The ATLAS Level-1 Central Trigger System in Operation

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Abstract. The ATLAS Level-1 Central Trigger (L1CT) system is a central part of ATLAS data-taking. It receives the 40 MHz bunch clock from the LHC machine and distributes it to all sub-detectors. It initiates the detector read-out by forming the Level-1 Accept decision, which is based on information from the calorimeter and muon trigger processors, plus a variety of additional trigger inputs from detectors in the forward regions. The L1CT also provides trigger-summary information to the data acquisition and the Level-2 trigger systems for use in higher levels of the selection process, in offline analysis, and for monitoring.

In this paper we give an overview of the operational framework of the L1CT with particular emphasis on cross-system aspects. The software framework allows a consistent configuration with respect to the LHC machine, upstream and downstream trigger processors, and the data acquisition. Trigger and dead-time rates are monitored coherently on all stages of processing and are logged by the online computing system for physics analysis, data quality assurance and operational debugging. In addition, the synchronisation of trigger inputs is watched based on bunch-by-bunch trigger information. Several software tools allow to efficiently display the relevant information in the control room in a way useful for shifters and experts. We present the overall performance during cosmic-ray data taking with the full ATLAS detector and the experience with first beam in the LHC.

1. Introduction
The ATLAS experiment is one of the four large experiments at CERN’s Large hadron Collider (LHC). It will be exposed to proton-proton collisions at the centre-of-mass energy of 14 TeV with a bunch spacing of only 25 ns. A three-level trigger system selects interesting events and cuts down the initial rate of 40 MHz to about 75 kHz at Level-1, to about 3 kHz at Level-2, and to about 200 Hz at the final stage. The first-level trigger is based on custom-built electronics and synchronously – at 40 MHz – processes trigger information from the calorimeters and muon trigger detectors.

The Level-1 Central Trigger (L1CT) system [1], see figure 1, is the last stage of processing in the first-level trigger: the Central Trigger Processor (CTP) reduces the trigger information to a single bit, the Level-1 Accept Signal (L1A), using programmable logic applied onto the various trigger input signals: muon, electron/photon, tau/hadron and jet multiplicities, as well as event energy information and individual signals from dedicated detectors in the forward region. The Muon-to-CTP-Interface (MUCTPI) collects muon trigger information from the 208 trigger sectors and sums up multiplicities of 6 different transverse-momentum thresholds which are passed to the CTP. The CTP also receives timing signals from the LHC machine, most notably...
Figure 1. The components of the Level-1 Central Trigger System: Central Trigger Processor (CTP), Muon-to-CTP-Interface (MUCTPI), sub-detector timing receivers (20 links), LHC radio-frequency receiver (RF2TTC) and beam pick-up system (BPTX).

The 40 MHz bunch clock, and distributes them, along with the L1A, to the sub-detectors through the timing, trigger, and controls (TTC) network.

ATLAS commissioning has started in 2005 along with the installation of the detector. Many millions of cosmics events have been recorded so far. In September 2008, data was taken successfully during the period of single LHC beams [2]. The L1CT system plays a key role in the data taking process of ATLAS, in particular during the commissioning phase.

This paper concentrates on the software aspects of operating the L1CT system, with emphasis on cross-sub-detector tasks. Seven examples are given: configuration coherent with the up and down-stream trigger systems, the distribution of timing signals to the sub-detectors, dead-time, luminosity blocks, rate monitoring, alignment of trigger signals, and the handling of per-bunch information.

2. Trigger Configuration

The Level-1 trigger decision in the CTP is formed in a number of steps, whose configuration is programmable via the VMEbus of the system. As illustrated in figure 2, out of the 372 possible trigger input bits, 160 are selected and mapped by switch matrices onto the look-up tables (LUT). The LUTs produce 256 trigger conditions, including internal triggers (random and bunch crossing triggers). Ternary content-addressable memories (CAMs) combine them to form 256 trigger items, which can be individually pre-scaled by counter-based 24-bit pre-scalers. The veto block applies dead-time and allows for masking, before the final logic OR yields the L1A.

A coherent configuration between all Level-1 trigger components and the High-Level Trigger is ensured using an XML description of the full trigger definition. A compiler, written in C++, translates part of this XML description into hardware configuration settings that can be loaded into the CTP. The whole configuration, including the compiled hardware files, is held in the Oracle trigger database. The trigger configuration is downloaded to the hardware during the configuration process and is immutable during a run; only pre-scales and the bunch trigger composition can be changed on luminosity block boundaries (see Section 5).
3. Distribution of Timing Signals

The CTP receives timing signals from the LHC – the 40 MHz bunch clock and a turn pulse (ORBIT) – and fans them out to the sub-detectors along with additional signals, most importantly the L1A. The distribution is done through a tree-like network: the Trigger, Timing and Controls (TTC) network (see figure 3). The signals are received by common receivers, which consist of one Local Trigger Processor (LTP) module per TTC partition. A TTC partition is an independent TTC distribution sub-tree, which feeds either a whole or an integral part of a sub-system and can be operated in stand-alone mode, without using the CTP. In stand-alone mode, the LTP plays the role of the CTP.

Several LTP modules can be used in daisy-chain, controlled by the first LTP in the daisy-chain, indicated in the figure as horizontally arranged LTP modules. LTP-interface (LTPi) modules allow for parallel connections between sub-detectors, so that certain combinations of sub-detectors can operate independently of the CTP, which is available for other sub-detectors. Such parallel connections can be seen in the figure as vertically connected LTPi modules; they are connected in a loop which allows any partition to control the other partitions downstream. The TTC receivers are configured and controlled by common software, which operates within the ATLAS Trigger-DAQ on-line framework and ensures coherent configuration, control and monitoring. It includes a conversion of TTC signals to TCP (Transmission Control Protocol) messages that can trigger a standard slice of the ATLAS data acquisition for sub-detector stand-alone runs without the need of the Level-2 trigger system.

4. Dead-time

The CTP is the only place in ATLAS where dead-time is applied – time when valid L1A signals are vetoed. There are two types of dead-time: preventive dead-time and dead-time through a throttling signal (busy signal) from the data-acquisition. The preventive dead-time is needed to protect the sub-detector front-end derandomiser buffers from overflowing. It is programmable in the CTP; typical settings are at least 4 dead bunch crossings after each L1A and on average
not more than 8 triggers in 80 microseconds.

Each sub-detector TTC partition collects the busy signals from all its read-out drivers and feeds it back to the CTP through its TTC link (see figure 3), but in opposite direction to the timing signals. The CTP collects these busy signals and combines them with the logical OR of its own busy signals and the dead-time. The result of this combined veto signal is applied to the trigger items in the veto-block, see figure 2. It is important that at every node in the busy tree, the correct busy signals are taken into account: only busy signals that correspond to enabled detector parts that take part in the combined read-out. The correct busy masks are automatically determined from a database description of the busy tree cabling and the enable/disable state of every component. It is possible to disable busy read-out parts during an on-going run, if they are busy for longer than a time-out parameter, which can be individually configured for each sub-system. The disabling mechanism can be applied either automatically or manually by operator intervention. In both cases, the conditions database is updated to reflect the disabled read-out parts. Figure 4 shows a graphical application that displays the busy status in the CTP: the busy percentage of the 20 TTC partitions linked to the CTP as well as busy signals coming from the Level-2 trigger and the CTP itself. This display allows to quantify the individual sub-detector’s contribution to the overall dead-time and is therefore an important operational tool in the ATLAS control room.

5. Luminosity Blocks

Luminosity blocks split an ATLAS run into smaller time intervals of length of the order of minutes. They are the time quantum of stable data taking for luminosity determination, data quality, and related monitoring processes. In a typical cross-section measurement, the cross-section times branching ratio \( (\sigma \cdot BR) \) of a process can be calculated by the number \( N \) of background-subtracted signal events, divided by the efficiency \( \epsilon \) and the integrated luminosity

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\sigma \cdot BR = \frac{N}{\epsilon \int dt d \cdot p \cdot L}
\]
The term for the integrated luminosity consists of the integral over luminosity blocks $dt$ of good data quality and known luminosity $L$, dead-time corrections $d$ and pre-scale corrections $p$.

The CTP is an important system in distributing the luminosity block number through ATLAS and providing meta-data for the luminosity block, dead-time and pre-scale corrections. It receives a luminosity block command, which is issued from run control based on configurable criteria such as time, number of recorded events, and change in detector and read-out conditions. The new luminosity block number is injected into its trigger and read-out data, through which it becomes visible at the second level of the trigger system and becomes part of the event header during event building. The CTP records start and stop time for each luminosity block in the conditions database, which is important for calculating the term $dt$, but also for translating between the two specifications of the interval of validity in the conditions database: timestamps and pairs of run number and luminosity block number. It also records dead-time and pre-scale corrections to the conditions database per luminosity block.

6. Rate Monitoring

Rate monitoring inside the Level-1 trigger system is important for trigger diagnostics in order to ensure stable trigger conditions and spot hot and dead channels. In the MUCTPI, the input rates of each sector are measured as well as the output rates of the muon multiplicities. In the CTP, the input rates are measured as well as the rates of each trigger item before and after pre-scale and veto, which are used for dead-time and pre-scale corrections. In addition, the trigger rates are monitored per bunch crossing identifier for each of the trigger bits, see figure 8 in the following section.

These rates are constantly monitored at all stages of the L1CT system, published to the Information Service [3] and logged in the conditions database. Generic and specific viewing tools exist to retrieve the data and visualise it in a suitable manner.

![Figure 5. Graphical display to visualise the muon input rates (simulated data) of the MUCTPI.](image)
Figure 5 shows the example of displaying the rates of the 208 different muon trigger sectors as they are received by the MUCTPI. They are displayed according to their geometrical position in a 'rolled-out' detector layout in order to facilitate their interpretation. In figure 6, rates of trigger signals from the beam pick-ups [4] (BPTX), minimum-bias trigger scintillators (MBTS) and the luminosity detector (LUCID) are shown over time, during a period of single beam of the LHC in September 2008, in which a proton bunch was injected every 40 seconds and made several turns around the LHC without RF-capture.

7. Timing Alignment of Trigger Signals
For a proper functioning of the Level-1 trigger processing, it is important that all trigger signals, which come from different sub-detectors and from different regions of ATLAS, arrive at the CTP at the same time. There are two methods of measuring the time mis-alignment of trigger signals that allow their alignment by adjusting the individual delays at the input of the CTP or MUCTPI. The first method makes use of the enlarged read-out window of the CTP: upon each L1A, the trigger bits in the CTP are read out in a window of up to 63 bunch crossings around the L1A. Analysis of this data allows the comparison of the timing of one trigger bit with respect to others. Figure 7 shows the trigger bits per bunch crossing number of events triggered by the beam pick-ups (BPTX). The timing of the MBTS, the forward muon trigger chambers (TGC) and selected Level-1 calorimeter trigger items (Tau5, J5, EM3) are shown, before timing alignment. Small offsets and spreads are observed for the MBTS and the Level-1 calorimeter;
information that was subsequently used to align the timing further. For the TGC, a two-peak structure is observed, corresponding to the two end-cap sides that are 4 bunch crossings apart. The right peak at bunch crossing number 5 corresponds to downstream timing, which is close to collision timing.

The second way of timing alignment is based on trigger rate monitoring per bunch crossing identifier. The top part of figure 8 shows the trigger rates, normalised to one, for each trigger bit (vertical axis) and each bunch crossing identifier (horizontal axis). The figure shows rates from simulated data with mis-aligned triggers in the presence of background. The LHC nominal bunch structure with its 12 SPS batches and the long abort gap at the end of the bunch train is visible in the trigger rates and therefore can be used to time-align the trigger signals with respect to one another. The bottom part of the figure zooms into the region of the start of the bunch train for a small number of trigger inputs, including the beam pick-up signals (trigger bits 36 and 37). Their perfect efficiency and purity gives a sharp pattern of the bunch structure and their simple timing allows them to be used as absolute beam reference for the bunch crossing identifier. The mis-alignment of each trigger bit can be seen by their offset with respect to the beam reference signals.

8. Handling of Per-bunch Information
The LHC will collide a large number of bunches: 2808 under nominal conditions. The large number of bunches and the large amount of per-bunch information from the LHC and ATLAS requires a software framework for handling per-bunch information on-line. The CTP alone produces 160 quantities of per-bunch information, the previously mentioned trigger bits, and the MUCTPI produces input rates per bunch crossing for each of the 208 trigger sectors.
A software monitoring framework was developed which receives per-bunch information every few seconds from the LHC and ATLAS, applies configurable algorithms on it, publishes the result on-line, and stores it to the conditions database. This framework is used for on-line adaptation of Level-1 bunch crossing triggers to the beam structure, for the timing of trigger inputs, for the calculation of the on-line luminosity, and for general beam background studies.

9. Summary
The L1CT is a key system for data-taking in ATLAS. It has many tasks to fulfil which span across sub-detector boarders: coherent trigger configuration, distribution of timing signals, dead-time configuration and monitoring, luminosity blocks, rate monitoring, timing alignment of trigger signals, and on-line handling of per-bunch information. The system has been successfully used in runs with cosmic rays and single beams and is in good shape for collisions.

References
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