The CMS Barrel Muon trigger upgrade

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Abstract: The increase of luminosity expected by LHC during Phase1 will impose tighter constraints for rate reduction in order to maintain high efficiency in the CMS Level1 trigger system. The TwinMux system is the early layer of the muon barrel region that concentrates the information from different subdetectors: Drift Tubes, Resistive Plate Chambers and Outer Hadron Calorimeter. It arranges the slow optical trigger links from the detector chambers into faster links (10 Gbps) that are sent in multiple copies to the track finders. Results from collision runs, that confirm the satisfactory operation of the trigger system up to the output of the barrel track finder, will be shown.

Keywords: Modular electronics; Trigger concepts and systems (hardware and software)
1 Introduction

In 2013–2014 the Large Hadron Collider (LHC) was upgraded and a second period (Run-II) of data taking started at the beginning of 2015. The center of mass energy was increased from 8 to 13 TeV, and the number of interactions per collision and the instantaneous luminosity have reached the values of 50 and $1.5 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$ respectively. Due to this upgrade the first trigger level (L1) of the Compact Muon Solenoid (CMS) [1] experiment had to cope with an increase of the total event rate of roughly a factor 6 [2].

CMS is a multipurpose particle detector placed on the LHC ring and designed to study a broad range of physics processes. In figure 1 a schematic view of a quadrant of the detector shows its layer structure. The CMS detector is built around a solenoid magnet able to produce a powerful magnetic field up to 3.8 T. Muons are detected both by a silicon tracker, that sits inside the solenoid, and by a dedicated muon detector interleaved in the return yoke. The readout frequency is limited by the design of the front end electronics to 100 kHz. The trigger is divided into two stages: a fully hardware L1 trigger and a high level trigger (HLT) running on a computer farm. The L1 trigger reduces the event rate from the LHC bunch crossing frequency (40 MHz) to the maximum sustainable readout rate.

This paper will describe in section 2 the L1 trigger upgrade of the muon detectors with a particular focus on the barrel region. Section 3 and 4 will go in the detail of the electronics building blocks of the data concentrator and the track finder processor adopted in the barrel region. Finally, recent developments regarding the combination of trigger primitives from different muon sub-detectors will be presented in section 5.
2 The L1 muon trigger upgrade

In view of the increase of luminosity due to Phase1 upgrade of LHC, the muon trigger chain of CMS underwent considerable improvements. The muon detector was designed to preserve the complementarity and redundancy of three separate muon detection systems, Cathode Strip Chambers (CSC), Drift Tubes (DT) and Resistive Plate Chambers (RPC), until they were combined in the Global Muon Trigger. The upgrade of the muon trigger aimed at exploiting the redundancy of the three muon detection systems earlier in the trigger processing chain in order to obtain a high-performance trigger with higher efficiency and better rate reduction [2]. Since every additional hit along a muon trajectory further improves the fake rejection and muon momentum measurement, the upgrade seeks to combine muon hits at the input stage to the Muon Track-Finders layer rather than at its output. All the hits should then contribute to the track irrespectively of the sub-system that detects them. As for the Run-I muon trigger the track processing is still segmented in sectors of $\varphi$ and $\eta$. The upgrade introduced a regional segmentation that treats muon tracks separately depending on $\eta$. It distinguishes a barrel region (low $\eta$), an endcap region (high $\eta$) and a transition region between them ($|\eta| \sim 1$) called overlap. Such regions will result in different triggering algorithms but also in different deployments of hardware processors. The final sorting and ghost cancellation of muon candidates are also expected to be handled separately for each of the three regions in $\eta$.

Figure 2 shows the modification of the L1 muon trigger architecture that has been completed during Run-II. In the legacy system the muon port card, the sector collector, and the link boards sent the CSC, DT and RPC hits or primitives to the respective track finders (pattern comparator in RPC case). The tracks from the three systems were sent to the Global Muon Trigger (GMT) after
the sorting. In the upgraded system hits from the CSCs are sent to the Endcap Muon Track Finder (EMTF) [3] and the Overlap Muon Track Finder (OMTF) [4] via a mezzanine on the muon port card. Endcap RPC hits are sent via the link board to the concentrator pre-processor and fan-out (CPPF) card and barrel RPC hits are sent to the TwinMux concentrator card. DT hits are sent to the TwinMux card via a copper to optical fiber (CuOF) mezzanine. The EMTF receives RPC hits via the CPPF card. In addition to the CSC hits the OMTF receives DT hits and RPC hits via the CPPF and the TwinMux, which also provides DT and RPC hits to the Barrel Muon Track Finder (BMTF) [5]. The new µGMT [6] sorts the muons, performs duplicate removal, adds isolation information from the calorimeter trigger and sends the best eight muons to the Global Trigger. At present (during Run-II) CPPF has not been deployed yet and HO is not connected to TwinMux yet.

2.1 The L1 trigger chain in the barrel region

In the new muon trigger chain, the adaptive layer for the track finder in the barrel region is called TwinMux. It allows for bringing forward the merging of the DT, RPC and HO (HCAL Outer barrel) trigger primitives, unburdening the trigger processors. TwinMux is in charge of sending such combined primitive to the BMTF and, in addition, also the RPC and DT data are sent to the OMTF after applying a clusterization of the RPC hits. In both cases a scale up in the transmission rate, and hence a reduction in the number of links, is provided. TwinMux is also responsible for duplicating the trigger primitives in order to reduce connections between trigger processors increasing the reliability of the system. In the barrel region the combined primitives are sent to the BMTF that implements the legacy trigger algorithm of the DT track finder with the addition of several improvements in rate reduction at higher efficiency and quality. For instance BMTF implements an extension of the legacy algorithm for the Pt assignment that using the primitive bending angle obtains a factor 1.5 gain in rate for typical thresholds and the same efficiency at plateau for prompt muons. Moreover the BMTF reduced the legacy algorithm latency running at a speed three times faster than the legacy hardware.
Both TwinMux and BMTF are single slot double-width and full-height $\mu$TCA board based around a Virex-7 FPGA and embedding the optics for high speed data transmission (up to 13 Gbps). The BMTF board is an MP7 card (multipurpose hardware widely used in the trigger upgrade of CMS) while for the TwinMux a custom hardware development was necessary since the DT on-detector electronics transmit data at a low rate requiring a deserialization done by the standard I/O input of the FPGA.

Figure 3 shows the trigger chain of the combined DT and RPC trigger data. From each minicrate, the Server Board (SB) transmits the DT trigger primitive over 8 LVDS links (these links are optically converted by CuOF boards, not shown in the figure). For the RPC detector five Link Board Masters (LBMs) compress the trigger hit data relative to one $30^\circ$ sector and serialize it through the GOL transmitters. TwinMux is in charge of forwarding this data to the BMTF and to the OMTF applying a scale up in the transmission rate (and hence a reduction in the number of links). TwinMux is also responsible for duplicating (up to four times for the sectors of the outer wheels where data are shared between barrel and overlap track finders) in order to reduce connections between trigger processors increasing the reliability of the system. The minimum bandwidth required for forwarding trigger data of one sector is 16 Gbps for DT data and 8 Gbps for the RPC which needs a total of three high speed links.

3 TwinMux: the barrel concentrator

TwinMux is a single slot double-width full-height $\mu$TCA board, equipped with 6 front panel SNAP12 receivers and 2 Minipods (one transmitter and one receiver) for high speed data transmission (up to 13 Gb/s). Figure 4a shows a picture of TwinMux where only the optical modules needed to receive one full sector of DT and of RPC are mounted. Based around a Xilinx Virex-7 FPGA, the TwinMux achieves the merging of several 480 Mb/s trigger links to higher speed serial links and compensates delays to provide BX alignment of the trigger data coming from the different inputs. Twelve of the 72 TwinMux inputs are routable to GTH inputs to be able to handle the GOL based 1.6 Gb/s links. The 72 CML lanes need to be level translated to cope with the LVDS input of the Virtex 7. The clock distribution is based on two very low jitter PLLs that can broadcast to all the FPGA’s
Figure 4. (a) TwinMux board. (b) TwinMux installed in 5 μTCA crates in the underground counting room at CMS.

Transceivers two different clocks for performing synchronous or asynchronous data transmission. Finally a microcontroller is responsible for managing the IPMI interface on the backplane that handles low level operations like hot-swap or temperature sensors monitoring.

To cover the full barrel, 60 TwinMux are hosted in 5 μTCA dual star crates (figure 4b), each of which is equipped with an AMC13 [8] for clock and slow control commands distribution and for providing a connection to the central DAQ. Each crate is also equipped with a commercial μTCA Carrier Hub (MCH), a redundant power module and a JTAG switch used for programming remotely each TwinMux board. In figure 4b it is possible to see the full TwinMux system after the cabling of input and output connections, for a total of more then 3000 optical fibers.

4 The Barrel Muon Track Finder

The BMTF consists of two μTCA crates (figure 5b), each of them hosts 6 Master Processors Virtex-7 (MP7) boards (figure 5a). The MP7 card hosts the Virtex7 xc7vx690tffg1927-2 FPGA that can drive high bandwidth 10 Gb/s optical links [7], control and status logic through IPbus interface, TCDS (Trigger, Control and Distribution System) decoding and clock management logic, package formatting and transmitting to the DAQ, I²C and SPI interfaces to configure and read the status of on board Phase Lock Loop (PLL) and minipod optics and finally the algorithm that runs parallel track finders within one barrel wedge and chooses the best three candidates.

4.1 BMTF algorithm

The main algorithm components of the BMTF are presented in the block diagram of figure 6a. BMTF receives data from one reference and two neighboring wedges served by the TwinMux. Each
MP7 synchronizes the data and feeds the three branches of the algorithm: the ETA Track Finder which computes $\eta$ values from the ETA primitives or the track addresses; the PHI Track Finder that uses an extrapolation mechanism to identify muon trajectories from their track segments (TS); the Assignment Unit that assigns the physical parameters to the identified muon candidates. The results are forwarded to the wedge cancel-out and sorter block in order to remove tracks found by neighbor track finders and to select the best 3 muons that are sent to the $\mu$GMT [5].

4.2 Algorithm improvements

Compared with the DTTF (the legacy muon track finder), the BMTF has improved the transverse momentum (pT) granularity by extending the Look-Up table LUTs and the assigned bits from 5 to 9. As a result the pT has a linear pT scale starting from 3 GeV and increasing in steps of 0.5 GeV to a maximum value the 140 GeV.

In contrast to DTTF, BMTF contains one additional pT assignment mechanism called new pT algorithm. It runs in parallel with the old one and has the priority under two conditions: firstly the track segments of the found muon have to be correlated and secondly the pT output of the new algorithm has to be less than the old algorithm. The new assignment algorithm is based on calculations from $\phi_b$ inputs (bending angle) rather than $\Delta \phi$ inputs (difference in phi of track segments).
4.3 Muon barrel efficiency plots

The performance of the Level-1 muon trigger has been presented during the 2016 International Conference on High Energy Physics (ICHEP16) [9]. For these data, the RPC were not used in the BMTF. Figure 7a and figure 7b show respectively the $p_T$ and the $\eta$ efficiency obtained in such preliminary studies of the muon trigger performance [10]. As mentioned, the BMTF finds muon candidates within the pseudorapidity range $|\eta| < 0.83$. Hence in the plot of figure 7b this region gives the $\eta$ efficiency of the BMTF system. The drop seen in figure 7a at high $p_T$ is due to a firmware problem in the endcap region, which has been fixed later.

Those plots, have been computed by the tag and probe method with offline reconstructed muons from pre-selected Drell-Yan events decaying to the muon final state [11]. The tag muon was reconstructed with the CMS particle flow algorithm [12] with $p_T > 27$ GeV and an isolation variable lower than 0.15, matched to an HLT trigger object within $\Delta R < 0.3$. To calculate the efficiency a L1 muon from the triggering bunch crossing must be found matching the probe muon within $\Delta R < 0.5$.

The plots show a good performance, in $p_T$ and across $\eta$, compatible with the performances achieved in Run-I. Later studies will include the RPC data in the BMTF. This will allow the systems to reconstruct tracks with higher quality and thus lead to better rate reduction and higher efficiency.

5 The super-primitives

In addition to DT trigger primitives TwinMux can forward to the track finder another group of primitives, called super-primitives, that are built from DT or RPC data. We distinguish between two kinds of super-primitive that will be described in detail in the following paragraph: the DT primitive re-timed according to a RPC coincidence and the primitives built from coincidences in two RPC layers.
The main goals of the super-primitives are three:
1. To improve the bunch identification of the DT primitive using the timing of the RPC hit
2. To improve tracks with mixing of DT and RPC primitives
3. To improve segment efficiency in case of low quality DT or RPC only segments

**Bunch assignment.** The RPC clusterization algorithm implemented in TwinMux can output up to two clusters of RPC hits per bunch crossing and per RPC roll (smallest segmentation of the RPC chamber in the \( \eta \) view) [1]. In the barrel region an RPC station is composed of a number of rolls that ranges from 2 to 5. In one DT sector TwinMux receives up to 8 clusters for MB1 and MB2 and up to 4 cluster for MB3 and MB4. The bunch assignment algorithm calculates the \( \phi \) difference between each of the two DT primitives position and all the RPC cluster positions in the same station in a temporal window of \( \pm 1 \) bunch crossings. Afterwards a sorting (1 out of 24 for MB1 and MB2 and 1 out 12 for MB3 and MB4) chooses the minimum \( \phi \) difference. Finally the DT primitive is time shifted according to the bunch crossing that gives the minimum \( \phi \) difference. In case of conflict between two DT primitives that result in the same bunch crossing the priority is given to the one that is already in that specific bunch crossing. The firmware implementation of the algorithm provides also the possibility of adding a quality cut of the DT primitives affected by the time shift and a maximum \( \phi \) difference windows in which to look for the time matching.

**RPC only primitive.** In the first two stations where there are two RPC layers around the DT chamber it is possible to build a trigger primitive starting from the RPC cluster positions. Such a primitive can have a position given by the average angular position (\( \phi \)) of the two clusters in a temporal coincidence and a bending angle given by
\[
\phi_b = \arctan\left(\frac{x_2 - x_1}{D}\right) - \phi \tag{5.1}
\]
where \( x_1 \) and \( x_2 \) are the cluster positions and \( D \) is the distance between the two RPC layers. Every bunch crossing a sorting is applied to all the RPC only primitive that has been built from any couple of RPC clusters and the one with the smallest \( \phi_b \) is chosen. In order to avoid duplicating muons, the RPC only primitive is forwarded to the BMTF only if there is not already a DT primitive in the same bunch crossing.

### 6 Conclusion

The increase of luminosity of LHC demanded considerable improvements in L1 trigger algorithms and consequently to the electronics used for their implementation. In this paper we have shown in detail two components of the L1 muon trigger system that have been installed in CMS at the beginning of 2016. They are the DT and RPC data concentrator for the barrel region and the associated muon track finder. Both systems have been presented in terms of hardware and firmware. A smooth operation of these systems has been achieved during Run-II. Present activities focus on the validation of the DT-RPC primitive combination that aims to combine good RPC temporal resolution with the good DT spatial resolution. Furthermore the generation of RPC only primitives, for merging DT and RPC segments at the track finder level in order to increase its efficiency, is under test.
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