Status and Prospects of the data acquisition systems of the Large Hadron Collider experiments

Niko Neufeld
CERN, Geneva, Switzerland
E-mail: niko.neufeld@cern.ch

Abstract. Data Acquisition systems are an integral part of an LHC experiment. They are designed to meet the needs set by the physics programme. Despite some very interesting differences in the architecture, the unprecedented data-rates expected at the LHC have led to a lot of commonalities among the four large LHC data acquisition systems. All of them rely on commercial local area network technology and more specifically mostly on Gigabit Ethernet. They transport the data from the detector readout-boards to large farms of industry standard servers, where a pure software trigger is run. These four systems will be reviewed, the underlying commonalities will be high-lighted and interesting architectural differences will be discussed. In view of a possible LHC upgrade we will briefly discuss the suitability and evolution of the current architectures to fit the needs of SLHC.

1. Introduction
The DAQ systems each of ALICE, ATLAS, CMS and LHCb have been designed for the specific needs of their specific experiment. Now that they are deployed and have already passed a first functional test in extensive cosmic runs and before they will face the first real collision data is a good moment to review the convergence and differences between the architectures, common challenges, problems and solutions. The author has been fortunate to be one of the co-designers of one of the large DAQ systems (LHCb) and so I cannot resist to devote some space to a general reflection on the architectures. For the operational matters, which are now occupying all the Online/DAQ teams, two topics have been selected, which illustrate many of the issues the experiments are currently worrying about. Completeness in listing all the work done in the design and operation of these complex systems has not been attempted and apologies are presented to people, whose work is only summarily acknowledged here in the introduction. In the references recent publications and papers presented in this conference have been preferred, but clearly much of the work is still in progress and in particular performance figures must be taken as snapshots at the time of writing.

2. General features of the LHC DAQ systems
The challenges for the LHC DAQ systems are indeed considerable. The primary beam-crossing rate and the amount of channels are unprecedented\(^1\). There are of course sophisticated first-level trigger systems in hardware, which reduce the original crossing-rate to more manageable

\(^1\) The bunch-crossing rate will be 40 MHz out of which 30 MHz will be filled. Up to 100 hard interactions can be expected and \(O(10^7)\) channels need to be read out
Table 1. Main properties of the LHC front-end links

|                | speed            | # links | receiver DAQ side              | flow-control |
|----------------|------------------|---------|--------------------------------|--------------|
| ALICE DDL      | 200 MB/s, full-duplex | 400     | custom PCI-X card in PC         | yes          |
| ATLAS SLink    | 160 MB/s         | 1600    | custom PCI-X card in PC         | yes          |
| CMS SLink-64   | 200 - 400 MB/s   | 500     | interfaces to commercial NIC card | yes          |
| LHCb Glink / GOL | 200 MB/s      | 400     | interfaces to custom-build NIC card | no           |

frequencies. But the physics challenges at the LHC are such that only sophisticated software running on a general purpose CPU has any hope of efficiently finding the rare and interesting events.

2.1. Front-end links
What the DAQ “sees” of the detector is primarily the front-end link. The characteristics of these links will have an important influence on the design, the size and the number of individual components. Table 1 shows a comparison of the front-end links. Most of them use fibre-optics. CMS uses a relatively short-range (15 m), high-speed, LVDS variant of the standard CERN Slink protocol and LHCb uses copper analogue links for one of its major subsystems. They are all in the $O(1)$ Gbit/s class. Most implement back-pressure via flow-control on the link, but only the ALICE DDL is fully bi-directional, a fact that is exploited frequently in the ALICE system.

2.2. Technological developments
Previous DAQ systems were usually based on a bus-technology of some kind: VME or Fastbus are the most prominent examples from the LEP era and VME is still used in the first stage of data-collection in many systems, most notably the Tevatron experiments. Simple band-width considerations immediately show that bus technologies are unsuitable for acquisition systems of the size of LHC experiments. The only place where buses are left are in the cases where sub-event building is done within a PC, and even there it should be noted that the latest generation of PCI, PCIe, is at the lower, implementation level a switched, point-to-point network. So it can be said that modern DAQ systems are based on point-to-point, serial links and are switched networks.

Also in contrast to previous experiments, where custom transfer protocols had to be developed, this was never seriously considered for the LHC era. Many commercially available local area network technologies have been evaluated. Cost and performance have driven the choice almost universally to Ethernet in its 1 and 10 Gigabit variants. The only notable exception is the first level of the CMS event-building system, where Myrinet is used. It does not seem too daring to predict that this trend will continue and that any LAN-based DAQ will be using Ethernet in the future.

2.3. Architecture
The majority of commercially used network protocols follow the push paradigm. The most prominent examples are Ethernet and IP, but this is also true for example for Myrinet. Data are sent to a specific node or address when the line is clear. Various flow-control mechanisms are in use to ensure that the message can be transferred and received. Higher-level protocols

\[^2\] LHCb has no link-based flow-control, but a global throttle mechanism, using a dedicated unidirectional network.

\[^3\] PCIe preserves the bus-like semantics of PCI.
such as TCP/IP employ sophisticated rate-control mechanisms to avoid packet-loss or the use of lower-level protocol flow-control.

Push-protocols are intrinsically simple protocols, they require very little or no knowledge at the sender about the state of the receiver or the network between them. This allows keeping the input stage of the event-builder simple and minimise the need for buffering in the data-sources (readout-boards). Data can be lost however due to overcommitment along the network-path or due to some unavailability of the destination. The probability for such a loss can be lowered by having sufficient buffering at the critical junctions in the network and at the receiver.

In a pull-protocol the data-sinks drive the data-transfer. The source has to wait for a message from the sink before it can send. This means that buffering is required in the source as well as the capability to handle the communication protocol with the sink. This additional complexity at the input stage results in two advantages:

- Buffering in the network can be kept low, if the sinks can be controlled with respect to each other
- Since the sink determines the transfer, the protocol can be chosen to be most efficient for the sink

Network based DAQ systems must also take a decision on push or pull. It turns out that a pure push protocol is difficult to realise in practise. There are two main reasons for this:

- In case of a missing sink or a broken link data will be lost, because reconfiguring via the control system will be too slow.
- If the source is implemented in hardware (like an FPGA) it is difficult to cope with sinks of variable capacity. Look-up tables and cumbersome approximations are needed to create the right ratio.

Every DAQ system in LHC uses a combination of push and pull. Where push is used it is used either together with flow-control (central, local or implicit by using TCP/IP) or with some form of traffic shaping. In the last stage of the event building the entire detector data are collected into a trigger process for a final selection by the high level trigger algorithms. All systems, except for LHCb, pull the data for this final event-building step.

On a more global scale one of the main differences between the LHC DAQs is between partial and full-readout. ATLAS uses its famous Region of Interest scheme after the hardware trigger, which every experiment has, and which is everywhere based on high $p_t$. In ATLAS the result of the Level-1 trigger seeds the partial read-out of the interesting slice of the experiment. This Level-2 trigger is augmented by on-demand data retrieval capability, so algorithms can potentially access all data within the limits of the overall latency and bandwidth. Clearly this elegant scheme requires a sophisticated protocol.

CMS and LHCb have opted for a more radical approach, which reduces the complexity of the protocol at the expense of increasing the required bandwidth in the readout-network. They read out the entire detector for every positive decision of the first level trigger. After a 3-level hardware trigger ALICE has an optional high-level trigger stage, whose main aim is to reduce the rate to storage at high luminosities, by compressing the event-data and optionally discard them. In standard operation ALICE writes all events which have been selected by the hardware triggers.

The standard parameters of the LHC Trigger DAQ systems can be found in Table 2.

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4 This is advantageous for a large system because the receivers are usually cheap general-purpose servers while the senders are expensive specialised electronics boards
5 Notably remote DMA
6 This argument does not apply when computers are used because the floating point unit can be used. Similarly for very modern high-end FPGAs this can most likely be overcome
Table 2. Basic parameters of the LHC DAQ systems

|                          | ALICE | ATLAS   | CMS      | LHCb     |
|--------------------------|-------|---------|----------|----------|
| # of trigger levels      | 4     | 3       | 2        | 2        |
| Level-1, 2 rate [Hz]     | Pb-Pb $5 \times 10^3$ | L1 $75 \times 10^3$ | Level-2 $3 \times 10^3$ | Level-1 $10^5$ |
|                          | p-p $10^3$ | Level-2 $10^3$ | Level-1 $10^6$ | Level-1 $10^6$ |
| Event size [Byte]        | Pb-Pb $5 \times 10^7$ | $1.5 \times 10^6$ | $10^6$ | $3.5 \times 10^4$ |
|                          | p-p $2 \times 10^6$ | $10^6$ | $3.5 \times 10^4$ | $3.5 \times 10^4$ |
| Readout bandwidth [GB/s] | 25    | 4.5     | 100      | 35       |
| HLT Output [MB/s] (Events/s) | Pb-Pb $1250 \ (10^2)$ | $300 \ (2 \times 10^2)$ | $\sim 1000 \ (10^2)$ | $70 \ (2 \times 10^3)$ |
|                          | p-p $200 \ (10^2)$ | $10^2$ | $10^2$ | $10^2$ |

2.4. Convergence

During the design and development phase a lot of convergence between the different systems has been seen. Industry standard technologies are used wherever possible, local area networks dominate, serial point to point links transport the data. PC servers are the second pillar on which the Online systems rest. Even custom DAQ electronics to receive the readout-links is made to fit in a PC. Generous buffering is used, which is possible because memory in PCs is so comparatively cheap. On the protocol side all systems are faced with a high rate of messages and events. They counter this by coalescing the messages, which reduces the message transport and processing overheads.

Without wanting to belittle the existing differences, the question suggests itself, if one could not have used a single system for all experiments. In the opinion of the author, strictly technically speaking this is true. However it should not be forgotten that the DAQ systems and the people who build and operate them are an integral part of their experiments. The tight fit which is required to best accommodate the various requirements of all the complex sub-systems are best met by a tailored system. Nothing prevents and has prevented the LHC DAQ teams to learn from each other and work together. However these collaborations are rarely “formalised” and thus not as visible as collaborations in other areas.

3. The High Level Trigger farms

Except for ALICE all LHC experiments will need a huge amount of computing power to select the rare physics events out of the data accepted by the first-level trigger. This compute power is deployed as compute farms, which are an integral part of the experiment infrastructure. All the classical problems of large data-centres apply. Lessons had to be learnt by all teams, and in some cases interesting and not-so-common-in-industry solutions have been found.

For comparison some numbers characterising the size are given in Table 3, where also the corresponding numbers for CERN IT are given. In this section a few aspects of the installation and operation of these farms will be discussed.

When it comes to operating systems we will find Linux in the the two main supported CERN flavours (SLC4 and SLC5). Increasingly 32-bit installations are replaced by 64-bit infrastructure. Standard kernels are used wherever possible and there are no hard-realtime operating systems anywhere. Windows machines exist only in parts of the detector control systems, where proprietary drivers mandate the use of this OS.

The servers are typically dual-socket, which offers so far the best price/performance ratio. The systems are rack-mountable either directly or in blade-chassis. The processors are mostly Intel and some from AMD.
Table 3. Key figures for the High-Level-Trigger farms in February 2009

|                  | ALICE | ATLAS | CMS   | LHCb | CERN IT |
|------------------|-------|-------|-------|------|---------|
| # servers        | 81[6] | 837   | 900   | 550  | 5700    |
| # cores          | 324   | ~6400 | 7200  | ~34600 |
| total available power (kW) | ~2000[7] | ~1000 | 550   | 2900 |
| currently used power (kW) | ~250  | 455   | ~145  | 2000 |
| total available cooling power | ~500  | ~820  | 800   | 525   | 2900 |
| total available rack-space (Us) | ~2000 | 2449  | ~3600 | 2200 | n/a     |
| CPU type(s)      | AMD   | Intel | Intel | Intel (mostly) | Intel |

6 4-U servers with powerful FPGA preprocessor cards H-RORC
7 available from transformer
8 Powersupply rating
9 Current figure, can be extended.

These farms need a lot of network infrastructure as well, both in the form of core-routers and in the aggregation layer. The equipment chosen follows here the selection of the CERN-IT networking group. The central part of the network, called the “core”, sees (almost) all of the traffic. For this function equipment from Force10 Networks is used. In the racks, connecting directly to the equipment, we will find the so-called “edge” switches. These are chosen from the HP Procurve series.

There is a complex software stack starting from the operating system up to the application layer to be installed and managed on each computer. Various tools are used for this purpose. For system software RPM is the tool of choice, given that a RedHat based distribution is used. Software management [1] is of course not finished with package-installation and removal, so on top of RPMs additional tools are used, some home-made, some using the Quattor suite (www.quattor.org).

The hardware management is relying heavily on the IPMI industry standard. Monitoring of the computing infrastructure (“the fabric”) is done using standard open source software frameworks such as Nagios (http://www.nagios.org) and home-made frameworks such as Lemon or FMC.

One way to make the management of a large number of nodes easier is to operate them diskless. When the OS resides on an NFS server, it is just this image which needs to be updated. This is done by ATLAS and LHCb.

Finally, an interesting question is how to optimise the usage of the considerable resources represented by these farms throughout the course of the year. It is likely that in the coming years the LHC schedule will be more like the traditional running-scenario of CERN accelerator experiments, with an important winter shut-down period of 4 to 5 months. Clearly only a fraction of the online farms are strictly required for the tests and cosmic runs of the system. What can or should be done with the rest of this computing power, which in many cases outmatches that of the largest Tier-1 centres? The LHCb experiment has plans to use its farm for reconstruction. Of course such a scenario has important implications on the availability of system-services, the manpower required etc.

11 Intelligent Platform Management Interface
3.1. A specific challenge with a common solution: cooling

Like any modern data-centre, the event-filter farms are faced with the challenges of cooling and power. In the case of power the standard ways of using special transformers for harmonic loads and very tolerant differential circuit breakers\footnote{Compensatory safety measures have of course been taken.} have been followed to cope with the problems of in-rush current and harmonic distortions by PC power-supplies, whose quality is much inferior to that typically used in HEP electronics.

For cooling a common solution has been developed by all four experiments. Inspired by decades of experience with forced vertical cooling using water-cooled heat-exchangers in the rack, it seemed natural to apply the same idea to the horizontal airflow found in PC racks, namely putting the heat-exchanger with the water somehow at the rear of the racks for the computers.

An extensive search of existing solutions in the market came up with only one industrial solution, which implemented the main idea. However this product was found to be unsuitable for the environment in the LHC experiment areas and in addition suffered from serious technical defects. The impression at the time, confirmed all contacted data-centres in participating institutes, was that this solution had not found any acceptance in data-centres at the time.

Thus the LHC experiments anticipated by several years a development only now slowly gaining territory in the industry at large. The heat-exchanger designed by the experiments has been integrated into the back-door of the racks.

Figure 1 shows an installed rack-cooler door. Detailed measurements have shown that in a carefully closed rack up to 95\% of the dissipated heat can be removed\footnote{Compensatory safety measures have of course been taken.}. Clearly the long familiarity with water-cooling in HEP was important in this development, which elsewhere has been prevented by strong prejudices to have water so close to the servers. This is a particularly nice example of a common solution based on an informal initiative between the experiments.

3.2. Networks

Large farms need also large networks. The networks of the LHC experiments consist of 1000s of Ethernet ports, many 10-Gigabit Ethernet links and hundreds of switches and routers. These networks are very performance critical because they are not only used as high-speed interconnects like anywhere else but more importantly the networks are the main and most important part of the data acquisition. A lot of sophisticated monitoring and performance optimisation has been developed. Most of the infrastructure is 1000 BaseT, that is Gigabit Ethernet over unshielded twisted pairs. Most of the equipment comes from two manufacturers Force10 networks and Hewlett Packard. There are usually several independent, only very loosely connected networks in the experiments: the experiment network used for controls and management, the data acquisition network, the CERN technical and general purpose networks. The first of these is in some cases operated by the CS group of CERN/IT, the second is always operated by the experiment teams themselves, while the last two are again centrally manged by IT. Strict security measures are in place to protect the integrity of the experiment networks. There is a common forum to define policies and exchange experiences called CNIC\footnote{Compensatory safety measures have of course been taken.}.

Apart from Local Area Networks, ALICE\footnote{Compensatory safety measures have of course been taken.} and LHCb also use rather large Storage Area Networks (SAN) based on fibre-channel.

3.3. Problems

The problems encountered during initial operation are almost all related to the scale of the systems. Commercial of the shelves (COTS) hardware is of varying quality. And even relatively large mean time between failure (MTBF) values will cause a noticeable number of failures in a
Figure 1. The rack-cooler door used in the event-filter farms of the LHC experiments.

large system. The CERN purchasing rules\textsuperscript{13} require that the best-price technically compliant bidder is chosen. While this is of course a sound and responsible approach it leads over the years to a tremendous heterogeneity of the hardware, where equipment from over a dozen vendors is in concurrent use. This means many different vendor procedures, warranty providers and operational complexity. For example, in the case of a problem, where a specific device can not boot properly: to whom should the vendor call be addressed? The PC vendor, the network company, the server vendor?

What goes for hardware applies in a similar way to software. In particular, but not only, in the control system, proprietary software must be used, which cannot be easily ported to different operating system versions. This leads to a a large variety of different configurations 32-bit and 64-bit, Windows and Linux in several versions. Firmware like found in the switches or in the board-management controllers used for IPMI is also quite variable, even when in principle standardised. This leads to increased effort in providing and maintaining generic tools and

\textsuperscript{13} This is of course true for many other publicly funded institutions as well.
smooth integration into the overall experiment control systems.

While none of these are insurmountable problems, they all take their cost in terms of manpower needed for operation.

4. Run-control challenges
The moving of data is of course only part of a large data acquisition system. Configuring and controlling these large systems are formidable challenges in their own right.

Tens of thousands of processes have to be started or at least configured at every run-start. Tens of thousands of detector elements need to be initialised properly. During running all these elements have to be monitored, and crashed processes need to be restarted. Of course all this initialisation should be quick, so as not to waste valuable beam time.

Caching, parallelisation, pre-loading are used to speed operations up. Much if not all of the configuration is stored in databases. The database access by many tasks in parallel is therefore a hot-spot and natural starting point for any optimisation.

The run-control systems use a much more varied set of technologies than the readout systems. Industry standards as well as home-grown frameworks and protocols are in use. One will find anything from CORBA, SOAP or DIM for communication, different tools for job-control: CORBA, FMC [5], logging (log4C, log4j, syslog, ...).

A control system in charge of all these hardware and software components needs to group information and organise the states of the various elements in a hierarchical fashion. The controlled entities are represented by state machines. LHCb and ALICE use the SMI++ [6] package14 while ATLAS bases this functionality on CLIPS [7] and CMS [8] has incorporated it into their RCMS framework.

A lot of work has gone into integrating all these systems and in particular in to making them fast. The following Table 4 is of course only a “snap-shot” of what is currently possible for the LHC experiments. All the numbers are quite impressive if one considers the magnitude of the task. The time shown in the table is the time it takes from bringing the un-configured system into a running state. By “un-configured” a warm start is meant where no hardware actually needs to be powered on and all the infrastructure (like the operating system, the job-control daemons, the low-voltage power-supplies ...) is up and running. By “running” we mean that the system is taking data.

Table 4. Time required to get the Online system from an unconfigured to a running state in February 2009

|            | ALICE | ATLAS | CMS  | LHCb |
|------------|-------|-------|------|------|
| Time for warm start | ~ 5 min | ~ 7 min | ~ 5 min | ~ 4 min |
| Limiting factor   | detector FE config | detector FE config | one subdetector FE | one subdetector FE |

Needless to mention that all experiments are working hard to reduce this time, and that these times hold for ideal case, where nothing goes wrong. Bearing in mind the enormous complexity and number of elements in these experiments these numbers are already quite encouraging.

GUIs are an important factor in the user experience. After all the experiments should be able to operate with a minimum of non-expert operators, where it is hard to imagine that anybody could be an expert in all aspects of the operation of such a system. A coherent, easy-to-use access to all aspects of the operation is therefore a big boon. Figure 2 shows the LHCb

14 SMI++ is used by all collaborations in the Detector Control System (DCS)
main run-control panel. Similar GUIs are available for sub-detector operation and access to infrastructure monitoring and operation.

Figure 2. The LHCb main run-control panel implemented in PVSSII

4.1. Databases
Databases have always been important for the operation of large experiments. The LHC DAQ systems rely heavily on databases for keeping track of runs, histograms, conditions and calibration data, hardware inventory and last but not least for the storing different configurations for the DAQ and trigger.

An important user of databases is the PVSSII SCADA program, which is the backbone of
the Detector Control Systems\textsuperscript{15} PVSSII can store the various environmental data acquired in a database. This is called “archiving”. Given the number of various temperature, pressure and other sensors, the aggregated load of this archiving activity can be quite heavy.

PVSS archiving and many other applications rely on an Oracle RAC\textsuperscript{16} infrastructure operated for the experiments by the IT/DM group. Other database managements systems are in use by some experiments: most notably OKS, an object database used by ATLAS to manage their run-control configuration and MySQL used by ALICE throughout their DAQ.

Conditions data are exchanged between the experiments and the Grid sites responsible for working with the experiment data, in particular for reconstruction, using the Oracle Streaming technology.

5. Upgrades
The “staged” start-up and the long R&D phase of the LHC experiments have produced four mature and quite robust systems. So even though the test of reality is still to come, there are now some people, in particular more hardware oriented, available, who have time to think about possible upgrades of the Online systems.

Given the limitless imagination of people for algorithms in the high-level triggers, the event-filter farms will continue to grow until they hit the limits of power and cooling.

Barring unexpectedly high noise-levels or unexpected physics, which would lead to a significant increase in event-size above the safety margins in the network designs, the only factor which could call for a major DAQ upgrade is an increase in the Level-1 output rate. It is clear that only the physics in a few years can tell, if such an increase is needed. Needless to say that this requires completely new electronics on the detector front-ends. This is not such a forbidding problem as it might seem at first, because the inner (solid-state based) detectors, which have the highest numbers of channels and hence of associated readout electronics, need to be replaced after a few years. In any case the network technology in four to five years will have no problem accommodating bandwidth increase in the DAQ.

An interesting case is LHCb, because here it is already known\textsuperscript{17} that a lot of interesting events are lost in the high \( p_t \)-trigger. Depending on the signal this is up to 50\%. The LHCb upgrade\textsuperscript{9} therefore foresees to readout the entire detector at collision rate, i.e. to design a trigger-free DAQ.

Any such DAQ upgrade will require new, more powerful links from the detector, these links will need to be radiation-hard. The GBT\textsuperscript{10} project at CERN wants to create such a link as a common project for all experiments. This link promises also to be usable for DAQ, controls and timing information in both directions. It is too early to say if this link will be universally adopted, but if so clearly the upgraded DAQs will have to design against this link.

6. Conclusions
This paper summarises the status of the LHC DAQ systems approximately six months before they will go finally into operation. Each system has its own merits, all are operated by highly motivated and dedicated crews of experts. The deployment of the event filter farms, as far as it is not completed, will follow the needs of the high-level trigger algorithms, until power, cooling or financial limits are reached. While there are remaining challenges, in particular in the area of run-control, robustness and ease of use by non-experts, in the opinion of the author there is no doubt, that all four systems will perform as they have been designed to do. A testimony to

\textsuperscript{15} The Detector Control System (DCS) comprises what is traditionally called “slow-controls”, including the monitoring of the environment and the general infrastructure such as power, cooling water

\textsuperscript{16} Real Application Cluster

\textsuperscript{17} Because the hard production processes LHCb is using to create its B-events are well described by the Standard Model
this are the impressive amounts of data, which have already been taken, with cosmics [11] as is summarised in Table 5.

|          | ALICE | ATLAS | CMS   | LHCb   |
|----------|-------|-------|-------|--------|
| Events   | $216 \times 10^6$ | $600 \times 10^6$ | $0.4 \times 10^6$ |       |
| Taken from | Jan 2008 | Sep 2008 | Jan 2008 | Jan 2008 |

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