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The upgrade of the CMS Global Trigger

Bernhard Arnold, Herbert Bergauer, Manfred Jeitler, Takashi Matsushita, Dinyar Rabady, Babak Rahbaran, Johannes Wittmann, Claudia-Elisabeth Wulz for the CMS Collaboration

Abstract

The Global Trigger is the final step of the CMS Level-1 Trigger. Previously implemented in VME, it has been redesigned and completely rebuilt in microTCA technology, using the Virtex-7 FPGA chip family. It will allow to implement trigger algorithms close to the final physics selection. The new system is presented, together with performance tests undertaken in parallel operation with the legacy system during the initial months of Run II of the LHC at a beam energy of 13 TeV.

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The upgrade of the CMS Global Trigger

J. Wittmann[a*], **B. Arnold**[a], **H. Bergauer**[a], **M. Jeitler**[a], **T. Matsushita**[a], **D. Rabady**[a], **B. Rahbaran**[a], **C.-E. Wulz**[a]

[a]*HEPHY Vienna - Institute of High Energy Physics of the Austrian Academy of Sciences, Nikolsdorfer Gasse 18, A-1050 Vienna, Austria*
E-mail: `johannes.wittmann@oeaw.ac.at`

ABSTRACT: The Global Trigger is the final step of the CMS Level-1 Trigger. Previously implemented in VME, it has been redesigned and completely rebuilt in MicroTCA technology, using the Virtex-7 FPGA chip family. It will allow to implement trigger algorithms close to the final physics selection. The new system is presented, together with performance tests undertaken in parallel operation with the legacy system during the initial months of Run II of the LHC at a beam energy of 13 TeV.

KEYWORDS: Trigger concepts and systems (hardware and software); Modular electronics.

*Corresponding author.

Contents

1. CMS Level-1 Trigger Upgrade

For the first LHC Run from 2009 to 2012, the accelerator operated at center-of-mass energies up to 8 TeV. During the Long Shutdown 1 (LS1) between 2012 and 2015, many parts of the LHC and the CMS detector were upgraded to allow for higher energies and an increased luminosity. The center-of-mass energy of the proton collisions will be at least 13 TeV during Run II. The luminosity will also rise from $7.7 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$ to over $2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$. These changes will cause increased pileup for the LHC experiments. To obtain the required performance of the CMS Trigger subsystems, the Level-1 (L1) trigger hardware was updated [1]. The architecture of the new Level-1 trigger systems is shown in figure 1. It shows the upgraded calorimeter trigger systems on the left side and the new muon trigger path on the right side. The upgraded Global Trigger is at the end of the complete L1 trigger path and combines the information provided by both branches.

The goal of the trigger upgrade is to limit the rates for the readout to a reasonable level while keeping the efficiency and precision high, in spite of the rising collision rates. To obtain this goal, better resolution in transverse momentum and geometrical coordinates is provided. More and highly sophisticated trigger algorithms can be used, including complex correlations between different types of objects and the calculation of invariant masses. The upgraded Global Trigger (uGT) receives more trigger objects than the old system. For the muons, 8 instead of 4 candidates are sent to the uGT. The upgraded calorimeter system also sends more data: 12 electron/gamma objects instead of 8, 12 jets instead of 8, and 8 tau objects instead of 4 during Run I. By the same token, the amount of signals received from other detector sources was doubled and is now 256 bits [2].

2. The new Global Trigger System

The upgraded Global Trigger system is designed to deal with the conditions of Run II of the LHC explained in section 1. It is capable of using more objects for its calculations than the old trigger system. Also, the number of algorithms is significantly higher than before. The upgraded Global Trigger supports the use of at least 512 different trigger algorithms. A study for providing more than the 512 algorithms has also been carried out and the concept for this approach is presented

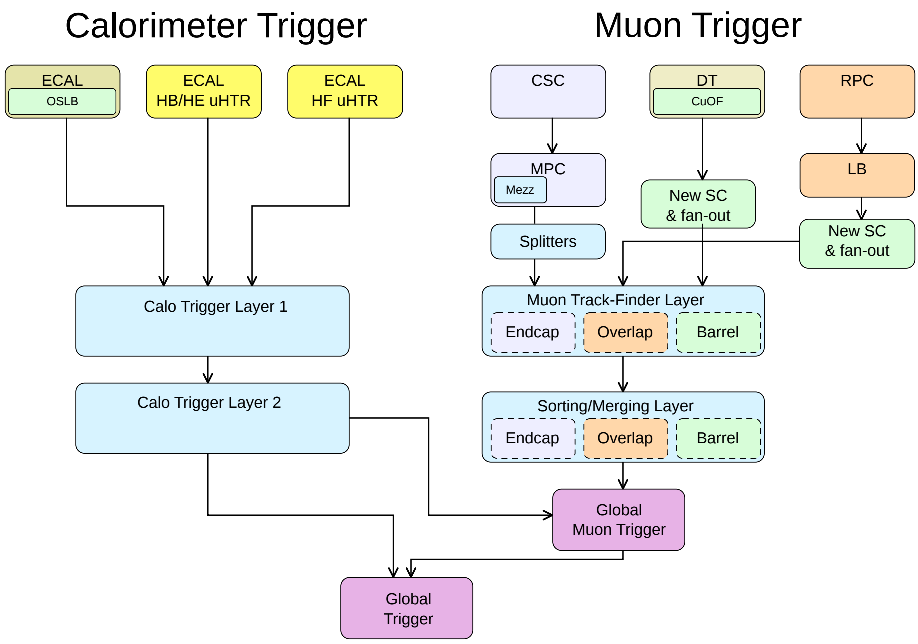

Figure 1. The upgraded Level-1 Trigger.

in this section. In addition to the inputs of the muon and the calorimeter paths, there are also data from other CMS subdetectors (ZDC, CASTOR) and other sources (TOTEM, BPTX) used in the Global Trigger (External Conditions) [3].

The new trigger system builds upon the modern MicroTCA standard. The great number of different hardware manufacturers for this commercial telecommunications standard secures the future prospects for the L1 Trigger systems. The Global Trigger itself uses an Advanced Mezzanine Card (AMC) platform compliant with the MicroTCA standard. The module is called MP7 and was developed by Imperial College (IC), London. The MP7 is shown in figure 2. Apart from the Global Trigger, it will also be used in several other subsystems of the new L1 Trigger. The board utilises a modern and powerful Virtex-7 Field Programmable Gate Array (FPGA) from the Xilinx company. The chip combines the possibility to implement logic requiring many resources and a very high bandwidth for transferring the data. The MP7 is capable of transmitting data with a bandwidth of up to 720 Gbps [4].

As mentioned above, the system for integrating trigger information from additional sources, the so called External Conditions, has been redesigned. The number of these inputs in the upgraded trigger system is two times higher than in the legacy one. Now, 256 signals can be used for complex calculations in the algorithm logic of the Global Trigger. There are 64 inputs for RJ45 (Ethernet) type connectors located in two External Conditions patchpanels in the Global Trigger rack. Each connector contains four differential signal lines in the LVDS standard. These inputs are then combined in 8 very high density VHDCI cables and sent to four AMC502 boards, each equipped with a specially built receiver mezzanine module. The AMC502 was built by Vadatech especially for the

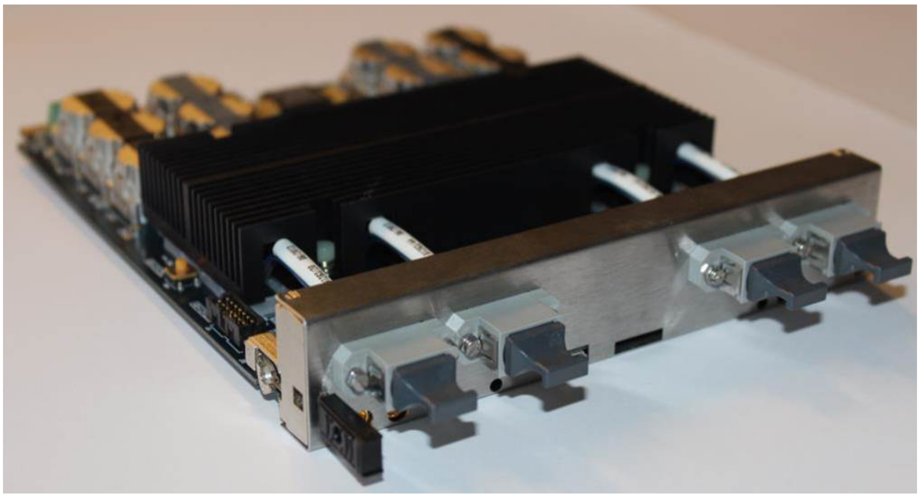

Figure 2. The uGT target platform MP7 (© IC London).

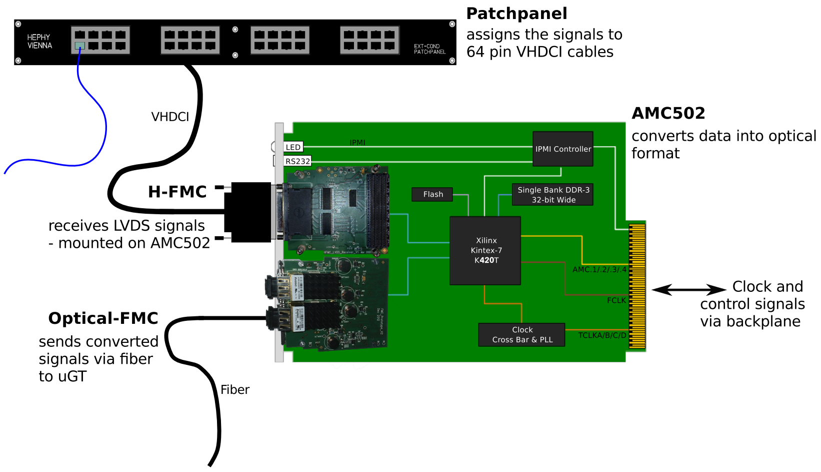

Figure 3. The new External Condition data flow.

needs of the Global Trigger system. It is equipped with a Kintex-7 FPGA from Xilinx capable of transmitting data with a rate up to 12.5 Gbps. Additionally, there are two expansion slots for mezzanine boards (FMC) available, which allows for high flexibility and additional connectors. The first FMC module accommodates the inputs for the galvanic signals. On the AMC502 board, the External Conditions are synchronised and converted into the appropriate format to be transmitted via the optical fibers to the Global Trigger hardware. For this purpose, a second mezzanine board with fast 10 Gbps optical transceivers (QSFP+) is mounted on the AMC502 board [5]. The newly developed External Conditions system is shown in figure 3.

Among the main requirements for the upgrade of the Global Trigger were modularity and scalability. To be able to adapt the system to future requirements, the Global Trigger was designed for easy extension of the available resources. The logic for calculating the trigger results can be distributed over several MP7 modules if the chip resources of one board are exhausted. The design of the Global Trigger offers the possibility of using up to 6 separate MP7 modules and combining the logic resources of all of these boards. With this solution, we expect the system to be prepared for future challenges. With the approach of using up to 6 boards, the Global Trigger produces 6 different final decision signals, each from a single MP7 board. The Trigger, Control and Distribution System (TCDS), which is responsible for providing timing information, receiving status signals and broadcasting the trigger decision to all subsystems, expects just one single binary input from the upgraded Global Trigger [1]. Therefore we provide a solution for collecting these separate signals, combining them and making a final decision for the L1 Trigger system. Also for this purpose, the AMC502 module (mentioned above) will be used. In contrast to the high bandwidth optical connections used for transmitting data between the several L1 trigger subsystems, the final decision is sent via a galvanic low voltage TTL (LVTTL) connection. This format is easy to manage and sufficient for a single 40 MHz output line. Additionally, latency is being saved by avoiding the serialisation and conversion into an optical format. By using both FMC expansion slots of the AMC502 board, all information from up to 6 Global Trigger modules can be received. The global decision by considering all inputs is then made and just one final signal will be sent to the TCDS for broadcasting the Level-1 Accept (L1A) signal to all subsystems.

The centrepiece of the L1 Global Trigger firmware is the trigger menu. It is based on the inputs from the several subsystems: the calorimeter path, the muon path, and the External Conditions. All these signals are used together to arrive at the trigger decision. This trigger menu can be adjusted to meet the requirements for different physics conditions in the LHC and the CMS detector. To simplify the access to this menu for physicists, a special framework for graphically modifying the L1 Trigger menu was designed. The menu produced in this way is stored as an XML file, which is the basis for the generation of the VHDL (hardware description language) code of the uGT firmware as well as for the input of the emulator. Also, a new grammar was specially developed for expressing the menu logic in a human-readable way and to handle the increased complexity of the system. As an example, an algorithm could contain a jet with an transverse energy equal to or greater than 105.5 GeV. In the new grammar, this will be expressed in the editor like this: JET.ge.105p5. If the jet which is to be triggered on is expected to occur one bunch crossing after the event, the term will look like this: JET.ge.105p5 +1. The geometric coordinates of an object are azimuth ϕ and pseudorapidity η. So, to select only a delayed jet with pseudorapidity between -2.2 and $+2.2$, the expression would be: JET.ge.105p5 +1 [JET-ETA_2p2] [6].

A completely new feature of the uGT logic will be the integration of invariant mass calculations in the trigger menu. This allows to identify the hypothetical mother particle of two decay products whose momenta have been measured. In the legacy system, invariant mass calculations were only performed by the High Level Trigger, which is implemented in a computer farm. Due to the increased performance of modern FPGAs such complex calculations can now also be done in the Level-1 system. This could be implemented using look-up tables in the trigger logic. Another approach using digital signal processors (DSP) is being evaluated.

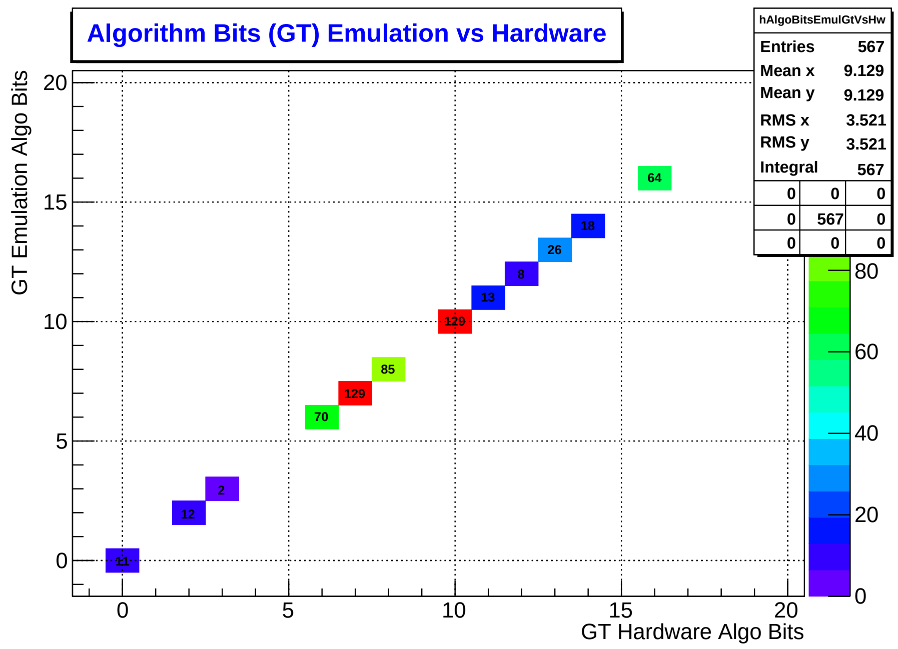

Figure 4. Results of the uGT hardware compared with the emulator.

3. Performance and plans for a "parallel run"

Before switching from the current Global Trigger to the upgrade system, the newly developed logic has to be tested extensively. Is has to be verified that the upgraded trigger has a better performance than the old one and that the calculations are performed correctly. Therefore, the Global Trigger emulator, a software framework which performs the algorithms in software, is used to cross-check the hardware results. This software is being developed by a group from Ohio State University (OSU). Furthermore, for commissioning the Global Trigger upgrade for including it in the Run II, the data acquisition (DAQ) readout data of the system have to be verified. This was also done with the help of the emulator software.

To test the proper functionality of the uGT logic, a local standalone test setup was used, which requires no other subsystems apart from the Global Trigger and the corresponding emulator. The software provides specific test patterns in the expected format which are processed by the Global Trigger logic. These data trigger certain algorithms in the menu logic. The results are then compared with the outcome of the emulator. By plotting these data, it is easy to detect differences between the hardware and the software results. Figure 4 depicts the results of a test with $Z \rightarrow ee$ input data going through a preliminary trigger menu and shows the outcome of both systems. If all algorithm results are on the diagonal, both systems fully agree on the analysed data.

Parallel running of the old and the new L1 Trigger system can be used for verifying the proper functionality of the L1 upgrade. The menu of the upgraded Global Trigger has to be very similar to the legacy one, to be able to compare the results. The trigger decision in this setup will still be made

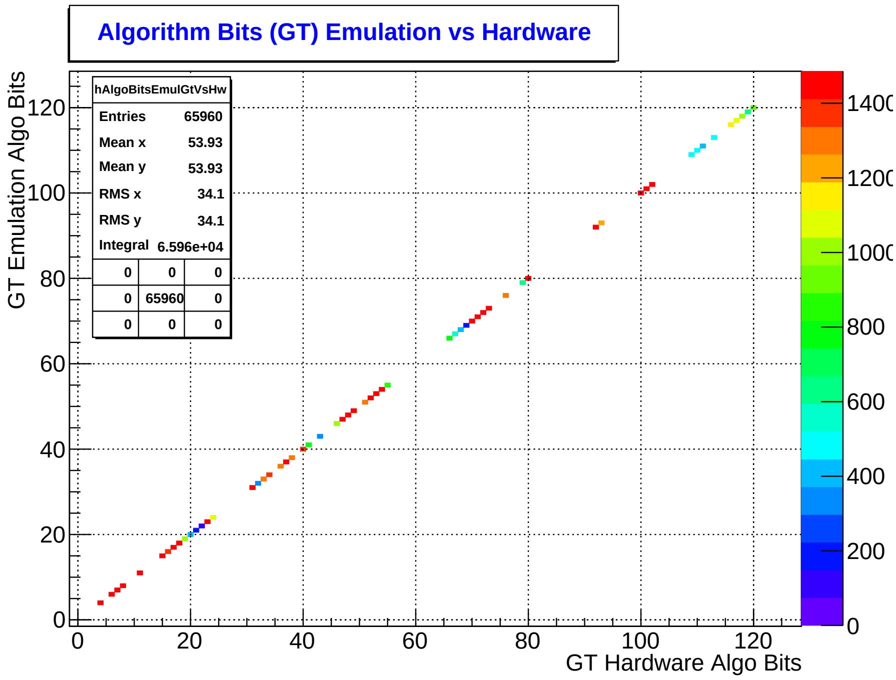

Figure 5. Results of the DAQ records verified with the emulator.

by the old Global Trigger. The L1A signal generated by it will then be sent not only to the legacy subsystems but also to the upgrade systems. This triggers the readout and the recorded data can be compared afterwards. To prepare for the planned parallel operation, some more comprehensive tests have been done. The most crucial part is the proper readout of the collected data from the uGT to the DAQ. These tests included the complete Global Trigger crate, the path to the DAQ and the creation of correct dump files in the DAQ system. As input for the Global Trigger $t\bar{t}$ (top-antitop quark pairs) events were used. In contrast to the test flow described above, the generated output was recorded by the DAQ system and analysed by the unpacker software developed by Ohio State University. The records from three consecutive luminosity segments (23 second periods) were used and the results plotted in figure 5. The fact that all results show up on the diagonal shows that there is a perfect match between the emulator and the result provided by the Global Trigger hardware to the DAQ. Another important step for the commissioning of the upgrade of the CMS Global Trigger was a "stress test" together with the DAQ system. This test includes reading out data from the system with a rather high event rate of 100 kHz under DAQ backpressure and with frequent resynchronization signals. Hence, the uGT is prepared for the challenges of the parallel run.

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