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The CMS Level-1 Calorimeter Trigger Upgrade for the Run II of the LHC

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The CMS experiment has implemented a sophisticated two-level online selection system that achieves a rejection factor of nearly 10^5. The first level (L1) is based on coarse information coming from the calorimeters and the muon detectors while the High-Level Trigger combines fine-grain information from all sub-detectors. During Run II, the LHC will increase its centre-of-mass energy up to 13 TeV and progressively reach an instantaneous luminosity of $2\times34\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. In order to guarantee a successful and ambitious physics programme under this intense environment, the CMS Trigger and Data acquisition system must be consolidated. In particular the L1 calorimeter trigger hardware and architecture will be modified. The goal is to maintain the current thresholds (e.g., for electrons and photons) and improve the performance for the selection of tau leptons. This can only be achieved by designing an updated trigger architecture based on the recent microTCA technology. Racks can be equipped with fast optical links and latest generation FPGAs can be used. Sophisticated object reconstruction algorithms as well as online pile-up corrections can thus be envisaged. The plan to consolidate the CMS trigger system will be presented as well as the recent hardware and firmware developments. Algorithms to select efficiently electrons and photons, will also be presented along with the expected performance.

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1. Introduction

The Compact Muon Solenoid (CMS) detector has been designed to study proton-proton and heavy ion collisions produced by the LHC, primarily to search for new particles and physics processes [1]. The search for new physics crucially relies on the performance of the trigger system used to select the most interesting collisions amongst the millions occurring per second [2]. The CMS trigger system is organised in two consecutive steps [3] : the hardware-based L1 trigger utilises coarse energy deposits in the calorimeters and signals in the muon systems to reduce the rate from about 40 MHz to 100 kHz; this is followed by the software-based High Level Trigger (HLT), implementing selection algorithms based on finer granularity and higher resolution information from all sub-detectors in regions of interest identified at L1. The output rate of the HLT is about 300 Hz. The CMS electromagnetic calorimeter (ECAL) provides a precise measurement of the energies and positions of incident electrons and photons for both triggering and offline analysis purposes. The energy measured by the hadronic calorimeter (HCAL) is used to help identify and isolate electromagnetic signals. A set of configuration parameters enables the performance of the electron/photon trigger to be optimized for the wide range of luminosities experienced at the LHC.

Run I of the LHC (2010-2012) already reached an instantaneous luminosity of nearly 8×10^{33} $cm^{-2}s^{-1}$ with p-p collisions at $\sqrt{s}$=8 TeV, 50 ns bunch-spacing and up to about 40 pileup events per bunch-crossing, almost double the design pileup. Nevertheless, the trigger system performed extremely well. Run II will start in Spring 2015 with p-p collisions at $\sqrt{s}$=13 TeV, with 25 ns bunch-spacing and an instantaneous luminosity expected to reach up to $2\times10^{34}cm^{-2}s^{-1}$. The number of pileup events may be up to 70 per bunch-crossing. To avoid a significant increase in triggering energy thresholds, which would be detrimental for physics, an upgrade of the L1 trigger system is required [4].

2. Triggering on electrons and photons at Level-1

The CMS ECAL, composed of a barrel (EB) and two endcaps (EE), comprises 75848 lead tungstate ($PbWO_4$) scintillating crystals equipped with avalanche photodiode (APD) or vacuum phototriode (VPT) light detectors in the EB and EE respectively. In the EB, 5 strips of 5 crystals (along the azimuthal direction) are combined into trigger towers (TT) corresponding to a 5×5 array of crystals in η/ϕ. The arrangement in the EE is similar but more complicated due to the X-Y layout of the crystals. The transverse energy (E_T) measured by the crystals in a single TT is summed into a trigger primitive (TP) by the front-end electronics and sent to off-detector Trigger Concentrator Cards (TCC) via optical fibres. The TCCs transmit groups of TPs to the regional calorimeter trigger (RCT), which in turn combines pairs of TPs into L1 trigger candidates in each region of interest (4×4 TT). The electron/photon identification algorithm is based on a 3×3 trigger tower sliding window. The E_T of an electron/photon candidate corresponds to the central TP of the sliding window summed with the largest deposit in one of its 4 adjacent towers.

3. Consolidating the Level-1 trigger system for Run II

As the LHC restarts and delivers higher luminosity collisions, not be capable of maintaining the thresholds required for the CMS physics programme. For example, a double-electron trigger, with thresholds of 13 GeV and 7 GeV in E_T for the two electrons respectively, had a L1 rate of 5 kHz in 2012; this would increase to about 50 kHz for the expected Run II conditions. A single electron trigger of 18 GeV threshold would give about 40 kHz (compared to 6kHz during Run I). In these intense conditions, the implementation of pile-up mitigation techniques is required already at L1 to reach acceptable performance.

Modern technologies offer an effective solution to achieve these goals. The trigger primitives generated by the detector will be transmitted by newly installed optical synchro-link boards (oSLB: 4.5 to 6.4 Gb/s) replacing the existing copper cables (1.2 Gb/s), to a new system based on the μTCA electronics standard. The system is based on custom designed AMC (Advanced Mezzanine Card) with Xilinx Virtex-7 FPGAs. These FPGAs use 10 Gb/s tranceivers to gather information from the entire calorimeter for each event in one FPGA, where sophisticated algorithms may be implemented. The complete view of the calorimeter will allow the trigger to compute global quantities such as the average energy density that can be used to estimate the pile-up level.

3.1 Level-1 Trigger achitecture revisited for Run II

The new calorimeter L1 system [4] is currently being commissioned. The system is composed of two processing layers instrumented with Virtex-7 FPGAs. The first layer is designed for data formatting and pre-processing. The second layer will be used for object reconstruction and identification. Two types of card form the two layers and are custom made AMC boards [5]. The CTP7 layer-1 cards (Calorimeter Trigger Processor) have a regional view of the calorimeter that can potentially be extended through dedicated connections to the μTCA backplane allowing data sharing across different calorimeter regions. They are used for pre-processing data that only needs a reduced view of the detector. The MP7 layer-2 cards (Main Processor) on the other hand, have access to the full calorimeters at trigger tower level on single FPGAs via a large number of optical inputs. These cards are suitable for running algorithms that need a global view of the detector and enhanced granularity. A total of 36 CPT7 and 12 MP7 has been required to implement the calorimeter trigger to be used in 2016. The current system will nevertheless be kept, with small changes, in order to be able to run both the current and the upgraded systems in parallel during 2015. The duplicated optical outputs of the oSLB will allow the ECAL trigger primitives to be sent to the RCT and to the first layer of the upgraded system. In order to accommodate the new optical links, the Receiver Mezzanine (RM) of the RCT will be replaced by an optical version (oRM). At the end of the commissioning period in 2016, the new trigger will be operational and used as baseline trigger.

3.2 Electron and photon trigger algorithm for Run II

Sophisticated algorithms have been developed in order to benefit from the capabilities offered by the new trigger architecture. Improvements with respect to the current electron and photon reconstruction are: improved energy reconstruction with dynamic clustering of trigger towers; better position reconstruction, with the tower granularity instead of the granularity of an entire RCT region; additional discrimination of electrons (or photons) and jets, based on the shape of the reconstructed clusters and more precise isolation criteria that account for the level of pile-up, without boundaries.

The algorithm is described in Fig. 1. The maximum size of the clusters is limited (at most 8 trigger towers can be clustered) in order to minimize the impact of pile-up energy deposits while including most of the electron or photon energy. An extended region in the ϕ-direction is used to obtain a better containment of the shower since electron and photon showers spread mostly along the ϕ-direction due to the magnetic field. The E_{T} deposited in an isolation region as depicted in Fig. 1 is computed. This isolation region has a size of 5×9 trigger towers excluding the footprint of the e/γ candidate. The threshold is a function of η and depends on an estimator for the number of pile-up interactions in the event. A first version is being tested in the layer-2 cards. The performance of this algorithm is compared with the Run I trigger. The efficiency curves as well as the expected rate are shown in Fig. 3. The turn-on curve obtained is sharper due to the recovery of energy lost through bremsstrahlung using a dynamic clustering at the trigger tower level. The rate of the single electron trigger can be reduced using the isolation while maintaining the efficiency. Benefitting from the enhanced granularity, the e/γ candidate position can be computed as an energy-weighted average centered on the seed tower. This gives a factor 4 improvment with respect to the Run I algorithm which considered the centre of the RCT 4×4 TT region as the position of the candidate.

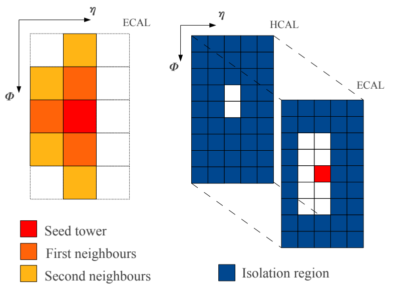

Figure 1: The L1 e/γ clustering and isolation. A candidate is formed by clustering neighbour towers (orange and yellow) if they are linked to the seed tower (red). A candidate is considered as isolated if the E_{T} in the isolation region (blue) is smaller than a given value.

4. Firmware Implementation

The firmware implementation is particularly challenging as the electron finder along with the tau and jet finders must fit within a single XC7V690T Xilinx FPGA. The firmware also includes core firmware, which comprises all the necessary logic to control the 72 input/output optical serial links. It also includes the configuration registers, the input pattern buffers, output spy buffers that should be accessible by software. The core firmware represents at this stage a total of 5% of the chip leaving enough resources to implement the algorithms and guarantee a certain flexibility in their design. The software interface is based on the IPBUS standard using libraries such as μHAL developed at CERN.

A total of 36 CTP7s are connected to each MP7 by two optical serial links running at 10 Gb/s. The calorimeters have a granularity of 72 TT in the ϕ direction and 28 TT in the each of the positive and negative η direction (E+ and E-). A dedicated 16-bit word format has been adopted to encode the energy sum of ECAL and HCAL along with extra words to locally compute these energies separately and extract the ratio. Each η slice of 72 TT is read out starting from the center of the detector, alternatively on the positive and negative side. Up to 4.3 BX (25 ns) are required to receive all data from both ECAL and HCAL. An input pipeline is necessary to process the data at the incoming rate starting on the reception of the first data word. For the 32 bits received on each link, the internal computing frequency achieved is 240 MHz.

Upon reception, each of the TT is considered as a potential cluster seed. In order to reduce the amount of resources required by the implementation of several adders, only "quality flags" are set for each of the incoming TT. These flags are determined by predefined criteria such as seeding, sharing or trimming. The cluster energy is thus computed as the sum of TT with quality flag. The identification, H/E and shape identification criteria are implemented as LUTs. Tau lepton candidates will be built from EG-type clusters but summing both ECAL and HCAL energies. As seen on Figure 2, a precise floor planning scheme has been developed to efficiently perform a place and route process and to guaranty that timing constraints will be satisfied after modification of VHDL sources during the development process. The VHDL design has been optimized by the implementation of generic components and resource sharing between the algorithms. A preliminary result of the jet algorithm implementation gives about 40% of the resources used including the core firmware.

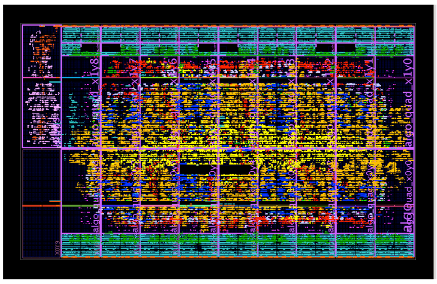

Figure 2: Floor planning of Xilinx Virtex 7 FPGA within the MP7 board. The blue and green areas represent the input-output logic within the core firmware and the yellow, red and dark blue ones represent the resources used by the algorithm. The purple corresponds to the DAQ interface.

Conclusion

The calorimeter trigger of the CMS experiment is being consolidated to face the intense conditions of the LHC Run II. Both systems will run in parallel in 2015. The upgraded system will be operational by 2016. The modern technologies employed allow the implementation of sophisticated algorithms that can improve by a factor four the position resolution of the e/γ trigger candidate and the energy resolution by 30% while maintaining similar triggering efficiencies and rates than during Run I. The clustering algorithm presented here is used to develop an efficient tau lepton trigger at L1. The global view of the calorimeters will allow the computation of global quantities such as missing transverse energy. The implementation of these algorithms within the firmware of the MP7 board is currently ongoing.

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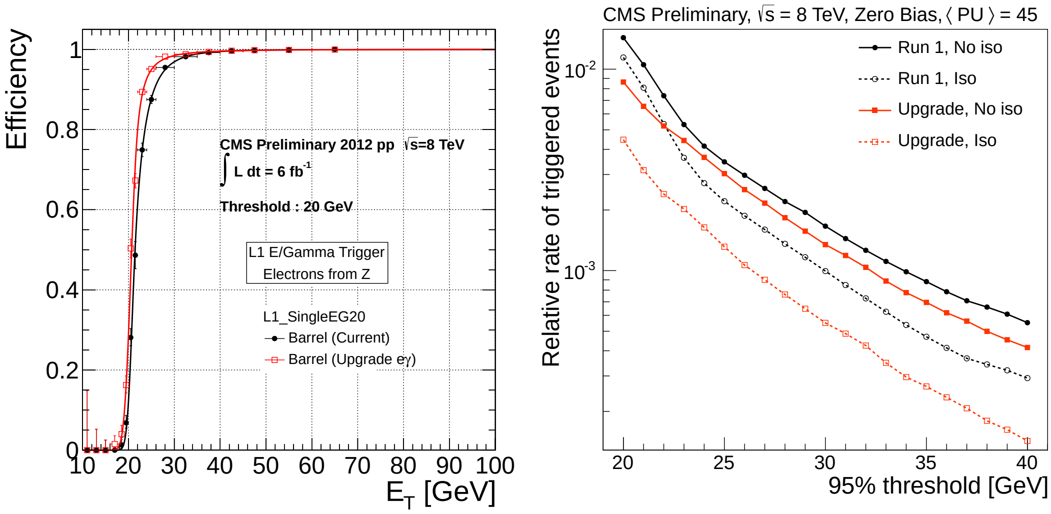

Figure 3: Electron trigger efficiency at L1 as a function of the offline reconstructed E_T in the EB (left) for a threshold of 20 GeV. The efficiencies obtained with the current and the upgraded algorithms are shown, without isolation criteria.(Right) Relative rate of triggered events from 8 TeV minimum bias data for an average pile-up of 45, obtained with the current (Run I) and the upgraded algorithms, both with and without their respective isolation requirements.

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