Installation and Commissioning of the CMS Timing, Trigger and Control Distribution System

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Abstract

The Timing, Trigger and Control (TTC) distribution system must ensure high-quality clocking of the CMS experiment to allow the physics potential of the LHC machine to be fully exploited. This key system provides the synchronization tools – bunch clock, first level Triggers and fast commands – that enable all sub-detector systems to take data for the same LHC collision. Its installation is described, along with the tools used to commission and synchronize the system.

I. INTRODUCTION

The CMS detector systems are currently in the installation and commissioning phase in preparation for data-taking with first beams in the LHC. The CMS Timing, Trigger and Control (TTC) system [1] serves to distribute the signals required to synchronise all CMS detector systems with each other and with the LHC collisions. We distinguish signals that are directly received from the LHC machine RF systems that provide the means to synchronise CMS data-taking to the beam collisions and those that are generated centrally within CMS to maintain the synchronisation between different detector subsystems within CMS.

II. CMS TIMING, TRIGGER AND CONTROL SYSTEM

CMS receives 5 signals from the LHC RF system: 3 clocks - the current clock used by the RF system of the counter-circulating beams 1 & 2 as well as a reference clock to which those two clocks are locked at the LHC flat-top energy of 7 TeV after the energy ramp; and 2 orbit pulses that mark the passage of bunch 1 of beams 1 & 2 past a particular point in the LHC ring. These 5 signals are transmitted optically from the RF systems located at the LHC Point 4 to each LHC Experiment where they are received and conditioned by the RF2TTC VME module. Conditioning involves timing (delay) adjustment and alignment of the different signals with respect to one-another before the selection of the pair of master clock and orbit signals that is to be distributed to CMS system via the electrical fanout modules TTCcf.

Figure 1 shows an overview of the CMS TTC system. Fast control signals that maintain the relative synchronization within and between CMS sub-systems are generated in the CMS Trigger Controllers. There is one Global Trigger Controller that is part of the CMS Global Trigger system - this is a 9U VME module known as the TCS (Trigger Control System). The TCS module runs CMS during Global data taking. Each sub-system also has its own Local Trigger Controller (LTC) that is used for standalone testing or debugging. The main difference between the two controllers is the number of partitions that can be driven: 32 in the case of the TCS in comparison to 6 for the LTC.

The smallest functional unit that can be independently controlled using the TTC system is known as a partition. At the head of each partition the TTCci (TTC CMS Interface) VME module translates the fast commands issued by the active Trigger Controller into the actual commands that are understood by the attached detector system. Thus at the level of the Trigger Controller all partitions understand the same commands, whereas flexibility in the actual definitions in hardware at the command receivers is maintained by the translation provided in the TTCci modules.

TTC data are transmitted optically using the system developed by the RD12 collaboration [2]. This system uses a time-division multiplexing scheme to send two channels of data (A & B) down one optical link to a remote receiver (TTCrx). Channel A is reserved for commands that have single clock-cycle duration - typically the Level 1 Accept Trigger. Channel B transmits framed commands that are decoded by the TTCrx and act either upon its internal settings or are placed on its output bus to control the attached electronics. The encoding of A & B Channels and optical transmission of signals is done by TTCex modules, which emit 10 copies of the same optical data, each of which may be optically split up to 32 ways. CMS gains some transmission margin by only splitting 16 ways, thus feeding a maximum of 16 destinations per optical channel.

Fast status, or throttling, information (Error, Out of Sync, Busy or Ready) is returned to the Trigger Controllers from the attached partitions via the Fast Merging Module (FMM) system that presents a summary "intelligent OR" of the state of a partition to the TCS and LTC. The Trigger controllers can thus automatically take actions like reducing the Trigger rate or initiating a re-synchronisation procedure.

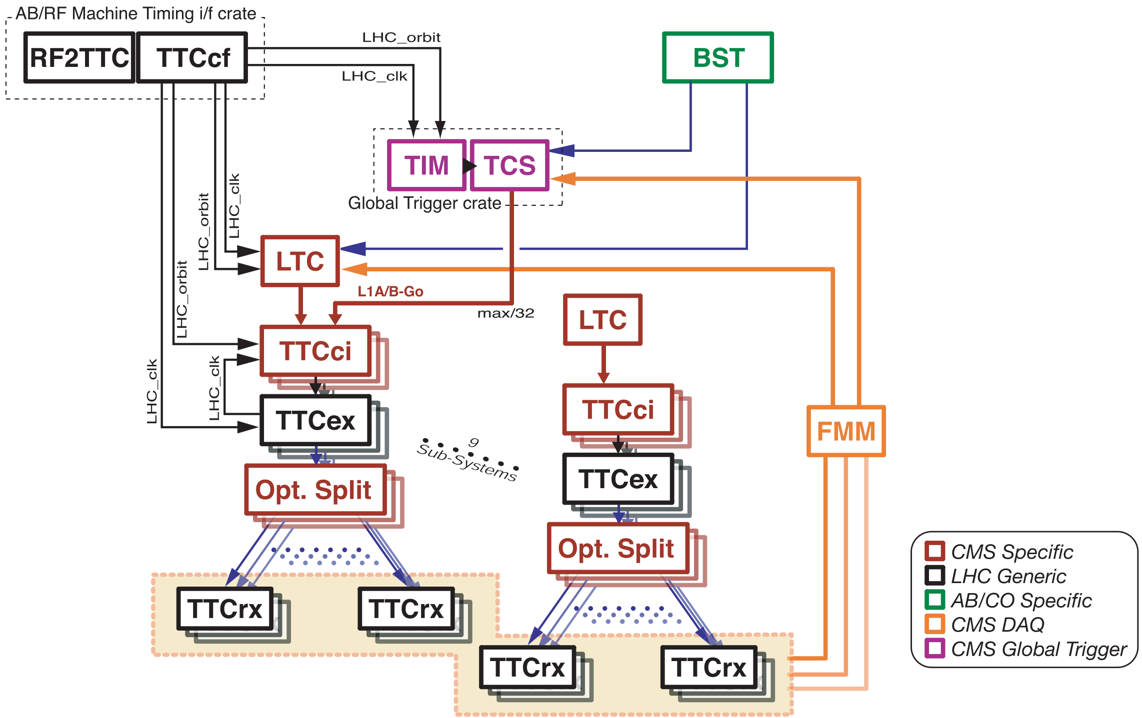

Figure 1: CMS TTC System overview

A. *Board Descriptions*

1) RFRX

Receives the clock and orbit signals that are transmitted optically from the RF generators at LHC Point 4 and converts them into an electrical signal that can be processed further. Each module has three inputs and a monitoring circuit to measure the frequency of the incoming signal. These monitoring data are made available to the LHC team that is responsible for the integrity of the signal transmission.

2) RF2TTC

All 3 clock and both orbit signals can be re-phased inside the RF2TTC to adjust the overall Experiment timing with respect to the LHC bunch train. Each clock channel is fed first to a QPLL and then a Delay25 circuit for jitter reduction and delay respectively. Both clock and orbit signals can be internally generated when the LHC beam is off.

3) BOBR

This is the timing receiver for the LHC Beam Instrumentation BST system. It receives data on beam conditions such as the machine mode and beam energy that are decoded and used in the CMS monitoring systems.

4) LTC

The CMS Local Trigger Controller can drive up to six partitions for stand-alone testing and commissioning. Each sub-detector has one module that can produce all fast control signals necessary to synchronize its partitions and issue test triggers while taking the Trigger Throttling System (TTS) signals into account.

5) TTCci

Partition-dependent coding for the fast control signals are stored in this module that carries out the translation of fast commands received from the active (Local or Global) Trigger controller. It can also act as controller for a single partition but lacks the feedback input from the TTS. Also widely used in test systems.

6) TTCex/tx

The TTCex module time multiplexes and encodes the A and B channel commands before transmitting them optically via its ten optical transmitters. The TTCtx module takes an already encoded electrical signal from the TTCex and simply fans it out via its 14 optical transmitters, thus providing a further level of fan-out.

7) Optical Splitter

The optical transmitters in the TTCex have sufficient output power to allow a split of up to 32 ways. CMS uses 16-way optical splitters in a compact VME-slot form factor.

B. *Control Software*

All CMS VME crates are controlled via a VME-PCI bridge by rack-mount PCs located together in horizontal-airflow racks in one section of the Upper level of the CMS underground counting room. The connection between VME-crate and PC is via Optical fibre. The PCs run the CERN Scientific Linux operating system.

The CMS DAQ group provides a CMS-standard software framework for communication with VME-based boards called the Hardware Access Library (HAL) and another higher-level software framework for remote control of data acquisition processes (XDAQ [3]). We have built a TTC-specific software library to control the VME-enabled TTC boards (RFRX, RF2TTC, LTC & TTCci) based upon HAL and XDAQ. This library is used by all CMS sub-detectors to control their LTCs and TTCcis.

The XDAQ framework provides a very convenient method of creating a Graphical User Interface in a web-browser using an interface called HyperDAQ. Figure 2 shows an example of how the LTC and TTCci can be controlled (remotely if desired) via the hardware-specific interface provided by our TTC library. This interface has proven extremely easy for newcomers and experts alike to use for control and debugging of hardware and systems.

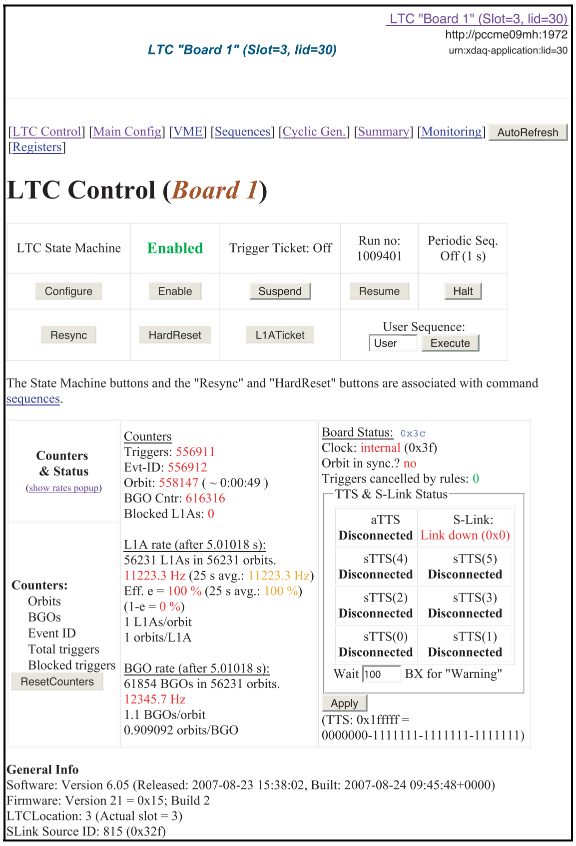

Figure 2: Main Page of the LTC HyperDAQ interface showing the state machine controls as well as some basic counters and rates.

In addition to handling the http form submissions used to pass commands from a web-browser to the XDAQ process actually controlling the hardware, this process listens to SOAP messages - which allows any network-capable process control over the hardware. This fact is exploited by higher-level run-control software in CMS to control the TTC boards of the sub-detectors in parallel, for example to configure them at the start of global data-taking.

III. Installation & Testing

1) *Installation in the CMS Underground Counting Room USC55*

All CMS TTC equipment resides in two racks in the lower level (S1) of the CMS Underground Counting Room USC55. The layout of these racks is shown in Figure 3. These racks are immediately adjacent to the Global Trigger rack on one side and very close to the shielding wall that separates USC55 from the Experimental Cavern (UXC55) to minimise the latency of the Level One Trigger (L1A). Within these two racks each sub-detector (of which there are nine in CMS) has a 6U VME TTC crate which is under their control. The tenth crate is the Machine Interface crate that houses the boards for LHC RF signal reception and distribution within the nine sub-detector crates.

Figure 3: Contents of the CMS TTC racks S1E02 (left) and S1E03 (right) located in the CMS underground counting room USC55.

Each sub-detector crate contains a crate controller, one LTC and a number of TTCci/ex pairs corresponding to the number of partitions within that sub-detector as shown in Figure 3. Single-mode optical fibres run from the TTC crates to the relevant sub-detector racks (both in USC55 and UXC55) where the optical splitters are located. From there the signals are either distributed over fibre to the detector front-ends or used directly by the local electronics.

2) *Post-installation testing*

All boards and their interconnections within the TTC crate and the Global Trigger are tested post-installation using test patterns. The correct installation of optical fibres is verified by measuring the magnitude of the optical signals arriving at the destination. Finally, each sub-detector carries out a functional test of the system to check that data is flowing through the system.

IV. Synchronization Procedures

1) *Overall Strategy*

Each sub-system has defined a strategy for time alignment of the sampling of its front-ends with the passage of particles coming from LHC collisions through its detectors. This strategy also includes the alignment of these samples to a CMS-wide definition of bunch and event number. The bunch number is defined as a number between 1 and 3564 that situates the bunch within the well-defined structure of the beam within one orbit of the LHC. The event number is a count of the number of Level-1 Triggers issued by the Trigger Controller.

In general, all sub-detector synchronization procedures allow for a coarse alignment of the front-end sampling before beam is available in the LHC that will require fine-tuning with data generated by particles coming from interaction point at the centre of CMS. Bunch and event number alignment between CMS sub-systems requires the use of a trigger for particles that can be observed in all the sub-systems that are to be aligned. This can be done by successively aligning sub-systems to one another using cosmic rays before the LHC beam turns on, as demonstrated by the CMS Magnet Test Cosmic Challenge (MTCC) carried out in 2006.

Finally, when beam becomes available in the LHC, a global shift of the clock and orbit signals in the RF2TTC module will be required to bring CMS into overall alignment with the LHC bunch structure. Histograms of hit-count per bunch crossing number for each sub-detector will provide the final verification of the correct timing in all parts of CMS when they are aligned with the bunch structure of the LHC machine.

2) Sub-System Procedures

The CMS Tracking Systems use the time of arrival at the Data Acquisition (FED) boards of the periodic tick marks inserted into the readout data by the front-end ASICs to determine the synchronization of the front-ends. This scheme depends upon knowing the length of the fibres that connect each front-end to its FED to better than 20cm in order to achieve the required sampling accuracy of 1ns. Thus all readout fibre lengths are measured after installation as part of the acceptance procedure of the cabling.

Both Calorimeter Systems make use of the fact that they read out multiple time-samples and re-construct the pulse shape to aid in timing synchronization. In addition, these systems participate in the trigger and thus their front-ends send regular signals once per orbit as a synchronization check. Knowing the cable lengths from the detector to the counting room it is possible to check synchronization from the arrival time of these signals. Both systems also have calibration systems that can inject pulses simultaneously in several front-ends. Measuring the arrival time in the Data Acquisition boards provides a further timing cross-check.

All three Muon Systems have a very similar synchronization scheme to that of the Calorimeters, except that test pulses are generated electrically in the front-ends and not optically. Knowledge of the relative cable lengths between front- and back-end is also important here. The muon systems are unique in that they also have particle triggers from cosmic muons available to them to aid in the timing-in of geographically distant parts of their systems without having to rely on triggers produced by other sub-systems to compare to.

3) Local direct verification of LHC bunch structure

In order to aid the final timing verification, both within one bunch and to the overall bunch structure, CMS uses beam pickups provided for Experiment use directly on the LHC beam line. Button electrodes used by the LHC beam instrumentation group to measure beam position around the LHC ring are configured to provide beam-derived timing information for the Experiments. CMS has two such BPTX detectors assigned to it, one for each beam - located at ~175m on each side of the CMS interaction point. The signals from the BPTX are analysed in the underground service cavern to provide the phase relationship of the bunches at CMS with respect to the timing signal received at CMS from the LHC RF system. Monitoring of this relative phase allows corrections to be made globally to CMS at the level of the RF2TTC module without having to carry out the entire fine-synchronization procedure at the CMS sub-detector level.

The BPTX system also provides a direct cross-check for the location of the first bunch in the train at CMS with respect to the Orbit signal received from the LHC RF system. CMS is thus able to verify that both types of timing signals received from the LHC RF system are stable with respect to the actual bunches in the machine. This could become important if propagation-delay changes are observed in the optical links between the LHC RF systems and CMS, something that might occur with seasonal variations in temperature for example - although as the cables travel in the LHC tunnel such variations are expected to be negligibly small in the CMS case.

V. Summary and Conclusions

Installation and commissioning of the CMS TTC system is nearing completion. The parts of the system that reside purely within the CMS underground service cavern have been largely installed and are in regular use by the various CMS sub-detector teams. CMS' interface with the LHC machine is still in the production phase and will be installed as soon as it is available.

Synchronization schemes are now in place for all sub-systems to allow the synchronization within a subsystem followed by synchronization with the LHC beam. These schemes are currently being exercised during the on-going detector commissioning. Once beam is available the central clock distributed to CMS will be adjusted to bring the entire detector into phase alignment with the bunch crossings. The BPTX readout system will provide a timing cross-check on the stability of this phase alignment allowing global problems to be spotted quickly.

VI. Acknowledgements

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VII. References

[1] Troska, J.; Corrin, E.; Kojevnikov, Y.; Rohlev, T.; Varela, J., "Implementation of the timing, trigger and control system

of the CMS experiment," Nuclear Science, IEEE Transactions on, vol.53, no.3, pp. 834-837, June 2006.
[2] B.G. Taylor “TTC Distribution for LHC Detectors,” IEEE Trans. Nucl. Sci., vol. 45, pp. 821, Jun. 1998.
[3] “Using XDAQ in application scenarios of the CMS Experiment”, Proc. of 2003 Conference for Computing in High Energy and Nuclear Physics (CHEP 03), La Jolla, CA, Mar. 2003. e-Print: hep-ex/0305076