Designing the ATLAS trigger menu for high luminosities

Yu Nakahama for the ATLAS collaboration
CERN, Meyrin, Geneve 1211, CH
E-mail: yu.nakahama@cern.ch

Abstract. The LHC has a bunch-crossing rate of 20 MHz whereas the ATLAS detector has an average recording rate of about 400 Hz. To reduce the rate of events but still maintain a high efficiency for selecting interesting events needed by ATLAS physics analyses, a three-level trigger system is used in ATLAS. Events are selected based on the Trigger Menu, the definitions of the physics signatures the experiment triggers on. In the 2012 data taking since April, approximately 700 chains are used online. The menu must reflect not only the physics goals of the collaboration but also take into consideration the LHC luminosity and the strict DAQ limitations. An overview of the design, the validation and the performance of the trigger menu for the 2011 data-taking is given. During 2011, the menu had to evolve as the luminosity increase from below $2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ to almost $5 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$. Re-designing the menu for the up-coming high luminosity of around $10^{34} \text{cm}^{-2}\text{s}^{-1}$ and large number of collision events that take place per each bunch crossing (pile-up) of around 35 interactions per bunch crossing at $\sqrt{s} = 8 \text{ TeV}$ is described. Initial performance in the 2012 data-taking is also reported.

1. Three-level trigger system and its rate limitations from the data acquisition system

The ATLAS trigger system consists of three levels (Level 1, Level 2 and Event Filter) [1]. A detailed description of the ATLAS detector can be found elsewhere [2]. The trigger system selects events of interest for ATLAS physics analyses with high efficiencies as well as for all detector calibrations and monitoring. At each level, the data acquisition [1], DAQ, system imposes strict limits on the trigger output rates. These limits include data request rates and CPU usage.

The Level 1 (L1) is hardware-based using fast custom-built electronics. Using the coarse data from the calorimeters and the muon detectors as input, the L1 finds Region-of-Interest (RoI), which are the coordinates in $\eta$ and $\phi$ and the passed thresholds of the selected L1 objects. Up to 256 types of combination of one or more objects above a certain threshold, such as muons, electro-magnetic clusters and jets can be used to select events. Event level quantities such as missing transverse energy, $E_T^{\text{miss}}$, are also used in the combinations. $E_T^{\text{miss}}$ is calculated from the vector sum of all energies deposited in the calorimeters, projected onto the transverse plane.

The L1 output rate is limited to 75 kHz in 2012 due to detector readout limits. The Level 2 (L2) and the Event Filter (EF) are software-based high-level triggers. The L2 runs fast dedicated trigger algorithms on a large PC farm. It refines RoIs using detector data at full granularity but reading out small regions around the position of the L1 RoI only. It can also reconstruct tracks and apply topological cuts based on information from two or more RoIs. The maximum L2 output rate is limited to 5 kHz mainly by the data request rate from the event builder [1].
An additional limitation is the L2 data request rate, which varies from 10 to 30 kHz, depending on the sub-detectors. The EF runs offline algorithms on a large PC farm using full event data. The average EF output rate should be kept below 400 Hz due to the limited offline computing resources and storage.

2. The Trigger Chains, Menu and operation strategy

A trigger chain is a sequence of reconstruction or selection algorithms to select a specific signal, with typically 2 to 10 algorithms for each chain. Most algorithms only reconstruct objects in the RoI selected by the L1. A trigger signature is defined as a group of closely related trigger chains, for example Muons, B-physics, or Jets. Each signature has primary, backup, supporting and monitoring chains. In general, all events passing the primary chains are kept because these are for physics signals and should have the highest efficiencies possible. Backup chains have higher thresholds than primary chains and are used in case of an unexpected increase in luminosity or detector malfunction. Supporting chains are used for maintaining or to support a physics analysis (e.g. to extract backgrounds in a data-driven way or to extract the trigger efficiency). Monitoring chains are used to monitor the data qualities (e.g. to check the performance of tracking by the inner detectors). A trigger stream consists of related signatures recorded to the same data-set. ATLAS has four such streams: muon, electron/photon, jet/tau/\(E_T^{miss}\) and minimum bias. Overlap between streams is designed to be minimal, at most 10 to 15 %.

The trigger menu is a full collection of the trigger chains, signatures and streams. In the start of the 2011 data taking, the trigger menu had approximately 300 chains. In the 2012 data taking since April, almost 700 chains are used online.

The ATLAS trigger menus are designed to work in a variety of LHC beam conditions. Typically beams are injected in the LHC, accelerated to collision energy and stored for several hours. During each such LHC fill, which often corresponds to a single ATLAS run, protons are lost from the beam and the luminosity declines. On a longer time scale the LHC luminosity increases as the operational parameters of the LHC are changed to provide maximum luminosity to the experiment.

The operation strategy during a fill is illustrated in Figure 1. Primary chains are kept as stable as possible, not only over a run but over data-taking periods of one month or longer, which is highly desirable for analyses. As the luminosity falls during a fill, additional end-of-fill triggers are enabled to take advantage of available L1 bandwidth. For example, di-muon triggers with \(p_T\) threshold of 4 GeV are enabled only at luminosity less than \(4 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}\).

The rates of supporting and monitoring chains are controlled by accepting only a fraction of events at a fixed output rate. The inverse of this fraction is called a prescale. In practice, the rates are adjusted within the limits during the fill with prescale sets, which are deployed during a run without the need for a stop or a restart.

3. 2011 Menu evolution for luminosity from \(10^{33} \text{cm}^{-2}\text{s}^{-1}\) to \(5 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}\)

In the 2011 data-taking, the trigger menu evolved in three steps according to peak luminosity from \(10^{33} \text{cm}^{-2}\text{s}^{-1}\) to \(3.6 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}\) as shown in Figure 2. Three different menus were deployed in 2011. Only small changes were made in the periods covered by a given menu.

3.1. Design strategy

ATLAS has a large physics program with various final states and a wide range of cross-sections. The major groups of physics analysis are: QCD, electroweak, \(B\) physics, top quark, Higgs Boson, supersymmetry and exotics. All these groups have specific signatures corresponding to trigger chains. During the long winter shutdown between 2010 and 2011, we designed the baseline \(10^{33}\) menu based on physics requirements collected after the discussions with all physics groups. There was especially a strong requirement to keep single lepton triggers down to \(p_T\) values
Figure 1. Illustration of the operation strategy of a trigger menu and the rates as a function of time during a fill. The primary chains, colored in red, are kept un-prescaled during the fill. Partway through a fill, the dedicated additional end-of-fill triggers are enabled. The supporting chains, colored in blue, are kept at a fixed output rate. The total rate, colored in black, is adjusted within the limits by the prescale sets.

between 20 GeV and 25 GeV in order to keep high efficiencies for leptonic decays of W and Z bosons. We decided the allocated bandwidth distribution for signature as shown in Figure 3. This was similar to the 2010 menu which worked at luminosities between $10^{27}$ cm$^{-2}$s$^{-1}$ and $10^{33}$ cm$^{-2}$s$^{-1}$, but was modified to reflect the physics requests.

3.2. Rate prediction
We predicted rates by using the trigger software on special offline data sets called Enhanced-Bias data. These data were collected online with a set of only L1 triggers with low thresholds for trigger menu developments. These predictions, along with estimates of effects of pile-up, were used to evaluate new L1 and L2/EF selections. We also predicted the data requests to the computers in the ATLAS readout system [1] and the CPU consumption by using the same monitoring framework in our offline tests as was used in the online system.

3.3. Performance in the 2011 data taking
The baseline $10^{33}$ menu was successfully commissioned at the start of the run. In the $2\times10^{33}$ menu, we moved to backup chains. In the $3\times10^{33}$ menu, we employed L1 items with tighter selections, higher thresholds or tighter isolation by tracking and many primary triggers with higher threshold by a few GeV than the original primary triggers at the EF. In Figure 4, the history of the average recording rate broken down by physics streams in 2011 is shown. The average rate increased with luminosity, but stayed below 400 Hz maximum, while keeping approximately the same balance between the physics streams.
Figure 2. The peak luminosity in the 2011 data-taking and the menus used for each period. From April to June, the baseline $10^{33}$ menu was used up to a luminosity of $1.3 \times 10^{33}$ cm$^{-2}$s$^{-1}$. From July to August, the $2 \times 10^{33}$ menu was employed up to a luminosity of $2.5 \times 10^{33}$ cm$^{-2}$s$^{-1}$. From September to October, the $3 \times 10^{33}$ menu was employed up to a luminosity of $3.6 \times 10^{33}$ cm$^{-2}$s$^{-1}$.

Figure 3. The allocated bandwidth fraction at the output of the EF for each signature in the baseline $10^{33}$ menu. From top to clockwise, the regions correspond to muon, e/gamma, tau, jets, b-jets, B-physics, $E_{T}^{miss}$ and minimum bias.
Figure 4. The EF stream recording rates in the 2011 data-taking, averaged over the period for which the LHC declared stable beams. From the bottom to the top, the orange band represents the muon/B-physics stream, the red one for the jet/tau/\(E_T^{\text{miss}}\) stream, the green one for the electron/photon stream, and the blue one for the minimum bias stream.

4.2012 Menu design for a luminosity of \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)

We prepared the baseline 2012 menu for a luminosity of \(8 \times 10^{33}\) cm\(^{-2}\)s\(^{-1}\) at \(\sqrt{s} = 8\) TeV taking account the high expected pile-up of around 35 interactions per bunch crossing.

4.1. Design strategy

The general strategy remains unchanged from the 2011 menu, but much improved trigger algorithms and selections are used for the higher luminosity scenarios.

4.2. Rate prediction

We based our prediction on an extrapolation from the 2011 enhanced-bias data sample taken at \(\sqrt{s} = 7\) TeV and a luminosity of \(3 \times 10^{33}\) cm\(^{-2}\)s\(^{-1}\). The prediction of the rates of jet and \(E_T^{\text{miss}}\) triggers are particularly challenging due to non-linear scaling with pile-up, which required additional safety factors.

4.3. Algorithm improvements

For example, we added isolation by tracking for single lepton triggers in order to keep the lowest \(p_T\) threshold below 25 GeV in the offline analysis. We employed improved algorithms at L2 and EF for all signatures as shown in the other proceedings on the ATLAS trigger signatures [3, 4, 5, 6]. We increased thresholds and applied tighter selections for all 2011 primary triggers to match the allocated bandwidth.

4.4. Combined chains

Instead of relying almost completely on single-object triggers, we shifted to combined triggers as much as possible in order to keep as low thresholds as possible. For example, in order to cover exclusive signal topologies of the Higgs Boson and the SUSY particles, we employed the combined triggers which are composed of jet, \(b\)-jet and \(E_T^{\text{miss}}\) or leptons and \(E_T^{\text{miss}}\).
4.5. Saving EF bandwidth-limited triggers
Since the DAQ and the offline storage can handle a higher bandwidth than 400 Hz, we defined several low-priority streams which are not reconstructed promptly but will be kept for reconstruction in 2013. For example, we keep di-muon triggers with \( p_T \) as low as 4 GeV for selecting events containing \( B \)-hadrons un-prescaled and save these to a dedicated \( B \)-physics stream at 70 Hz.

4.6. Performance at \( 2.5 \times 10^{33} \text{ cm}^{-2} \)
The full 2012 menu was successfully deployed in early April of 2012. The rates were as expected at a luminosity of between \( 2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1} \) and \( 5 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1} \) and within the DAQ limits. An example run is shown in Figure 5. Figure 6 shows trigger rates of primary triggers for some signatures in the 2012 menu as a function of luminosity, most of which exhibit a linear dependence on luminosity. In addition, strong pile-up effects leading to non-linear rates were seen for low-\( p_T \) multi-jets and \( E_T^{\text{miss}} \) triggers. After the fine-adjustments for the thresholds of low-\( p_T \) multi-jets and \( E_T^{\text{miss}} \) triggers, this baseline menu is expected to work at luminosity of \( 8 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1} \) and can be extended for the higher luminosity of \( 10^{34} \text{ cm}^{-2} \text{s}^{-1} \).

5. Summary
In order to reduce the trigger rates within the strict DAQ limits as well as to maintain high efficiency of selecting events for all ATLAS physics analyses, we designed Trigger Menus, which specifies which triggers are used during data taking and how much rate a given trigger is allocated.

We designed and deployed the 2011 baseline trigger menu and two evolved menus in the 2011 data-taking, which coped with the significant increase of the LHC luminosity up to \( 3.6 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1} \). In designing a trigger menu, we first determined the allocated bandwidth for each signature through discussions with all ATLAS physics groups. After selection improvements, we adjusted thresholds of un-prescaled primary, backup and supporting trigger chains for each.
signature to match the allocated the bandwidth. Before deployment online, we validated a full menu at a target luminosity by predicting rates extrapolated using a special data set and by estimating data requests and CPU consumptions using the same framework as in data-taking. The performances online were as expected within the DAQ limits.

We re-designed the baseline 2012 trigger menu for the up-coming higher luminosities under a higher pile-up at $\sqrt{s} = 8$ TeV, based on the same strategy from the 2011 menu but with many improvements. From the performance in the early 2012 data-taking, we expect that the baseline 2012 menu will work stably within the DAQ limits up to a luminosity of $8 \times 10^{33}$ cm$^{-2}$s$^{-1}$ and under a high pile-up environment of around 35 interactions at $\sqrt{s} = 8$ TeV. The 2012 menu could be extended for the higher luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ if needed.

6. References
[1] ATLAS Collaboration, “Performance of the ATLAS Trigger system in 2010”, Eur. Phys. J. C 72 (2012).
[2] ATLAS Collaboration, “The ATLAS Experiment at the CERN Large Hadron Collider”, JINST 3, S08003 (2008) 1-437.
[3] A. Oh, The ATLAS Muon Trigger at high instantaneous luminosities, in the proceedings of this conference, (2012).
[4] P. Czodrowski, Triggering on hadronic tau decays in ATLAS: algorithms and performance, in the proceedings of this conference, (2012).
[5] V. Cavaliere, b-jet triggering in ATLAS, in the proceedings of this conference, (2012).
[6] D. Casadei, Performance of the ATLAS trigger system, in the proceedings of this conference, (2012).