# The ATLAS TileCal Read-Out Drivers Signal Reconstruction

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***Abstract*—TileCal is the central hadronic calorimeter of the ATLAS experiment at the LHC collider at CERN. The Read-Out Drivers (ROD) are the core of the off-detector electronics. The main components of the RODs are the Digital Signal Processor (DSP) placed on the Processing Unit (PU) dautherboards. This paper describes the DSP code and its performance with calibration and real data. The code is divided into two different parts: the first part contains the core functionalities and the second one the reconstruction algorithms. The core acts as an operating system and it controls the configuration, the data reception, transmission, online monitoring and the synchronization between front-end data and the Trigger information. The reconstruction algorithms implemented on the DSP are the Optimal Filtering (OF), Muon Tagging (MTag) and Missing ET (MET) calculation. The OF algorithm reconstructs the for each TileCal cell the amplitude and time of the deposited energy. This reconstructed energy is used by the MTag algorithm to tag low transverse momentum muons that may escape the ATLAS muon spectrometer Level 1 trigger whereas the MET algorithm computes the total transverse energy and the projection on X and Y for the entire module that will be used by the Level 2 trigger system. The DSP code performance has been validated with offline reconstruction comparison. The DSP performance has been evaluated using calibration data from Charge Injection System.**

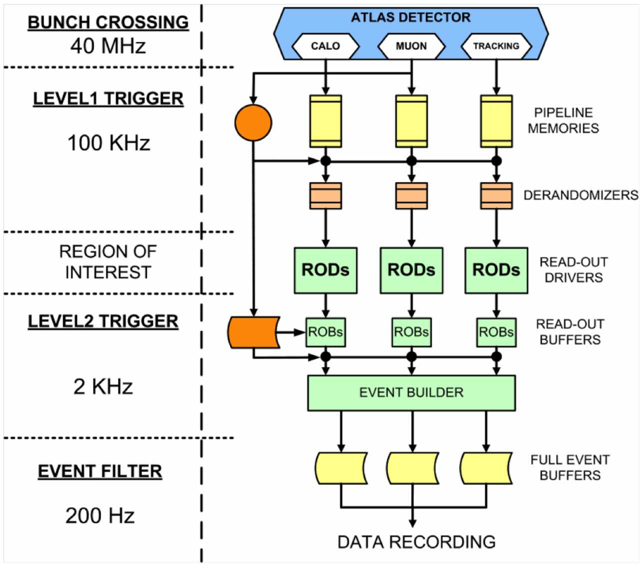

Fig. 1. The three trigger levels system of ATLAS.

## I. INTRODUCTION

TILECAL [1] is the central hadronic tile calorimeter of the ATLAS [2] experiment at LHC/CERN. The main component of the TileCal back-end electronics is the Read-Out Driver (ROD). The ROD system is part of the ATLAS trigger system. This system is based in three selection levels indicated as Level1, Level2 and Event Filter Level. The ROD system is placed between the first and the second level trigger. The data produced in the detector are gathered and digitized in the front-end electronics and transmitted to the RODs through high-speed optical links. At the first level trigger rate the ROD system has to compute in real time information from 9856 front-end channels in less than 10 $\mu s$. Finally, the processed data are transmitted through optical links to the Read-Out System (ROS) located in the second level trigger. The ATLAS trigger levels system is shown in Fig. 1.

The core of the DSP code acts as an operating system and it controls the configuration, the data reception, transmission, online monitoring and the synchronization between front-end data and the Trigger information. The main reconstruction algorithm is the Optimal Filtering (OF) [3] which computes the deposited energy and the arrival time of the data on every calorimeter cell within a front-end module. This reconstructed energy is used by the Muon Tagging (MTag) algorithm to tag low transverse momentum muons that may escape the ATLAS muon spectrometer Level1 trigger. The Total Transverse Energy algorithm computes the total transverse energy and the projection on X and Y for the entire module that will be used by a Missing $E_T$ Level2 trigger. The DSP performance has been evaluated using calibration data from Charge Injection System (CIS) [4]. The DSP reconstruction has been compared with an offline implementation of the OF method.

## II. THE TILECAL READ-OUT DRIVERS SYSTEM

The back-end hardware for the first level trigger and Data Acquisition (DAQ) of TileCal consists of four ROD crates. Each ROD crate contains eight RODs and reads out one out of four partitions in the calorimeter. The RODs are custom 9U VME64x boards and are equipped with two PU pluggable daughterboards (Fig. 2).

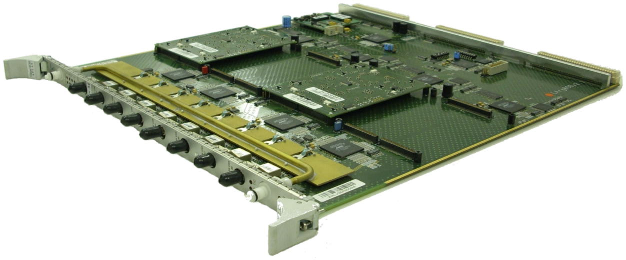

Fig. 2. Picture of a Read-Out Driver equipped with two PUs.

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The ROD has 8 input links which provide an input data bandwidth of 5.12 Gbps while the output data bandwidth is 2.56 Gbps.. Hence, the data have to be reduced at ROD level by compressing the information. The data coming from eight Tilecal front-end modules [4] are received at ROD level through the Optical Receivers (ORx) (Fig. 2). Then, the Staging FPGAs route the data to the corresponding PU. In the PU, the data are received through two Input FPGAs where the data are stored and transferred to the DSPs. Therefore, each DSP processes the data coming from two modules which implies 90 channels for a central barrel and 72 channels for the extended barrels [1].

### *A. The ROD Processing Unit*

The PUs of the TileCal ROD have two Texas Instruments TMS320C6414 DSPs , which provide an instruction cycle frequency of 720 MHz, 1024 KB of user memory and an interrupt latency of 900 ns. Besides, the PUs are also equipped with two Input FPGAs to check and transfer the input data, two FIFOs to store the output processed data and an Output FPGA to receive the Trigger, Timing and Control (TTC) [6] information and to provide the interface with the VME bus. The main functional blocks and data flow of the PU are shown if Fig.3.

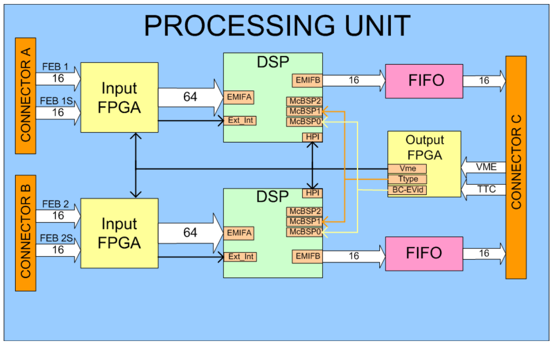

Fig. 3. Block diagram of the ROD Processing Unit and dataflow.

When an Input FPGA receives a complete event it sends an interrupt to the corresponding DSP and the whole event is transferred to the DSP input buffer. The data transfer between the Input FPGA and the DSP is performed through the External Memory Interface A (EMIFA). This is configured as synchronous memory interface and the width of the bus is 64 bits. This transfer is clocked at 100 MHz. There are two different interrupts from each Input FPGA in order to indicate which front-end module is the data source. The DSP Enhanced Direct Memory Access (EDMA) stores the received events in two circular buffers, one per front-end module. These input buffers store up to 16 events. When the buffer is full it stores the next event received in the first position. Once the event is reconstructed, it is copied to the DSP output circular buffer and transferred to a FIFO placed in the PU. The transfer between the DSP and the FIFO is handled by the EMIFB. In this case, the EMIFB has a 16-bit bus width, and it is clocked at 100 MHz.

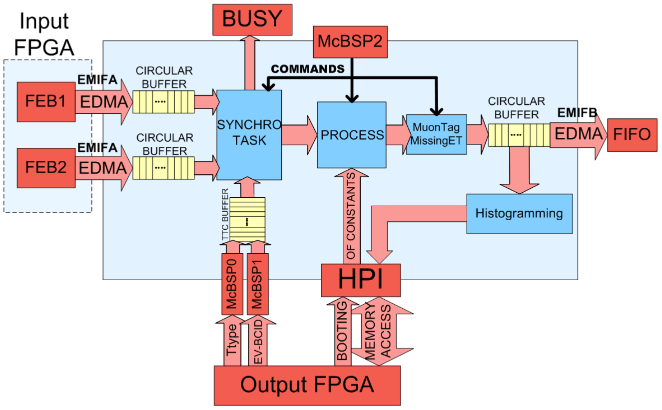

Fig. 4. Sketch of the data flow and main functional blocks of the DSP code.

The TTC information [6] is received at PU level through the Output FPGA, which provides the communication with the TTC FPGA. The TTC information is then transferred to the DSP through two Multichannel Buffered Serial Ports (McBSP) (Fig. 4). The McBSP0 is used to receive the Bunch Crossing Identification (BCID) and the Event Identification (EVID), whereas the McBSP1 is used for the Trigger Type (Ttype). The McBSP2 is used to receive commands and to read-out internal registers. Finally, the Host Port Interface (HPI) of the DSP is used to boot the DSP code and to read the internal memory and histograms while the system is running (Fig. 4). This information is accessible through the VME bus.

### *B. The DSP code functionalities*

The main reconstruction algorithms of the DSP are controlled by the kernel of the code. The kernel controls the data flow. The data is received in one circular buffer for each of the modules connected to a DSP. The data reception includes the TTC information which is received through the serial port from the TTCrx chip in the ROD. After TTC and front-end data synchronization the kernel executes the reconstruction algorithms and finally the result in formatted and transmitted to the output FIFO. The histogramming and monitoring applications are executed in parallel with the processing chain. These applications use the data stored in the input and output buffers. For raw data monitoring the input buffer is accessed whereas for the monitoring of reconstructed magnitudes the data are retrieved from the output buffer.

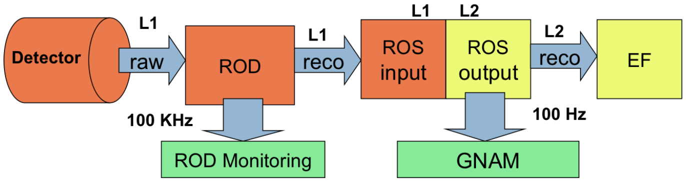

Fig. 5. High level block diagram of the TileCal monitoring system.

The GNAM monitoring system [7] and OHP histogram presenter are the common framework developed for monitoring of sub-detectors in ATLAS. However, this framework has been developed to sample data at the second level of trigger of ALTAS (Fig. 5). Thus, only events passing the second level trigger algorithms are monitored by GNAM and most of the events passing the first level of trigger are not monitored. In addition, the ROD replaces the raw data received from front-end by reconstructed magnitudes. Hence, the Level2 monitoring system monitors only reconstructed data. The aim of the ROD monitoring is to take advantage of the availability of the raw and reconstructed data at the first level of trigger rate.

### C. Optimal Filtering algorithm

Optimal Filtering [3] estimates the amplitude and the phase of the digitized signal through a weighted sum of digital samples. The procedure to compute the energy and phase with the OF algorithm are in equations 1 and 2 .

$$A = \sum_{i=0}^{n} a_i S_i \tag{1}$$

$$\tau = \frac{1}{A} \sum_{i=0}^{n} b_i S_i \tag{2}$$

where $S_i$ is the sample taken at time $t_i$. The amplitude, A, is the distance between the peak and the pedestal which is the baseline of the signal. The phase is the time between the received pulse and the pulsed used for the weights computation. Fig. 6 shows the pulse shape and the reconstructed magnitudes with OF with a set of weights computed for a pulse centered at $\tau = 0$ ns.

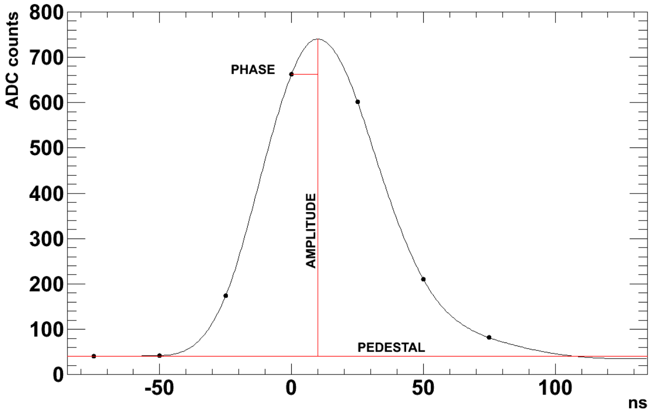

Fig. 6. Time shape of the signal with Optimal Filtering magnitudes for weights computed for a pulse centered at $\tau = 0$ ns.

The weights used in the OF algorithm are obtained from the pulse shape and noise autocorrelation matrix. The phase of the pulses during LHC operation is fixed because the digitization is synchronous with the TTC clock. Therefore, the weights are computed for the expected phase of every channel which can be predicted using the TileCal calibration system. The performance of the OF algorithm is sensitive to phase variations. The energy reconstruction presents a parabolic deviation proportional to the phase for small phases. This deviation can be corrected offline.

In addition, a Quality Factor (QF) of the reconstruction is computed to online detect deviations in the pulse shape due to pile-up or out of time pulses. The QF is estimated as a deviation of the received samples according to the expected pulse shape (see equation 3).

$$QF = \sum_{i=0}^{n} (S_i - (Ag_i + A\tau g'_i + p))^2 \tag{3}$$

Samples are estimated using the pulse shape, reconstructed amplitudes and an estimation of the pedestal (p). In addition, the derivative of the pulse is used to correct deviations in the pulse shape due to small phases.

## III. VALIDATION OF DSP RECONSTRUCTION

In addition to the reconstructed magnitudes the ROD can be configured to send out the front-end samples. This feature allows an offline reconstruction of the signal which has be used as a reference to validate the DSP online reconstruction. In particular, it has been used an offline implementation of the OF algorithm to reconstruct the samples. The obtained result is compared with the computed inside the DSP. In order to ensure that both algorithms are executed under the same conditions the offline and online algorithms should use the same set of weights and the same calibration constants for each channel.

### A. The Charge Injection System

The Charge Injection (CIS) is one of the calibration systems of TileCal [4]. It injects a configurable charge at the input of the shaper circuit allowing to calibrate the response of the readout electronics from the digitization. In addition, the injected pulse has programmable and fixed phase which allows to use the OF method. First, a preliminary study of CIS pulses allows to store in a database the value of the measured phase for each channel. Then, the corresponding weights are retrieved for each channel from this database and only small variations between the injected pulse and the phase stored in database are expected.

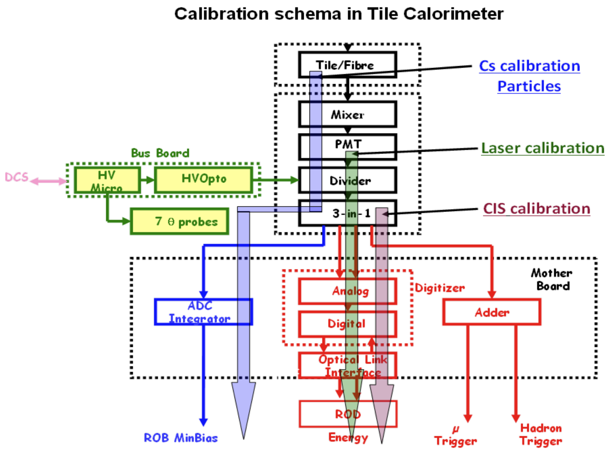

Fig. 7. Block diagram for the TileCal Calibration system.

### *B. Performance results of DSP reconstruction*

As detailed in the previous section the CIS calibration allows the injection of controlled pulses. It is used to emulate LHC conditions in terms of pulses with fixed phase. In addition, the amplitude of the pulse can be configured to study the performance of the reconstruction for the whole energy range both in high and low gains.

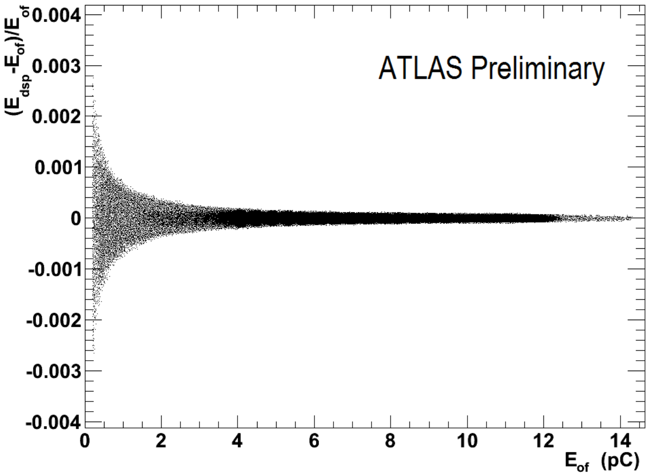

Fig. 8. Relative difference between energy reconstructed with Optimal Filtering in the DSP and offline for High Gain as a function of the energy reconstructed offline for a CIS scan run.

During LHC operation the ROD is configured to replace the front-end samples by reconstructed magnitudes (energy, phase and QF). However, during the detector commissioning phase and for calibration data the ROD can be configured to send the reconstructed magnitudes together with the front-end samples. It has been used to offline reconstruct the pulses in order to have a reference result to validate the online reconstruction. The offline reconstruction is performed within the Atlas offline software environment. This environment allows the usage of the databases used online to retrieve OF weights and calibration constants. Hence, we are able to perform online and offline reconstructions under the same conditions. Fig. 8 shows the relative difference between the energy reconstructed in the DSP and offline for the High Gain range as a function of the energy reconstructed offline. The absolute difference along the entire range is below 0.3%. The DSP precision is limited by the number of bits used to pack the DSP result. The High Gain range varies from -1 pC to 15 pC. The energy reconstructed in the DSP is packed using 15 bits which implies a maximum precision for the High Gain range of about $0.5 \cdot 10^{-3}$ pC. Assuming that offline reconstruction has infinite precision since the result is not packed, the DSP precision gives the expected difference between online and offline reconstructions. The result shown in Fig. 8 is consistent with the expected result.

Concerning the phase reconstruction the DSP precision is also limited by the number of bits available to pack the result. In this case, the range of phases varies from -64 ns to 64 ns. Tilecal data format uses 10 bits to pack the phase result. Therefore, the precision of the DSP for the phase is 0.0625 ns. The obtained results for the phase are also consistent with the difference between the online and offline precision.

## IV. CONCLUSIONS

The Optimal Filtering algorithm has been implemented in the DSPs of the TileCal RODs. The online reconstruction has been evaluated using calibration data and the results have been compared with an offline implementation of the OF method. The precision of the DSP reconstruction is limited by the number of bits used to pack the result obtained for energy and phase reconstruction. The offline implementation does not have this limitation. Therefore, the maximum expected difference between online and offline results is limited by the DSP precision. The obtained results for both energy and phase reconstruction corroborates the expected result. The relative difference between online and offline energy reconstruction is below 0.3% for the High Gain range which has a maximum precision of about $0.5 \cdot 10^{-3}$ pC. Concerning the phase reconstruction the maximum precision in the DSP is 0.0625 ns and the obtained result for CIS data are also consistent. The OF reconstruction implemented in the DSP will be used to reconstruct the first LHC collisions and from these data it will be possible to have a final assessment of the signal reconstruction in real experimental conditions.

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