Upgrade of the Global Muon Trigger for the CMS experiment

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ABSTRACT: To continue triggering with the current performance in the Large Hadron Collider’s Run 2, the Global Muon Trigger (GMT) of the Compact Muon Solenoid experiment will have to undergo a significant upgrade. In this upgrade the GMT will be reimplemented in a Xilinx Virtex-7 card utilizing the microTCA architecture. The available high-capacity input and output will be used to increase the number of sent and received muon objects. Furthermore their data size will increase from currently 32 bits to 64 bits per object. Additionally the GMT will calculate a muon’s isolation using energy information received from the calorimeter trigger. This information is added to the muon objects forwarded to the Global Trigger. It may also be possible to migrate the final sorting stage of each muon subsystem to the GMT using the increased bandwidth and processing power. A summary of the current status of the future GMT’s development will be given.

KEYWORDS: Trigger concepts and systems (hardware and software); Trigger algorithms

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1 Current system

The current Compact Muon Solenoid (CMS) Level-1 Trigger is based on VME technology utilizing mainly Field-Programmable Gate-Arrays (FPGAs) as well as Application-Specific Integrated Circuits with galvanic links for inter-card communication. It reduces the event-rate from the nominal LHC bunch-crossing frequency of 40 MHz to 100 kHz. In order to do this the Level-1 Trigger is synchronized to the Large Hadron Collider (LHC) clock of 40 MHz and works in a fully pipelined mode.

The general operating principle is to find local features of physics objects in early stages and successively combine these to regional physics objects whereupon they are sorted in a global stage before being sent to the Global Trigger (GT). The GT then can trigger a read-out decision based on 128 programmable algorithms. These algorithms work on full physics objects such as muons and jets and can include topological conditions.

This principle may be found in the muon trigger (see figure 1): Hit information from two of the muon systems in CMS (cathode strip chambers (CSC) and drift tubes (DT)) are sent to a local stage where they are combined to track stubs within a single muon station. These track stubs are used to form muon tracks in the track-finder level and subsequently sorted. The four best tracks found in both the CSC and DT systems are then sent to the Global Muon Trigger (GMT). The resistive plate chamber (RPC) system uses a pattern-matching based approach. It then sends the four highest-ranked muons for both the barrel and endcap region to the GMT.
Figure 1. Block diagram of the current CMS Level-1 muon trigger.

The GMT matches the muon tracks from complementary muon systems. RPC tracks are merged with matching CSC or DT tracks according to programmable algorithms that find an improved track based on the two original tracks. Due to the geometry of the CMS detector a muon can be reconstructed in both the barrel as well as the endcap muon systems. The GMT finds such tracks and then cancels the duplicate. The resulting muons are sorted in two stages before the four highest-ranked muons are sent to the GT. The current GMT is described in more detail elsewhere, see ref. [1].

The GT can then combine the muon tracks with information received from the calorimeter trigger in 128 algorithms of which each can trigger a read-out decision. A complete description of the Level-1 Trigger is provided in the Technical Design Report, see ref. [2].

2 Motivation for the upgrade

The LHC’s expected instantaneous luminosity after Long Shutdown 1 exceeds the original design specification. The number of pile-up interactions already surpassed it in the 2012 run.

Still, the Level-1 Trigger will be required to support a physics program that both allows searches at the TeV scale and is sensitive to electroweak scale physics. This cannot be achieved by increasing the Level-1 accept rate as several detectors would require major upgrades in order to accommodate the required read-out rate.

Especially the pile-up sensitive multi-object triggers will require significant increases in their trigger thresholds. This fact necessitates an improvement in several areas of the Level-1 Trigger. For the muon trigger this mainly means the introduction of muon isolation as well as an improvement in the muon parameter precision, especially for its transverse momentum.
3 Upgrades for the muon trigger

The track-finders will be upgraded both concerning their hardware as well as their firmware. This should lead to increases in the track-finders’ precision for muon track parameters as well as greater flexibility for future improvements. They will also be able to absorb hit information from the RPC system in order to increase the quality of reconstructed tracks at an earlier stage than in the current system. Furthermore an additional track-finder will be introduced to cover the overlap region between the CSC and DT systems. The track-finders will then consist of a barrel, overlap and forward track-finder (see figure 2).

In order to accommodate the track-finders’ increased precision, muon objects will be increased in size from currently 32 bit to 64 bit. This will also allow the Level-1 Trigger to move to a linear scale for the muon track parameters as well as remain flexible for possible later changes (see table 1).

Finally the number of muons delivered to the GT by the GMT will be increased from 4 to 8. This will allow greater flexibility for the trigger algorithms such as using lower quality muons for b-tagging.

A comprehensive description of the planned upgrades is given elsewhere, see ref. [3].

4 Hardware

For the Level-1 Trigger upgrade the current VME crates will be replaced by a microTCA crate system. This system provides system-level health management, redundant power supplies and cooling as well as a high-capacity back plane.

The GMT will be implemented in a Xilinx Virtex-7 690 FPGA placed on an Advanced Mezzanine Card (AMC). This means a significant increase in resources compared to the currently
Table 1. Comparison of bit widths for muon objects at the GMT’s input.

|                | Current GMT | Upgraded GMT |
|----------------|-------------|--------------|
| \( \phi \)     | 8 bit       | 10 bit       |
| \( \eta \)     | 6 bit       | 9 bit        |
| \( p_T \)      | 5 bit       | 9 bit        |
| quality        | 3 bit       | 4 bit        |
| charge         | 1 bit       | 1 bit        |
| charge valid   | 1 bit       | 1 bit        |

Table 2. Comparison of resources available for the upgraded GMT with the current GMT’s usage.

|                | Current GMT | Virtex-7 |
|----------------|-------------|----------|
| Logic cells    | 190 000     | 693 120  |
| Block RAM      | 384         | 2940     |

used chips. However, the current GMT consists of 10 Virtex-II chips while the upgraded system will utilize only one chip. This means an increase in logic resources of only a factor 3 (see table 2).

The Virtex-7 also includes digital-signal processors (DSPs) for fast integer addition and multiplication, as well as 80 transceivers capable of a maximum input and output bandwidth of 13.1 Gb/s each.

The current target card is the Imperial Master Processor, Virtex-7 (MP7, see ref. [4]). This AMC module supplies 72+72 10 Gb/s channels for receiving and sending via optical links. Multi-fiber Termination Push-on (MTP) connectors are used for I/O, one connector bundles 36 fibres.

5 Planned algorithms for the upgraded GMT

The future GMT will change significantly in its design when compared to the current system, as it will not be necessary to merge muons from the track-finders with those delivered by the RPC system. There will also be two overlapping regions between both barrel and overlap track-finders as well as overlap and forward track-finders instead of the current single overlapping region between CSC and DT track-finders. Finally the future GMT will compute the isolation of a muon based on the energy deposits in the calorimeter around the muon’s track.

5.1 Muon sorting

With 72 high-bandwidth inputs available on the target card a significant increase in the number of input muons is possible. The GMT could absorb the track-finders’ muons directly without using dedicated sorter cards, thereby saving latency otherwise required for de-/serialization at the optical transceivers. As each track-finder consists of 12 processor boards, each with an output of 3 muons, the GMT then would absorb 108 input muons at 64 bits. Apart from the latency savings this will allow to remove ghosts between the track-finders at an earlier stage in the processing chain.
5.2 Muon isolation

The GMT will calculate an isolation variable for each muon sent to the GT. This will allow algorithms to be used that ignore muons created in jets from in-flight decay. This value can be either calculated using a fixed threshold for the energy deposited around the muon’s track (absolute isolation) or using the ratio between the energy deposited and the muon’s transverse momentum (relative isolation). Current studies indicate that at a few percent efficiency cost a rate reduction on the order of 35% can be achieved, assuming an improved $p_T$ resolution. This is estimated using $p_T$ values obtained by the high-level trigger (HLT) using only muon system information, i.e. an estimate for the best possible performance for the Level-1 muon trigger.

6 Implementation

6.1 Muon sorting

As explained in section 5.1 the future GMT could absorb the current final sorters. In such a scenario muon sorting will be accomplished in two stages (see figure 3). In the first stage the muons from each track-finder will be sorted separately. Muons from the overlap and forward track-finders will be sorted separately for the positive and negative sides of the detector. Sorting will be done according to a rank assigned depending on $p_T$ and the quality of a muon as given by the track-finders. In parallel the muons from each track-finder are matched in order to find possible ghosts (see section 6.2). The duplicate muon with the lower quality will then be canceled out in the sorter.

The second sorter stage receives four muons each from the positive and negative regions of both the overlap and forward track-finders, as well as eight muons from the barrel track-finder. The best eight muons out of these 24 are then sent to the GT after being assigned isolation values that are supplied by the isolation unit.

6.2 Ghost busting

Ghost busting in the upgraded muon trigger will be necessary between the different track-finders, but also for muons from neighbouring sectors or wedges in the same track-finder. In the current system this cancel-out is either not necessary as no information is shared between neighbouring stations (as for the CSC track-finder) or done already in the barrel sorter in the case of the DT track-finder.

The future GMT thus needs to perform ghost busting between the following areas:

- barrel and positive overlap track-finders
- barrel and negative overlap track-finders
- positive overlap and positive forward track-finders
- negative overlap and negative forward track-finders
- neighbouring wedges or sectors of each track-finder

Tracks can be matched either based on their spatial coordinates or based on common track segments used during the tracks’ assembly.
Figure 3. Block diagram of current version for upgraded GMT functionality. Latency according to software simulations. The GMT sorts input muons from the positive and negative sides of the detector in the endcap and overlap region as well as the input muons from the barrel region separately. In parallel ghost-busting takes place as well as calculation of pile-up in the calorimeter and an extrapolation for each muon to the vertex. In a second sorter stage muons from all detector regions are sorted again and the eight best are sent to the isolation unit in order to determine their isolation. Finally these eight muons and their isolation values are sent to the GT.

Coordinate-based cancel out. Matching based on spatial coordinates uses a matching window $\Delta R^2 = \Delta \eta^2 + \Delta \phi^2$. A match quality value is assigned to each pair of muons depending on $\Delta R^2$. Additional coefficients can be introduced for both $\Delta \eta$ and $\Delta \phi$. This type of matching requires no additional information from the track-finders, however it is less accurate than the track-address based cancel out described below.
**Track address-based cancel out.** Ghost busting using the track addresses works by matching the track segments used for a muon’s track for each station. If a certain number of shared track segments were used for two tracks they are flagged as duplicates of each other. This is more accurate than matching based on spatial coordinates and is currently used in the DT barrel sorter. However, significantly more information is required to perform this kind of ghost busting.

### 6.3 Muon isolation

The upgraded GMT can receive 5 bit energy values for $2 \times 2$ trigger tower\(^1\) regions from the Layer-2 calorimeter trigger with the available bandwidth. An isolation algorithm similar to the to the one currently being studied (see section 5.2) has been written and synthesised successfully. The algorithm pre-calculates $5 \times 1$ sums of the $2 \times 2$ regions. In parallel muon tracks are extrapolated to the vertex. The final muons selected by the last sorter stage are then used to select the $5 \times 1$ sums to be used for $5 \times 5$ sums around the muon tracks. Finally the isolation value is determined based on the calculated $5 \times 5$ sums as well as the muon’s $p_T$ in the case of relative isolation.

Pile-up subtraction will be performed in the Calorimeter trigger before sending the energy sums to the GMT. However it may be beneficial to provide this functionality in the GMT if an improved algorithm can be found for pile-up removal when isolating muons.

### 7 Interface

The trigger systems will communicate via optical links.

**GT.** The GMT will send eight muons at 64 bits to the GT. One 10 Gb/s link will transfer two muons.

**Track-finders.** Each track-finder sends 36 muons at 64 bits. One 10 Gb/s link per track-finder processor will transfer three muons to the GMT.

**Calorimeter trigger.** The calorimeter trigger will send 5-bit energy values for each $2 \times 2$ trigger tower region to the GMT. Due to the time-multiplexed nature (see ref. [5]) of the calorimeter trigger there are 3 links possible per Layer-2 processor board. This means that the energy values will be transmitted over a period of 10 BX.

### 8 Summary

An overview of the current developments for the upgraded CMS Global Muon Trigger has been given. Due to the significantly increased luminosity that will be provided by the LHC during Run 2 an upgrade of the CMS Level-1 Trigger is necessary. In the context of this upgrade the GMT will be reimplemented in a Virtex-7 FPGA using the microTCA crate technology. The increased input and processing capabilities will be used to provide muon isolation as well as increase both the number and precision of muon objects. Muon sorting in the GMT could potentially save latency as well as allow improved ghost busting.

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\(^1\)A trigger tower has a size of $\Delta \phi = 5^\circ$ and $\Delta \eta \approx 0.1$. 

References

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