80Mbit/s Digital Optical Links for Control, Timing and Trigger of the CMS Tracker.

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Abstract

The development of a radiation hard 80Mbit/s digital optical link system for transmission of control, timing and trigger signals to and from the CMS Tracker is almost complete. This paper reviews the status of the project and summarises the performance of the most recent prototype components and links.

I. INTRODUCTION

Digital optical links will be used as part of the CMS Tracker control system to transmit the LHC clock and CMS Level-1 trigger at 80Mbit/s, as well control signals at 40Mbit/s to and from the Tracker front-end. Table 1 lists the key requirements of the optical link system[1].

The links form part of the 'control rings'[2,3], as shown in Fig. 1, that start and end at the Front-end Controllers (FECs) in the counting room. The boundary of the optical link system at the front-end in the Tracker is the electrical interface of the digital optohybrid (DOH), where signals are transferred to and from a copper ring of CCU modules which communicate with the various front-end ASICs. At the back-end the boundary of the optical link is at the transceiver (TRx) on the FEC.

There are 8 optical link channels per control ring. Four channels are required to communicate the TTC and control signals. The four other links are part of a redundancy scheme in case of component failures in the control ring[3].

Table 1: Main requirements for the CMS Tracker control links.

Item	*Min*	*Typ*	*Max*	*Notes*
Wavelength (nm)		1310nm		To share components with analogue readout links.
Speed (Mbit/s)	2		80	AC coupled. 10 consecutive zeros sent for reset signal.
Bit-error-rate		10^{-12}	10^{-9}	
Jitter (ns)			0.5	rms
Skew (ns)			2	Fibres to or from same optohybrid
Environment	CMS Tracker			10 years irradiation. 4T B-field. –10°C.

There will be 320 redundant rings in the Silicon Tracker, which requires 2560 optical links. This quantity, plus additional links for other CMS sub-detectors including ECAL, Preshower and Pixels, is however still much smaller than the analogue optical link readout system of the Silicon Tracker, which has ~40000 channels. The philosophy of the digital link project has therefore been to use as many of the same component parts as possible from the much larger analogue optical link system. The resources and effort required for link development have therefore been minimized and we have avoided the need to qualify a new set of front-end components[4,5].

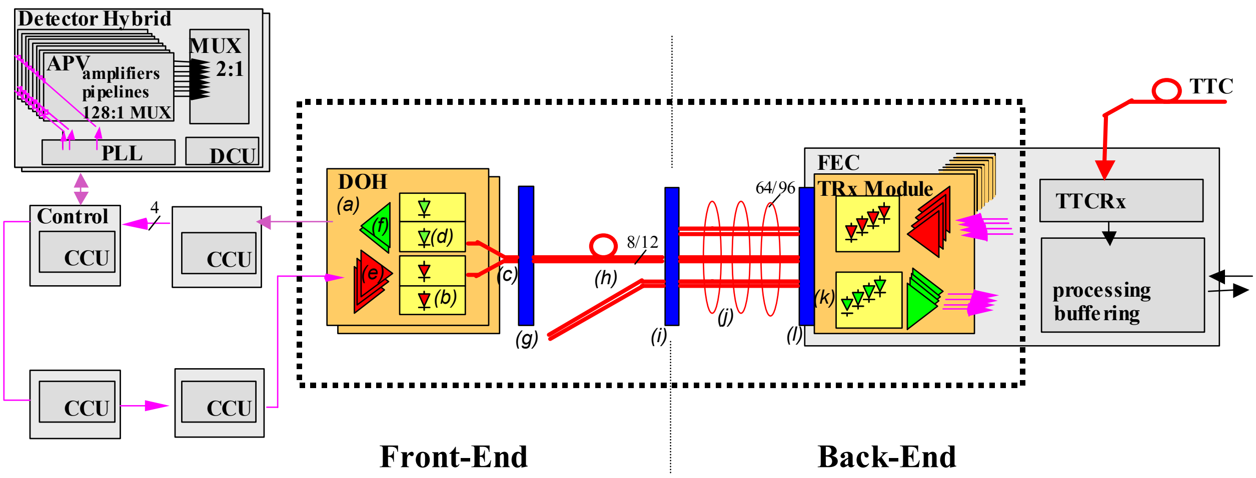

Figure 1: CMS Tracker control ring[1]. The front-end is exposed to radiation, a 4T magnetic field, and will operate at -10°C. The labels *(a)* through *(l)* correspond to references in the text.

Some components are specific to the digital control links. Suppliers of these components have been identified and prototypes tested, as will be outlined in the following Sections.

The final specifications of the system and components and their interfaces are currently being finalized with a plan to be ready for production of links in 2003. The development of 80Mbit/s digital links for the CMS Tracker is therefore close to completion.

In this paper we review the system components and architecture and then present results of recent measurements on prototype front-end optohybrids, back-end digital transceivers and complete prototype links.

II. Link Components and Architecture

On the front-end DOH, labelled *(a)* in Fig. 1, the lasers *(b)* are 1310nm InGaAsP/InP edge-emitters, pigtailed with single-mode 9/125/250/900µm fibre *(c)* that is terminated with an MU connector. The receivers on the DOH are InGaAs/InP p-i-n photodiodes *(d)* pigtailed in the same way as the lasers. Also mounted on the DOH are the LLD[6] laser driver ASIC *(e)*, and the RX40[7] receiver ASIC *(f)*.

After the distributed patch panel *(g)*, which houses MU-sMU connections, the fibres attached to components on a given DOH (and its redundant back-up DOH) are then fanned into a 12-way ruggedized ribbon cable *(h)* using a compact fan-in element. In each ribbon there are 4 fibres transmitting light to the Tracker, 4 dark fibres, and 4 fibres transmitting light from the Tracker. The 12-fibre modularity matches that of the fibre-ribbon components used in the analogue readout link system at the relatively small expense of the additional dark fibre.

The optical cables follow the same routing as for the readout links and will share the same in-line patch panels *(i)*, using MFS connectors. Groups of eight ribbons are then fanned into 96-way dense multi-ribbon cables *(j)*, which then pass to the counting room. A fully detailed cabling and connection map has been made for the Silicon Tracker[8].

At the back-end of the links in the counting room, 4+4 way transceiver modules *(k)*, each having a 12-way MPO optical interface *(l)*, will be mounted on the FEC.

As in the case of the CMS Tracker readout links, except for the custom-made ASICs, all of the components are either commercial off-the-shelf (COTS) components or devices based closely on COTS. All of the components situated at the front-end have therefore been qualified[4,6,7] for sufficient radiation hardness and reliability to operate inside CMS for at least 10 years. These tests were focused on the Tracker environment, though it is expected that the level of testing will satisfy other CMS sub-systems.

The radiation hardness issues and other aspects of the production of the digital optical links are outlined in the Quality Assurance manual[5], which details the production flows and the details of validation, qualification and lot tests of components.

Also, in terms of laser safety, a full analysis has been made[9] according to IEC standards. Since low levels of optical power at 1310nm are used in the digital links the lasers on the DOH and TRx are Class 1 components and the rest of the fibre-optic parts are rated as Hazard Level 1.

III. Prototypes and Testing

Extensive tests of many sub-components of the digital links, such as the lasers, LLD ASIC, p-i-n photodiodes and RX-40 ASIC have already been reported in earlier workshop papers[4,6,7]. Here the results focus on recent tests of the digital optohybrids (DOH) made at CERN, tests on back-end 4+4-way transceiver modules (TRx), and a brief report of a full prototype link built from of these components.

A. Front-End Digital Optohybrids, DOH

Two series of prototype DOH have been designed at CERN. The most recent iteration is shown in Fig. 2.

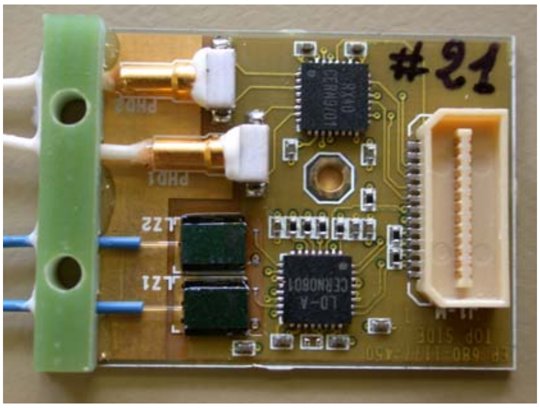

Figure 2: Photograph of prototype DOH showing the back-side containing the active parts. Left: two photodiodes above 2 laser diodes. Middle: packaged RX40 and LLD ASICs connected to the photodiodes and lasers respectively. Right: male 26-way NAIS connector, the electrical interface to the ring of CCU's in the Tracker. Several capacitors are mounted on the front-side.

The DOH footprint is 25x35mm^2 and its height is 5mm. The overall power consumption is expected to be 350mW, which corresponds to the worst-case of biasing both lasers at their maximum current.

The lasers on the DOH are Mitsubishi die in 'minipill' packages made and supplied by ST Microelectronics. These devices are representative of the final components. Photodiodes from Fermionics were used for these prototype DOHs though the final photodiodes have not yet been procured. Both lasers and photodiodes had ~1m single-mode fibre pigtails with FC/PC connectors. The final components will use qualified Ericsson fibre and MU connectors from Sumitomo.

This latest design of the DOH included packaged LLD and RX40 ASICs, which are also representative of the final components.

The electrical interfaces to the hybrid are the power supply (0 and 2.5V), LVDS input signals, and a reset output signal (active low). There are also I2C lines for controlling the LLD ASIC.

Five DOHs were produced in the second run with packaged ASICs and three have been tested to date. A new DOH production run is under way to provide a stock of components for use in control system development.

B. Back-End Digital Transceiver, TRx

The 4-way 2.5Gbit/s transceiver module (TRx) made by NGK Optobahn was chosen as the most suitable component for the on-going development of the control link system. In particular, the TRx modularity matches that of the control system and the MPO optical interface of the module matches the 12-way modularity of the cabling scheme. The module also appeared to be compatible with the main functional requirements of the system, even though it was designed for much faster applications.

The main objective of these tests has therefore been to establish whether or not these modules are indeed compatible with the DOH and the digital link system as a whole.

A PCI card (O-FEC) was designed for testing the TRx modules and to provide an interface to prototype FECs which have only electrical I/O. A further interface card also allows connection between an O-FEC and a bit-error-rate (BER) tester[10] (BERT). One O-FEC card has also been modified with the addition of a mechanical jig to hold the TRx in place for testing without the need to solder the TRx.

Following a preliminary evaluation of 3 pieces, a further 10 TRx modules were purchased for the digital link development at CERN, of which five have been fully tested to date.

C. Prototype DOH and TRx testing

The test procedure for both the DOH and TRx was relatively similar since both are transceivers. We measured the optical I/O characteristics: transmitter output signal amplitude and average launched power and the receiver sensitivity and saturation. In addition the ability of the DOH to output the correct reset signal was also checked.

1) Transmitter characteristics

An input 40MHz clock and 40Mbit/s data signal (with PRS-7 coding[11]) was sent to the DOH or TRx under test from the BERT. The DOH has LVDS electrical I/O and the TRx has LVPECL input and CML output. Level-translation interfaces were therefore made for each test-setup in order to be compatible with the ECL I/O of the BERT.

The optical output signal characteristics were measured using a calibrated optical head and oscilloscope. The optical output eye-patterns were very clean and wide open at these slow speeds and examples are shown elsewhere[1]. Figs. 3 and 4 summarize the optical transmitter characteristics of the tested DOH and TRx channels respectively.

The measured signals from DOH suggest that the dc offset could be too large and might saturate the TRx receiver stage, which is specified as –5dBm maximum average signal power. This problem can be avoided in the final system by selecting a more appropriate start-up I2C setting for the LLD dc current laser bias. A study is being made to determine the optimum I2C setting, whilst also taking into account the expected radiation damage to the laser threshold current over the experiment lifetime.

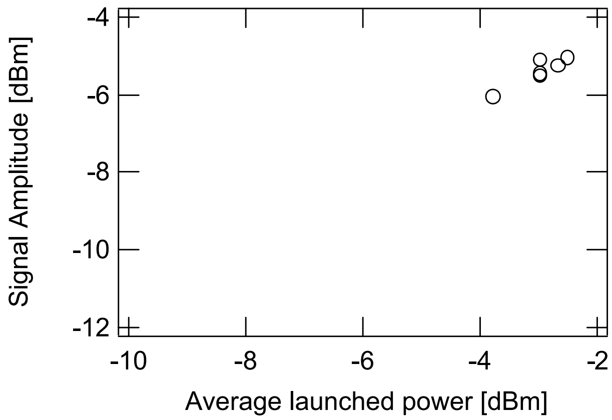

Figure 3: Transmitter optical output characteristics on the 3 DOHs tested. The measurements were made with the existing default I2C settings of the LLD ASIC at power-up of the DOH. These are 22mA dc bias and 12.5mS gain.

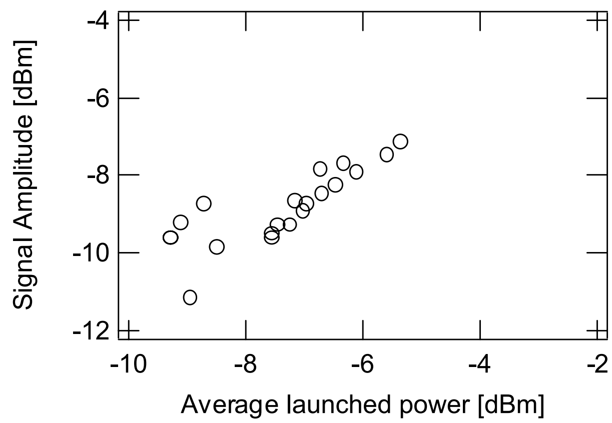

Figure 4: Transmitter characteristics on the 5 TRxs tested.

The measured TRx optical output levels were all compatible with the optical power budget intended for the digital link system. However there is a large range in the preliminary NGK-Optobahn TRx specification (average launched power between –13dBm and –5.5dBm), which will limit the ultimate safety margin in the system at the low-power end. This is because the RX40 sensitivity is limited by design to –20dBm input and there will be some insertion loss at each patch-panel (up to ~2.5dB). It may therefore be necessary to increase the TRx minimum signal size specification.

2) Receiver characteristics

Sensitivity and dc saturation measurements were made on the DOH and TRx optical receiver channels, using a test-setup similar to that shown in Fig. 5. There were minor variations to this setup depending upon the measurement type and whether a DOH or TRx was under test.

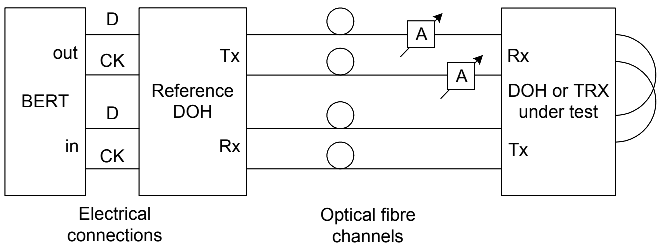

Figure 5: Receiver test-setup.

The sensitivity was measured by adding attenuation into a given fibre channel, using a variable optical attenuator, and then noting the power level at which the link started to fail. In these measurements the failure point was where the BER first exceeded 10^{-9}.

The dc saturation was measured by connecting the DOH or TRx under test to a reference DOH. The LLD dc-bias to the laser on the reference DOH was then increased until bit-errors were observed. The average power level into the Rx was then measured using an optical head.

The results for the DOH and TRx receivers are shown in Figs. 6 and 7 respectively.

The results of the DOH receiver tests were all satisfactory. In terms of the sensitivity, the input response of the DOH has been truncated by design within the RX40 to a power level of approximately -20dBm[7]. In further measurements, the DOH were also tested at the limits of their nominal input conditions, i.e. attenuation of the input optical signal to close to –20dBm. Measurements were made over 15 hrs yielding no bit-errors, corresponding to BER<3×10^{-13}.

Concerning the DOH receiver saturation, the RX40 was designed to be capable of compensating input dc currents up to 500µA. This capability was intended to compensate an increase in leakage current in the photodiode due to radiation damage but the same feature also works for (the potentially larger) dc offset of the input optical signal. In all but one receiver channel, where the saturation power level was 530µW, corresponding to a photocurrent of ~450µA, the DOH channels did not saturate until well above 500µA input.

For the TRx receivers, the sensitivity at least -22dBm and the saturation level was more than -3dBm. These values were significantly better than the respective preliminary module specifications of -18dBm and -5dBm, which suggests that there may be a possibility to increase the saturation specification. This would allow us to specify a higher start-up LLD I2C laser bias setting on the DOH providing a greater safety margin against radiation damage.

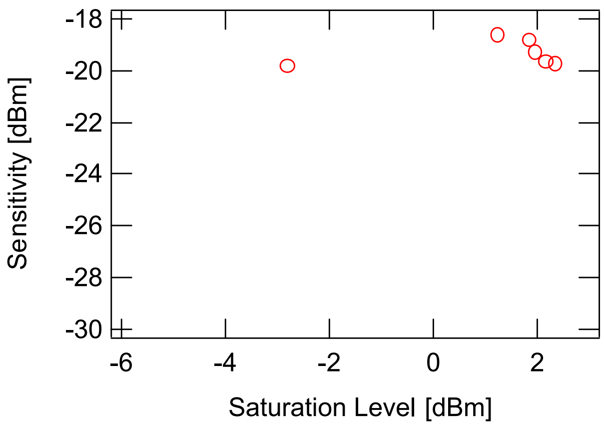

Figure 6: Receiver characteristics on the 3 DOHs tested.

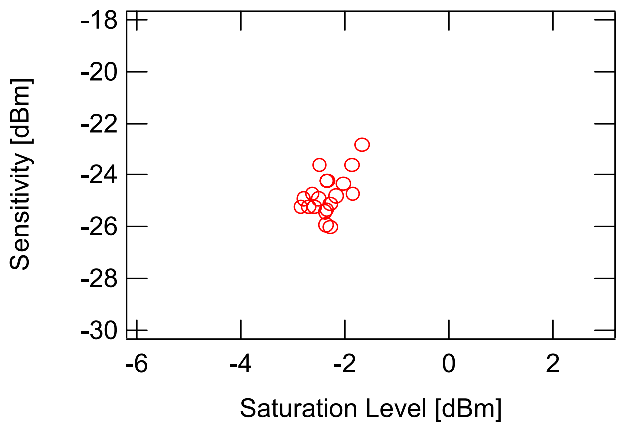

Figure 7: Receiver characteristics on the 5 TRxs tested.

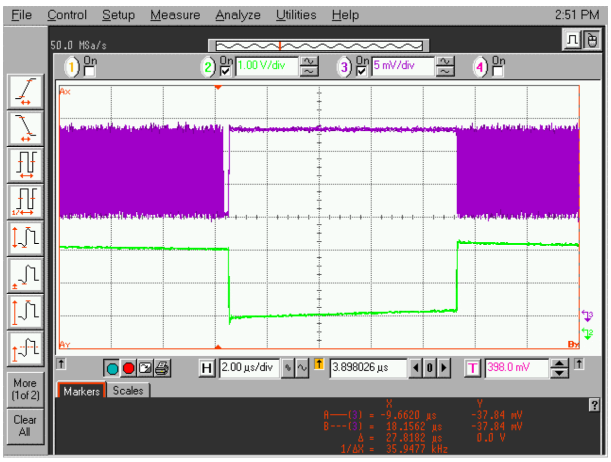

Figure 8: Reset action of RX40. The upper Trace is the input data signal where a train of 10 zero-levels generates a reset flag (lower trace) from the RX40. The data output is disabled during the period that the reset flag is set 'low'.

Finally, an arbitrary waveform generator (AWG) coupled to a reference TRx was used to test the generation of reset signals by the RX40. As already mentioned, the RX40 is designed to generate a reset signal after detection of a sequence of 10 consecutive 'zero' levels, i.e. 250ns 'low' signal on the data line. This signal was simulated at the AWG by removing an increasing number of 'one's on a 40Mbit/s clock signal. An example of the reset action of a DOH under test is shown in Fig. 8. The 3 DOHs tested (and 10 earlier prototypes) all generated reset signals from the appropriate input optical signal of at least 10 consecutive zeros on the data line.

D. Full Link Test

A full prototype digital link from DOH to TRx (mounted on an O-FEC) was constructed using more realistic cables and connectors as shown in Fig. 9. This is very similar to the DOH and TRx test set-ups but with an additional 100m of 12-way ribbon connected to the TRx. The signal out of the DOH receiver was looped back into the transmitter to simulate a ring of CCU modules.

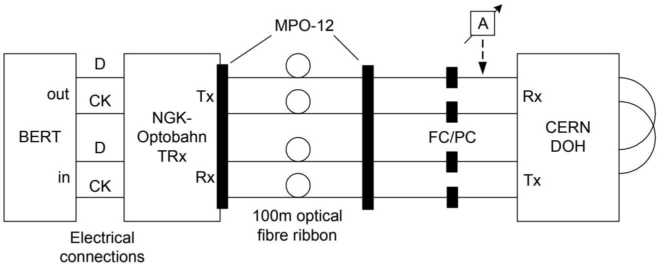

Figure 9: Full link test set-up.

The power margin in each link channel was determined using a variable optical attenuator placed in each optical channel in turn. The margin was defined as the additional attenuation required to cause the link to fail or to increase the BER significantly. In the optical links from DOH to TRx the margins were 17.5dB and in the optical links from TRx to DOH the margins were 10dB.

The difference in these margins is consistent with the differences in TRx and DOH performances shown in Figs 3, 4, 6 and 7. Based on these figures and allowing an estimated 1dB of loss for the additional MPO connection, the possible combinations of DOH and TRx available here would have had a range of margins of 16dB-21dB in the DOH to TRx channels and 8dB to 13dB in the TRx to DOH channels.

The prototype link was also operated for 15 hours with a 40Mbit/s PRS-7[11] signal from the BERT. No errors were observed, corresponding to BER$<3\times10^{-13}$.

In summary, these measurements, combined with the component measurements of the previous Section, confirm the robustness the digital control link system.

IV. CONCLUSION

Digital links are being developed for the control of the CMS Tracker and several other sub-systems inside CMS including the ECAL, Preshower and Pixels. These links transmit the 40MHz clock, trigger and reset signals as well as 40Mbit/s control data between the detectors and counting room.

All of the final link components have been chosen, with most being parts taken from the CMS Tracker analogue readout links. The photodiode, TRx and DOH parts, that are specific to the digital link, are in the late stages of prototyping and development and have not yet been procured.

Prototype digital optohybrids have been made and tested to work satisfactorily at CERN. Commercial back-end transceivers have also been tested and were found to be potentially compatible with the final system. A full prototype link system, using these prototype components and realistic cabling and connectors, operated with a large safety margin and BER$<3\times10^{-13}$.

The specifications and interfaces of the link system and components will be frozen at the end of 2002. In the meantime a small number of prototype digital links are available for control system testing and development.

V. ACKNOWLEDGEMENTS

We gratefully acknowledge the assistance of Federico Faccio and Giovanni Cervelli, who are the respective designers of the RX40 and LLD ASICs. Also we would like to thank Christophe Sigaud, Clement Richard and Ernest Murer for preparing the various test boards for the DOH and TRx modules.

VI. REFERENCES

[1] CMS Tracker digital control links project web-pages: http://cern.ch/cms-opto/control

[2] CMS Tracker Technical Design Report. CERN LHCC 98-6 (1998).

[3] CMS Tracker control system project web-pages: http://cmstrackercontrol.web.cern.ch/CMSTrackerControl/

[4] K Gill et al, *Proceedings of 7th Workshop on Electronics for LHC Experiments*, CERN/LHCC/2001-34, 160-164 (2001).

[5] CMS Tracker Optical Links Quality Assurance Manual. K. Gill, J. Troska and F. Vasey (2001).

[6] G. Cervelli, et al., *Proceedings of 7th Workshop on Electronics for LHC Experiments*, CERN/LHCC/2001-34, 155-159 (2001)

[7] F. Faccio et al., *Proceedings of 6th Workshop on Electronics for LHC Experiments*, CERN/LHCC/2000-041, 299-303 (2000).

[8] CMS Tracker optical links cabling scheme. A. Zanet and F. Vasey (2002). cms-tk-opto.web.cern.ch/cms-tk-opto/integ/cabling/

[9] K. Gill, CMS Internal Note 2002-10. The most up-to-date version is maintained on EDMS, document CMS-TK-YM-0001.

[10] Wandel and Golterman Type PF-5 Bit-Error Rate Tester.

[11] PRS-7 is a 2^7-1 bit pseudorandom bit pattern.