AN UPGRADED ATLAS CENTRAL TRIGGER FOR 2015 LHC LUMINOSITIES

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Abstract

The LHC collides protons at a rate of 40 MHz and for each collision, the ATLAS detector produces ∼1.5 MB of data. The ATLAS trigger system is implemented in three levels and selects only the most interesting collision events to reduce the event storage rate to about 400 Hz. The first level is realized in custom electronics modules and reduces the input rate to ∼75 kHz with a decision latency of ∼2.5 us. Based primarily on information from calorimeters and muon trigger detectors, the Central Trigger Processor (CTP) produces the Level-1 trigger decision. After a very successful first run, the LHC is now being upgraded to operate with increased luminosity and a center-of-mass energy of up to 14 TeV. To cope with the new conditions, the Level-1 trigger system will have to perform a more refined selection in order to not lose interesting physics data, while keeping the total Level-1 rate below 100 kHz. In the following, the current Level-1 Central Trigger system will be reviewed, the motivation for its upgrade will be outlined and the plans for how to meet the requirements for post-2014 physics runs at the LHC will be described.

INTRODUCTION

The Large Hadron Collider (LHC) [2] collides bunches of protons at rate of 40 MHz. To study the most interesting proton collisions, the ATLAS experiment [3] has a trigger system that selects a few hundred collision events per second for further analysis offline. As illustrated in Fig. 1, the trigger system consists of three levels which sequentially refine the selection. The hardware-based Level-1 trigger system uses reduced-granularity detector data to bring down the rate to at most 75-100 kHz, after which the Level-2 trigger and Event Filter perform the final selection by applying algorithms implemented in software on more detailed event information.

The Level-1 trigger is based on custom electronics modules and operates synchronously with the LHC collision frequency. Since the sub-detector data are kept in on-detector pipeline memories, the latency is limited to 2.5 µs. The system can be divided into three parts: the calorimeter and muon trigger processors and the central trigger processor (CTP). The CTP will be discussed in some detail in the following sections, but in summary it is responsible for forming the decision and generating the Level-1 Accept (L1A) signal by applying programmable criteria to the signals received from the Level-1 trigger detectors.

The calorimeter trigger processors apply algorithms implemented in hardware to find jet, e/γ and τ candidates, and also estimate the total deposited energy, its transverse component and the missing transverse momentum. These

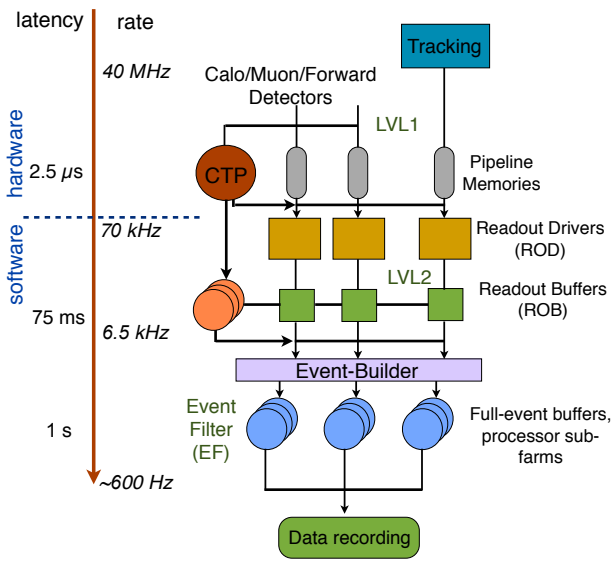

Figure 1: Overview of the trigger and data acquisition system in ATLAS.

calculations are done by processing the analog sums of the signals in so-called trigger towers from the electromagnetic and hadronic calorimeters, each typically covering an $\eta \times \phi$ region of 0.1×0.1. For each event, the observed candidate multiplicities passing various energy thresholds are reported, together with the energy-sum thresholds which were passed.

Two types of fast muon trigger detectors are used in ATLAS: resistive plate chambers cover the barrel region ($|\eta| < 1.05$) while the endcap and forward regions ($1.05 < |\eta| < 2.47$) are instrumented with thin-gap chambers. The muon trigger electronics identify muon candidates by looking for patterns of hits resembling those expected for muons emanating from the interaction point. Due to the bending of their trajectory in the magnetic field, the p_{T} of each candidate is estimated using six programmable thresholds.

Additional trigger input signals to the CTP come from beam pick-up detectors, minimum-bias trigger scintillators, the zero-degree calorimeter, luminosity detectors and beam condition monitors.

When a L1A signal is issued by the CTP, the read-out of all sub-detectors is triggered. The Level-2 trigger system receives Region of Interest (RoI) data signalling from where in the detector higher-granularity data should be re-

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trieved to further inspect candidates seen by the Level-1 trigger systems. By applying fast algorithms implemented in software, the rate is reduced by the Level-2 trigger to a few kilohertz. Finally, the Event Filter uses the complete event information and carefully reconstructs physics objects using algorithms similar to those used in the offline analysis to take the final trigger decision, reducing the rate of events written to disk by another factor of ∼10.

CURRENT LEVEL-1 CENTRAL TRIGGER

The Level-1 Central Trigger consists of two systems, the Central Trigger Processor (CTP) and the Muon-to-CTP Interface (MUCTPI).

The Central Trigger Processor

The CTP system is composed of several custom-built VME electronics boards connected via three dedicated backplanes which are housed in a VME64x chassis. The CTP has two main responsibilities: to form the Level-1 trigger decision, and to distribute it along with the LHC timing signals to all the sub-detectors in ATLAS. It receives multiplicities of trigger objects passing certain thresholds from the trigger detectors and combines the information to decide whether an event should be saved or discarded. The CTP system is shown in Fig. 2 and its modules are described below.

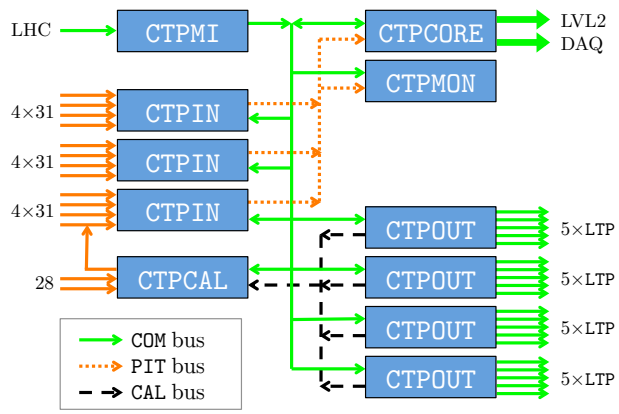

Figure 2: Overview of the Central Trigger Processor.

The CTP Machine Interface (CTPMI) receives the LHC timing signals, i.e. the bunch crossing (BC) clock and orbit signals, issued once per turn the particles travel around the LHC ring. These are distributed to the other modules via the common (COM) backplane.

Three CTP input (CTPIN) boards receive signals from the trigger detectors, synchronize and align them in time, and monitor their individual rates. Every module has four input cables carrying up to 31 trigger signals each. Out of the 372 inputs, 160 are selected using programmable switch matrices and sent over the pattern-in-time (PIT) bus to the other modules.

The CTPCORE board forms the Level-1 trigger decision and issues the L1A. Up to 256 so-called trigger items are formed through logical combinations of the 160 trigger inputs received via the PIT bus using look-up tables and content-addressable memories. After applying prescales and veto, the Level-1 decision is formed as a logical OR of the trigger items. The prescaling functionality allows to only accept every nth trigger of a certain type, allowing collection of only a fraction of events passing high-rate triggers. The possibility to veto triggers is implemented to introduce dead time to prevent the buffers of the sub-detector electronics from overflowing. There are two types of dead-time settings. The simple dead time controls how close two triggered events can be in time. Typically 4 BCs are vetoed after every L1A, corresponding to a minimum spacing of ∼125 ns between two consecutive triggers. The complex dead time is implemented using a leaky-bucket algorithm which effectively limits the average L1A rate to a programmable value, while allowing bursts of triggers of a configurable maximum length. Since the dead time can affect the recorded integrated luminosity, it is monitored by the CTPCORE module and propagated to physics analyses. Together with each L1A, the CTPCORE also generates an 8-bit word describing the type of trigger, indicating for instance whether the trigger is a physics trigger or a calibration trigger. This is used to control the read-out of the sub-detectors, allowing for example more aggressive zero-suppression of calorimeter data for calibration events that are only concerned with inner tracker data for beam-spot measurements. The L1A and trigger-type word are transmitted via the COM plane to the CTPOUT modules.

The four CTPOUT modules handle all communication with the ATLAS sub-detectors. They fan out the LHC timing signals, the L1A and trigger-type word to the local trigger processor (LTP) of the trigger, timing and control (TTC) partitions of the sub-detectors. They also receive BUSY requests from the read-out of the sub-systems. These are combined and propagated back to the CTPCORE which then generates dead time via its trigger veto mechanism in order to prevent buffer overflows.

The CTPCAL module receives calibration requests from the sub-detectors via CTPOUT modules and the CAL bus. It time-multiplexes the requests and feeds them in the form of a trigger input signal to one of the CTPIN modules.

The Muon-to-CTP Interface

The Level-1 Central Trigger is also responsible for summarizing the information about the muon candidates received from the sector logic electronics of the Level-1 muon trigger detectors and propagating this information to the CTP. This is done in the Muon-to-CTP Interface (MUCTPI) system depicted schematically in Fig. 3, which consists of the custom VME modules described below.

The 16 MIOCT modules each process the trigger candidates seen by the muon trigger detectors in an octant of the detector, i.e. an eighth in ϕ of one hemisphere. The boards calculate the local muon candidate multiplicity for each of the six thresholds and remove double-counted candidates from overlapping sectors inside the octant.

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The MIBAK backplane sums the multiplicities for all MIOCTs. It also handles the transfer of the read-out data and distribution of timing and trigger signals to all the modules in the system.

The MICTP module receives the timing and triggers signals and sends the final multiplicities to the CTP.

The MIROD module collects information from the MICTP and MIOCT modules, formats their data and sends it to the Level-2 trigger and the DAQ system via an optical interface.

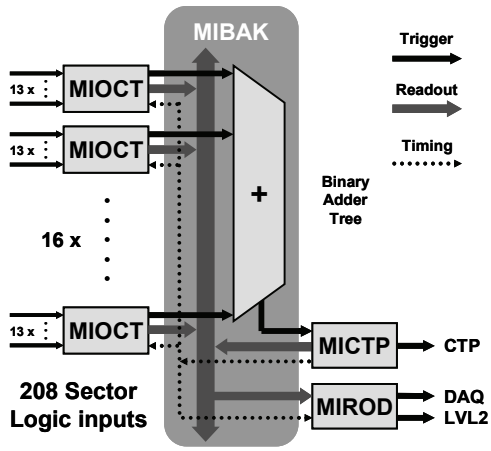

Figure 3: Overview of the Muon-to-CTP Interface system.

UPGRADE PLANS

In this section the motivation for upgrading the CTP and MUCTPI systems is presented, followed by descriptions of the planned upgrades.

Motivation for Upgrade

Starting from 2015, the LHC will be operated at nearly doubled center-of-mass energy compared to 2010-2012, reaching up to 14 TeV. In addition, the luminosity will be increased and exceed 10^{34} cm^{-2}s^{-1}. While these improvements are very welcome since they provide increased statistics for measurements of rare processes and additional reach in searches for high-mass particles, they pose technical challenges. In order to cope with these and future changes without compromising the physics performance, a number of upgrades to the ATLAS sub-detectors and trigger system are foreseen [4, 5, 6, 7]. For the Level-1 trigger, the challenge is to stay within 100 kHz, limited by the maximum read-out rate, without having to significantly raise the trigger thresholds and lose valuable physics data.

Table 1 shows typical resource usage for the CTP during a run in 2012. It is clear that the CTP is operating close to its limits for some of the features. Most notably, all of the PIT bus lines and almost all trigger items are being used, but also some monitoring features are fully exhausted. The primary motivation for upgrading the CTP is to remove these resource limitations to allow more flexibility in using the system during ATLAS operations.

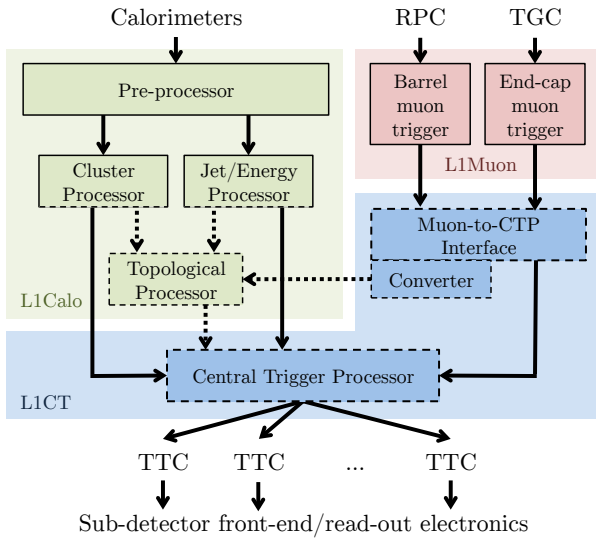

Figure 4: Overview of the upgraded Level-1 trigger system.

Table 1: Typical Usage of CTP Resources During 2012

Feature	Used	Available	Upgrade
CTPIN input cables	9	12	12
PIT bus lines	160	160	320
CTPCORE trigger items	241	256	512
CTPCORE bunch groups	8	8	16
CTPCORE front inputs	0	0	192
Max # bits in OR	6	12	15
Per-bunch item counters	12	12	256
Output cables to TTC	20	20	25

A topological trigger processor, L1Topo, will be introduced. By exploiting the geometric location of the physics objects in the detector, signal and background processes can be separated more efficiently already at the first trigger level. This requires a few changes to the Level-1 Central Trigger systems. Firstly, L1Topo needs calorimeter and muon candidate information. New calorimeter trigger processors are being developed to provide this. After the Phase-I upgrade scheduled to start in 2018, the entire MUCTPI system will be replaced and provide muon input signals to L1Topo with full resolution. However, by modifying the existing system and building an interface module, low-granularity muon information can be made available to L1Topo already in time for Run II starting in 2015. In addition, there must be room in the CTP to receive the L1Topo output signals. Figure 4 shows the upgraded Level-1 trigger system with the added or modified modules and connections indicated with dashed lines.

Hardware Upgrade of the CTP

The upgraded CTP system consists of completely redesigned versions of the CTPCORE and CTPOUT modules and the COM backplane. In addition, the PIT bus will be

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operated at double data rate (80 MHz) making 320 inputs available for forming the trigger items.

The new core module, named CTPCORE+, will feature 192 electrical or optical front-panel inputs, in addition to the electrical inputs via the backplane. These will allow new systems, such as L1Topo, to be connected. Since the introduction of L1Topo will add considerable latency, bypassing the CTPIN module and connecting it directly to the CTPCORE+ compensates partly for this latency increase. In total, 512 trigger inputs will be available, and the maximum number of trigger items is also doubled and matches this number. The number of per-bunch counters is dramatically increased from 12 to 256 which will allow improved monitoring.

The formation of a trigger item also includes bunch group masking. Bunch groups are lists of bunch-crossing identifiers (BCIDs) and are typically defined based on the structure of the beams. For example, the *physics bunch group* defines the BCIDs for which bunches from both beams pass through the center of ATLAS. In the existing system, eight different bunch groups can be defined and AND-ed with the trigger items using the content-addressable memories. With CTPCORE+, 16 bunch groups are available, and they will be applied *after* the formation of the trigger items. This enables monitoring of items before the bunch group requirement, which can be very useful for trigger timing studies and debugging.

A completely new feature is the possibility to operate several trigger partitions in parallel. In addition to the primary partition, up to two secondary partitions can generate independent L1A signals. The prescales, timing settings and trigger menu are common for all partitions, but each partition can select the trigger items which should contribute to the partition's L1A generation. The veto and dead time generation are independent for each partition. This feature is designed to allow for concurrent calibration and commissioning runs. It also simplifies performing calibration runs with timing settings identical to those used during a physics run. Only the primary partition will send event summary data to the Level-2 trigger and the data acquisition systems.

In order to allow sufficient connections to support multiple partitions, the COM backplane will also be updated. The new backplane allows a fifth CTPOUT module to be used, thus providing up to five additional TTC partitions. In order to accomplish these changes a new CTPCOUT+ module will be built. In addition to supporting the updated COM bus and multiplexing the trigger signals from the three partitions, this module will be capable of performing per-bunch BUSY monitoring.

Firmware Upgrade of the MUCTPI

While the MUCTPI will be completely replaced in the Phase-I upgrade of ATLAS and provide full-granularity data for L1Topo, an upgrade of the existing system allows providing low-granularity information already in Run II. The MIOCT modules have two local electrical front-panel outputs which were so far used to signal whether there were candidates observed in the barrel and/or endcap/forward regions. With a firmware upgrade, these local outputs can be over-clocked to send information to L1Topo about the candidates seen in each octant. Implementing this is challenging since the logic resources in the existing FPGAs are limited, and the latency increase must be kept to a minimum. Tests show that eightfold over-clocking allows transmission with a negligible bit-error rate. This allows 16 bits per octant to be transmitted per bunch crossing. After carefully reviewing the physics scenarios that would benefit from such triggers (e.g. B-hadrons decaying to two low-p_{T} muons, lepton-flavor violating τ decays) and comparing the physics performance of several proposed data formats, the preferred solution is to send information about up to two candidates from each octant, giving a resolution in $\eta \times \phi$ of $\sim 0.35 \times 0.1$ and discrimination between three different p_{T} threshold levels.

SUMMARY

Due to the increased luminosity and center-of-mass energy in Run II of the LHC, the ATLAS sub-detectors and its trigger system will undergo upgrades to cope with these changes without compromising the physics performance. The Level-1 Central Trigger systems will be upgraded to increase the hardware resources to allow more flexibility in how the ATLAS trigger can be operated and to add support the new topological trigger processor. In the CTP, the new CTPCORE+ and CTPOUT+ modules along with an updated COM bus will add support for more inputs, outputs, monitoring resources and configuration options. In the MUCTPI, two local outputs of each MIOCT board can provide coarse muon information to L1Topo already in Run II through firmware upgrades.

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