-flow software demonstrated to be robust and flexible enough to cope with non-standard and extreme running conditions. Due to the special working point of the cosmic data-taking, the DataFlow performance have also been evaluated in dedicated high-rate tests. Based on the current achievements, the ATLAS DataFlow seems to be powerful and scalable enough to fulfill the final ATLAS performance requirements.

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