PROCEEDINGS OF SCIENCE

ATLAS Phase-II Upgrade Pixel Data Transmission Development

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The current tracking system of the ATLAS experiment will be replaced by an all-silicon detector (ITk) in the course of the planned HL-LHC accelerator upgrade around 2025. The readout of the ITk pixel system will be most challenging in terms of data rate and readout speed. Simulation of the on-detector electronics indicates that the planned trigger rate of 1 MHz will require readout speeds up to 5.12 Gb/s per data link. The high-radiation environment precludes optical data transmission, so the first part of the data transmission has to be implemented electrically, over a 6-m distance between the pixel modules and the optical transceivers. Several high-speed electrical data transmission solutions involving small-gauge wire cables or flexible circuits have been prototyped and characterized. A combination of carefully-selected physical layers and aggressive signal conditioning is required to achieve the proposed specifications.

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1. ATLAS ITk pixel detector

The ATLAS Collaboration is preparing for an extensive modification of its detector in the course of the planned HL-LHC accelerator upgrade around 2025 [1]. The entire tracking system of silicon detectors and straw tubes will be replaced by an all-silicon detector (ITk), the five innermost layers of which will be segmented into pixels. A new on-detector pixel readout chip is being designed in the context of the RD53 collaboration [2]. The uplink (data) and downlink (clock/command, slow control) chains are foreseen to be optical transmission for most of their length, but radiation levels of order 1 Grad close to the beam pipe prevent the placement of optical components close to the readout chips. The first leg of the data transmission must be implemented with electrical signals, with a transition to optical signals roughly seven meters from the interaction region. The challenge is to balance requirements of very high bandwidth over a long distance against the desire to minimize the radiation lengths present in the ITk material.

2. Expected data rates

The increased luminosity at the HL-LHC implies increased data rates in the ITk pixel detector compared to the current ATLAS pixel detector. The expected data rates in the ITk pixel detector are derived from simulated $pp \to t\bar{t}$ events with 200 minimum bias events superimposed. Events pass through a full GEANT4 simulation of ATLAS and a custom digitization algorithm that has been validated with ATLAS data. The simulations do not include the expected effects of radiation damage, but they do assume a significant standard data compression factor. Results shown in Figure 1 assume a baseline L0 trigger rate of 1 MHz, although the outer layers may be read out at 4 MHz in a backup trigger strategy under development [3]. To allow for fluctuations in the data rate, the bandwidth must be large enough so that the average data rate does not exceed 70% of the available bandwidth. When this requirement is applied to the simulated data rates, the sustained data bandwidth is specified to be 5.12 Gb/s.

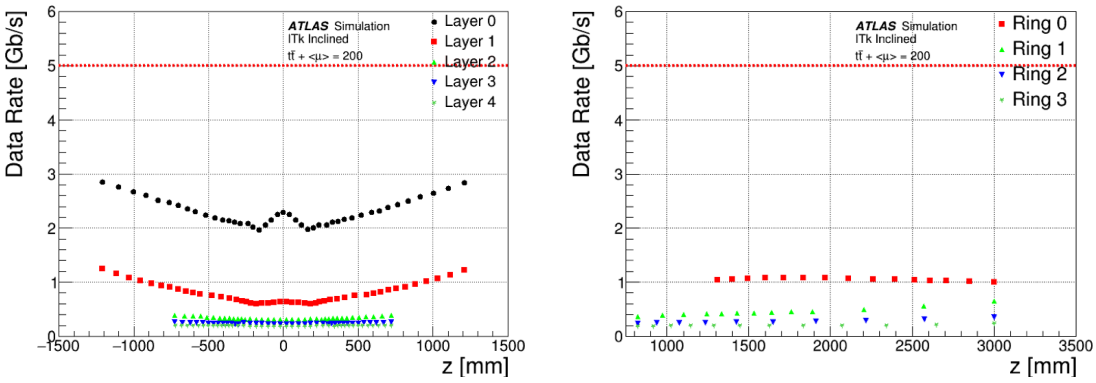

Figure 1: Expected data rates from the ITk pixel layers (left) and rings (right) as a function of z position. The average data rates per readout chip, after significant data compression, are calculated from simulated $pp \to t\bar{t}$ collisions with mean pileup density of 200 collisions per crossing.

3. Prototype electrical cables

The electrical links run from the pixel modules to the optical transceiver boxes outside the ITk volume. These links carry balanced low-voltage differential signals, with the exact protocol to be determined. To ensure reliable data transmission in the electrical link, the total end-to-end signal loss should be kept below 20 dB. This specification is based on the expected performance of the low-power drivers and receivers, and it matches common engineering practice. The bit error rate (BER) through the entire chain must be less than 1 part in 10^{12}, a requirement achieved with the current ATLAS inner detector and consistent with telecommunications standards.

Significant effort has been invested in finding data transmission solutions that satisfy these specifications. Long flexible twin-axial and twisted-pair cables have been prototyped, as shown in Figure 2. Flexible Kapton/copper printed circuit cables also offer a radiation-hard, low-mass electrical transmission solution. Two solutions for data transmission inside the pixel volume using Kapton flex technology with a differential embedded micro-strip arrangement and cross-hatched ground plane have been developed.

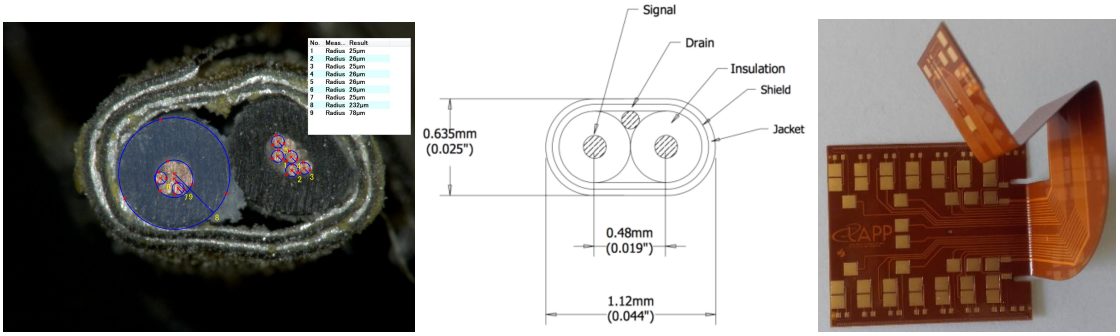

Figure 2: Prototypes of physical cables being studied for high-speed data electrical transmission. Shielded small-gauge twisted-pair copper cables (left), twin-axial copper-clad aluminum cables (middle), and flexible Kapton/copper circuits (right) are under study. Hybrid solutions are also possible.

4. Electrical characterization and performance measurements

Two different kinds of tests have been implemented to check performance of the prototypes. The first suite of tests used a vector network analyzer to measure the response of the device under test. Results from these scans are presented as differential S-parameters, following the usual definitions. The attenuation value is measured at 3 GHz, just above the Nyquist frequency for 5.12 Gb/s. A typical attenuation curve as a function of frequence is shown in Figure 3. The second suite of tests were conducted with a FPGA-based bit-error rate tester that sends pseudo-random bit sequences (PRBS-7 or PRBS-31) through the device under test [4]. The FPGA board implementing the tests is shown in Figure 3. Combined results from the two different kinds of tests are presented in Table 1, for a set of promising small-gauge electrical cables.

5. Signal conditioning developments

As shown in Figure 3, the high-frequency roll-off in the physical layer requires active compen-

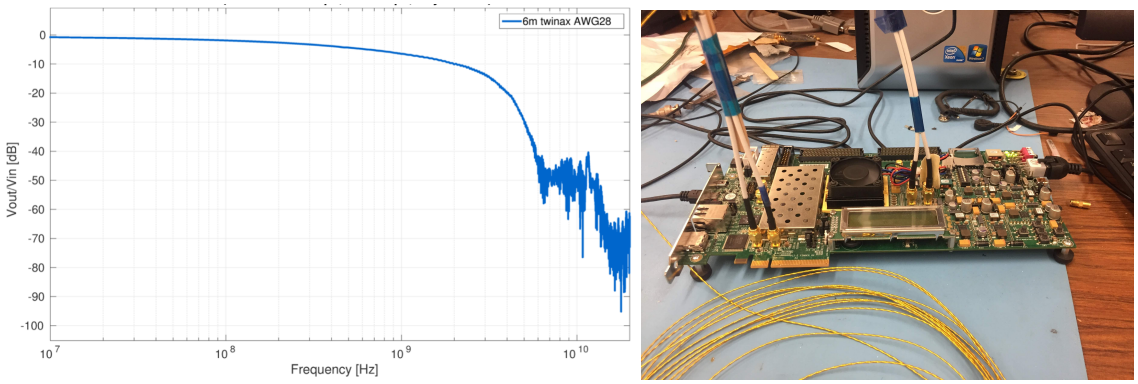

Figure 3: Example transfer function, showing attenuation of device under test (left), and FPGA-based bit-error rate tester (right).

Device	Length	Attenuation @ 3 GHz	Max Rate (DC bal.)
TA 28 AWG	6 m	14 dB	8.000 Gb/s
TA 30 AWG	6 m	17 dB	6.220 Gb/s
TA 34 AWG	4 m	20 dB	6.220 Gb/s
TWP 36 AWG	1 m	5 dB	4.976 Gb/s

Table 1: Test results from small-gauge electrical cables in twin-axial (TA) and twisted-wire pair (TWP) geometries. The maximum rate is defined as the highest throughput rate for which the bit-error rate specification is achieved. A DC-balanced code is assumed.

sation at the driver and/or receiver. At the driver, signal pre-emphasis boosts the high-frequency components of the wave-form, compensating for the specific properties (S-parameters) of a chosen data path. Receiver equalization acts as a high-pass filter, either fixed to compensate a specific roll-off function or based on dynamic feedback to optimize signals. An example of the improvement due to signal conditioning can be seen in the simulated eye diagrams shown in Figure 4.

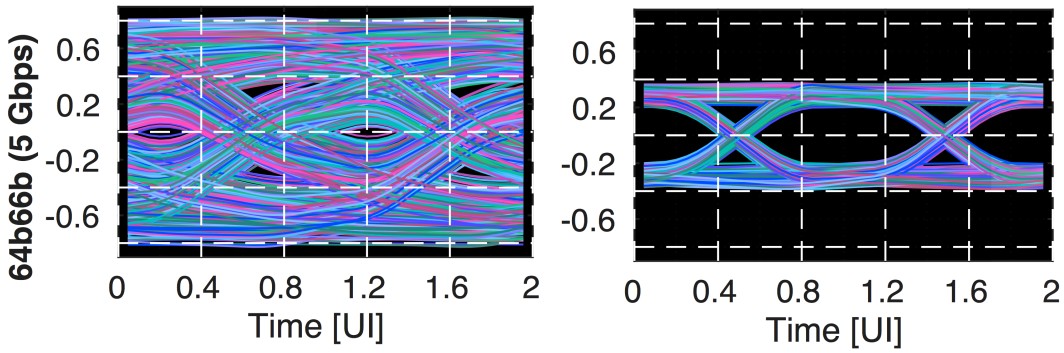

Figure 4: Simulated eye diagrams in long twin-axial cable before signal conditioning (left) and after signal conditioning with both pre-emphasis and equalization (right). The Matlab simulation convolves the pulse response (derived from S-parameter measurements) with an encoded bit sequence.

6. Conclusion

The pixel system of the ATLAS ITk project will require data transmission rates of up to 5.12 Gb/s. Several high-speed electrical data transmission solutions involving small-gauge wire cables or flexible circuits have been prototyped and tested, and some of the solutions fulfill the specifications for the project. A combination of carefully-selected physical layer and aggressive signal conditioning is required to achieve the proposed specifications.

References

[1] ATLAS Collaboration, "Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment," LHCC-I-023, CERN-LHCC-2012-022.

[2] RD53 Collaboration, "RD53A Integrated Circuit Specifications," CERN-RD53-PUB-15-001.

[3] P. Morettini, "Pixel DAQ and trigger for HL-LHC," JINST **12**, no. 03, C03042.

[4] J. Shahinian et al., "High speed data transmission on small gauge cables for the ATLAS Phase-II Pixel detector upgrade," JINST **11**, no. 03, C03024 (2016).