Predicting the In-System Performance of the CMS Tracker Analog Readout Optical Links

Stefanos Dris[1,2], Markus Axer[1], Karl Gill[1], Robert Grabit[1], Raquel Macias[1], Etam Noah[1], Jan Troska[1] and Francois Vasey[1]

[1]CERN, 1211 Geneva 23, Switzerland
[2]Blackett Laboratory, Imperial College, London, UK
Stefanos.Dris@cern.ch

Abstract

The analog optical links employed in the CMS Tracker readout chain consist of components whose individual gains determine the overall gain of each link. Production data on the components' gain distributions has been compiled, and this is used to perform a Monte Carlo simulation to establish the overall spread in link gain that can be expected in the final system. The results show that the performance of the optical links satisfies the design requirements.

I. Introduction

The ~10 million detector channels in the CMS Tracker [1] are multiplexed and read-out by analog optical links. These are embedded in the data acquisition system shown in Figure 1.

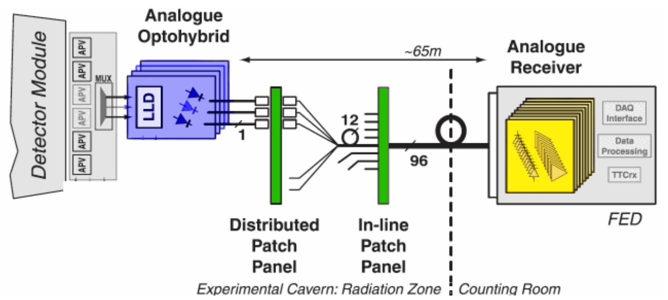

Figure 1: CMS Tracker readout system including the optical link [2].

The optical links operate single-mode at 1310nm wavelength [3]. Multiplexed electrical signals from the detector hybrids are converted to optical by the Analog Optohybrid (AOH). The Linear Laser Driver ASIC (LLD) [4] on the AOH directly modulates the edge-emitting laser diode drive current to achieve light amplitude modulation. Fibers from the pigtailed lasers are connected to a fan-in (Distributed Patch Panel) which merges single fibers into a 12-fiber ribbon via small form-factor MU-type single-way connectors. At a second break-point within the CMS Detector (In-Line Patch Panel), the transition to a rugged multi-ribbon cable (8×12-fiber ribbons/cable) is made via 12-channel MFS-type array connectors. In the counting room each ribbon connects directly to a 12-channel analogue optical receiver (ARx12) module on the Front End Driver VME card (FED), using MPO12 connectors. The receiver converts the optical signals to electrical for digitization and further processing.

Electronic, optoelectronic and optical components for the ~40 000 analogue optical links of the CMS Tracker are currently in production. The optical links built from these components must match the performance requirements of the overall readout system in terms of dynamic-range and resolution. The readout links are required to transmit 3.2MIPs with 8bit resolution[1] [5]. Production is sufficiently advanced that process monitoring has yielded a statistically significant set of test data to allow real distributions of the performance parameters to be extracted. One of the most important parameters, the overall link gain, is determined by the aggregate effect of all components. Hence a Monte Carlo simulation has been performed to compute the complete link gain distribution from the available component production test data. On the transmitting side, the LLD was designed with switchable gain settings to compensate for component gain tolerances. Four gain settings are available, with nominal values of 5.0, 7.5, 10.0 and 12.5mS, allowing a certain amount of gain equalization in the final system. The influence of switching the LLD gain setting on the overall link gain spread is investigated.

The current study expands on a previous simulation carried out before component production commenced [5]. The components' gain distributions were assumed to be uniform, within the manufacturers' specification limits. The previous study was essentially a worst-case scenario of the system's gain spread.

II. Method

A. Simulation Components

Figure 2 is a schematic representation of the optical link, showing the components simulated. In the case of the AOH, the gain contribution to the link has been extracted using two different approaches. First, the data for the overall gain of the AOH is used. This is compared to the gain calculated from production test data for the LLD and Laser Transmitter gains. Insertion loss data has been measured for the fiber connectors in the two patch panels. Responsivity data for the complete ARx12 has been collected, and this is used in the simulation. The 100Ω load resistor is specified at 1% tolerance. For simulation purposes a 4σ Gaussian distribution of the resistor value was assumed.

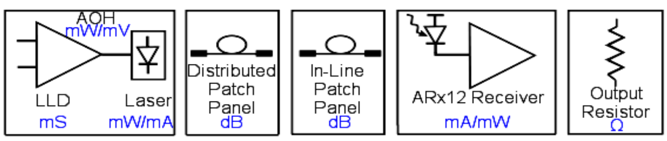

Figure 2: Optical link components used in the Monte Carlo simulation.

[1] For 320µm silicon strip detectors.

The probability distribution functions (PDFs) of the gain values for each of the components were estimated using the available production test data. Figure 3 shows the transconductance PDFs for each of the four LLD gain settings. The specification boundaries are shown by the shaded areas, while the calculated mean of each setting is also indicated. While remaining within specifications, all four PDFs have higher means than their corresponding nominal values. Figure 4 is the laser transmitter slope efficiency PDF. Again, the data seems to be on the higher end of the specification window (shaded area). It is therefore not surprising that the AOH efficiency PDFs (Figure 5) also have means above the specification boundaries' mid-points. The AOH efficiency PDF for each LLD gain setting is plotted for two different cases: Calculated efficiency obtained by multiplying the LLD and laser transmitter gains (dotted lines in Figure 5), and efficiency data from production testing of the whole AOH (solid lines in Figure 5). Figure 6 shows that both connector types have very low insertion losses compared to the specification limit. Finally, ARx12 responsivity is shown in Figure 7.

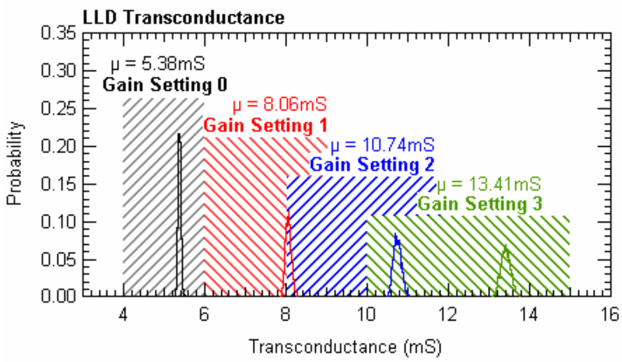

Figure 3: PDFs of Linear Laser Driver transconductance for each of the four gain settings selectable on the AOH.

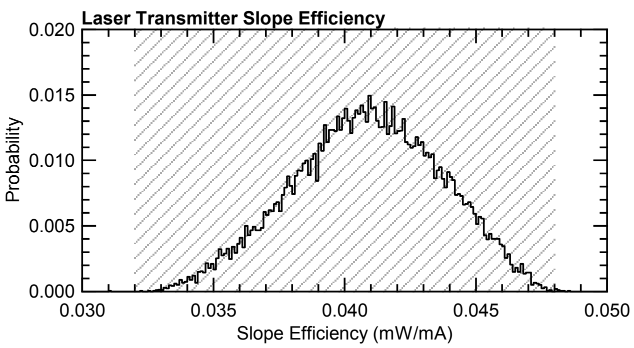

Figure 4: Laser Transmitter slope efficiency PDF, showing specification limits (shaded area).

Comparing the AOH efficiency distributions extracted from AOH production test data and by calculation from the LLD and laser transmitter data (Figure 5), there is a discrepancy. The difference observed could be attributed to the amount of test data available in each case. While the gains of ~15 500 LLD channels and ~21 500 laser transmitters were used to compile their corresponding PDFs, the gains from only ~3 300 AOH channels could be obtained to date. In addition, production tests for the LLD and laser transmitters take place in a different lab using different experimental setups than the AOH. It was decided to conduct the current Monte Carlo simulation using the combined LLD and laser transmitter gains. The decision can be reviewed as more AOH data becomes available, and the differences are understood.

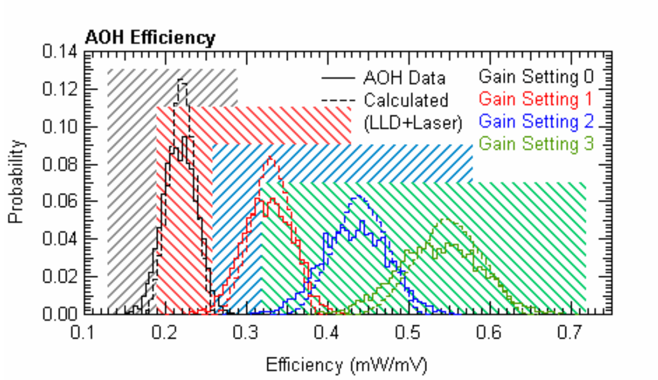

Figure 5: PDFs of AOH efficiency for all four gain settings, and both methods of gain extraction.

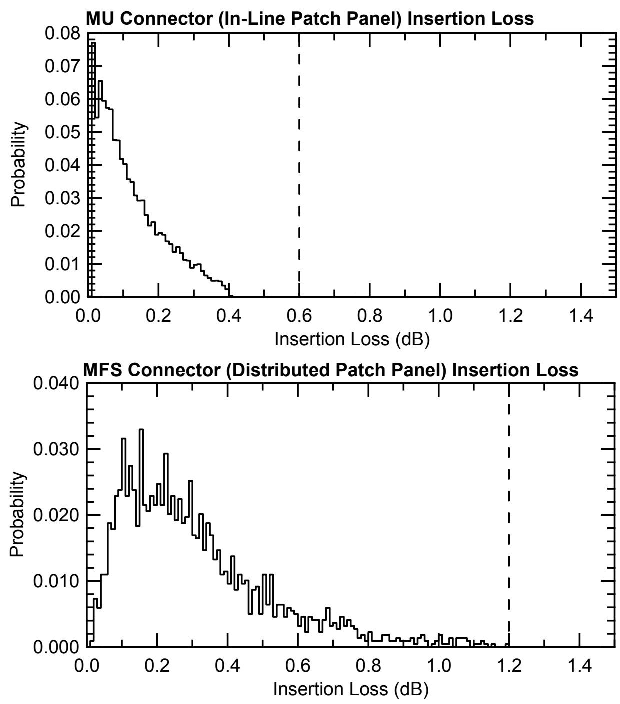

Figure 6: Insertion Loss PDFs for MU and MFS type connectors. The dotted lines show the maximum specification.

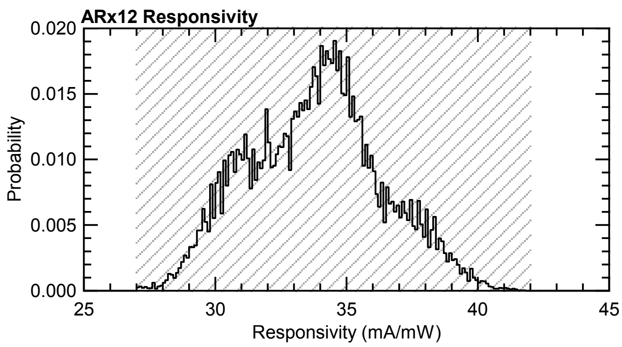

Figure 7: ARx12 Responsivity PDF, showing specification limits (shaded area).

B. *The Inverse Transform Method*

The inverse transform method [6] employed in the simulation provides a means of sampling any probability distribution function (PDF). It is briefly described here.

Suppose a random variable, x, has a PDF, $f(x)$, on the range $-\infty < x < \infty$, and a cumulative distribution function (CDF), $F(x)$. If x is discrete, the CDF will have a discontinuous jump of size $f(x_k)$ at each allowed x_k (k=1,2…). A uniform random variable, u, is chosen on (0,1), and the required sample value x_k is found such that:

$$F(x_{k-1}) < u < F(x_k) \equiv \Pr(x \le x_k) = \sum_{i=1}^{k} f(x_i)$$

The method is illustrated in Figure 8, showing how the LLD transconductance for gain setting 0 was sampled.

The same procedure was repeated for all components of Figure 2 in each iteration of the simulation. When multiplied together, the samples give the overall optical link gain in V/V. Any given run consisted of 1 million iterations. This gives a large degree of confidence in the limits yielded by the results, given that the final system will contain ~40 000 links.

The ability to switch the LLD was also incorporated in the model. A link gain value was calculated for each of the four LLD gain settings. Hence it was possible to simulate equalization of the optical links by choosing the setting closest to the nominal specified (target) value of 0.8V/V.

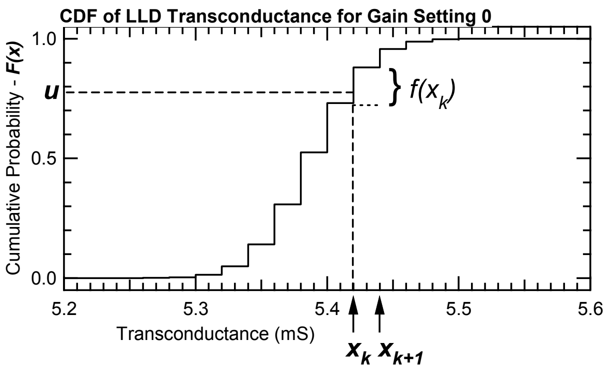

Figure 8: CDF of LLD transconductance for gain setting 0, illustrating the inverse transform method.

III. Results

A. *Simulation*

1) *Without LLD Switching*

The simulation was first run for the four gain settings of the LLD, without any attempt at equalization. The resulting distributions are roughly Gaussian (Figure 9). The nominal gain of 0.8V/V is also shown on the plot (dashed line). There is a very large gain range available using the available LLD settings. The position of the distributions with respect to the 0.8V/V specification suggests that lower gain links can be better compensated by using higher gain settings. The high-end tail of the Gain 0 trace exceeds the nominal gain, and since these links are already at their lowest setting, they cannot be further compensated.

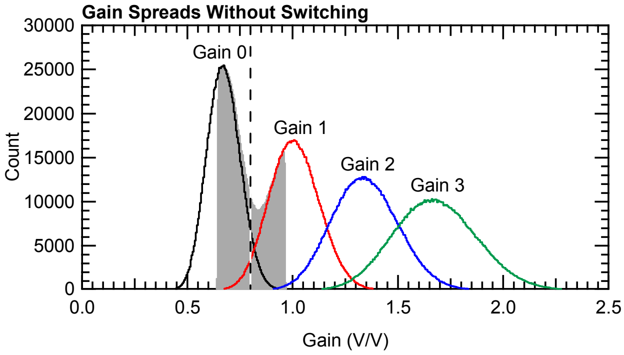

Figure 9: Showing the 'single gain' spread distributions obtained without switching of the LLD.

2) *With LLD Switching*

The simulation was run incorporating the ability to switch between LLD settings in order to equalize all gains as close as possible to the nominal value. Figure 10 shows the resulting spread. The laser driver switching process can be thought of as cutting into the source distributions and selecting the slices centered on 0.8V/V. This is best visualized in Figure 9, where the switched spread is superimposed on the 'single gain' distributions (shaded area).

Figure 10 shows the switched gain in more detail. The distribution has two distinct boundaries equidistant from the target gain value. This is due to the switching algorithm which selects the appropriate LLD setting simply by deciding which gain is closest to the target. It is possible to determine the extents of the distribution by simple calculation. The lower limit is ~0.64V/V, while the upper limit is 0.96V/V.

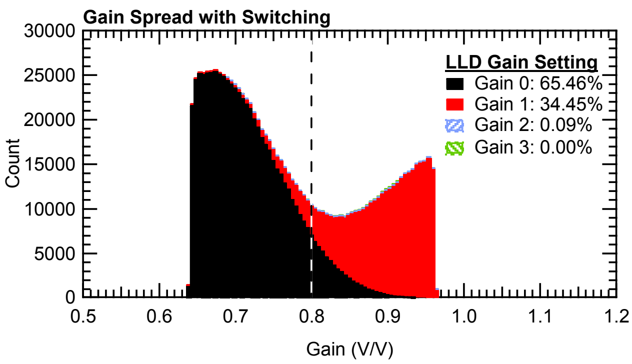

Figure 10: Overall link gain distribution with switching of the LLD, showing the contributions from each gain setting.

It should be noted that there are very few, statistically insignificant links that lie above the upper limit in the switched gain distribution, and are not visible in the plot. This is due to the tail of the Gain 0 distribution that exceeds the limit of 0.96V/V. These links are already at their lowest gain setting, and cannot be further compensated. Clearly, it is not an ideal situation to have any part of the Gain 0 distribution above the target gain of 0.8.

Figure 10 also shows the contribution from the 'single-gain' distributions. ~65% of the links are set to LLD Gain 0, ~35% to Gain 1, while almost none of the links have to be set to the two higher settings. The switched spread is not symmetric around the target value; the mean value is 0.775V/V with a standard deviation of 0.0977.

The results show that the optical links are well within the original gain specifications [7]. These set a gain range of 0.25-1.5V/V for the 'typical' LLD gain setting 1, and 0.3-1.3V/V for the switched gain case, at room temperature. The simulation suggests that the typical setting should now be changed to LLD gain setting 0.

It is worth noting that the Tracker will operate at -10˚C, while the production tests are carried out at room temperature. The temperature dependence of the AOH gain (and particularly that of the laser transmitters) is complex and cannot be predicted on a laser by laser basis. However, a previous study [8] on a number of transmitters showed their efficiency increased, on average, by ~7% when going from +20˚C to -10˚C. The variation on the gain change was approximately +/-10%.

In addition, the detector readout chip (APV25) is also expected to show an increase in gain. Temperature effects will be incorporated into the simulation in the future. The possibility of lowering the load resistor value can also be studied, hence compensating for the gain increase due to temperature.

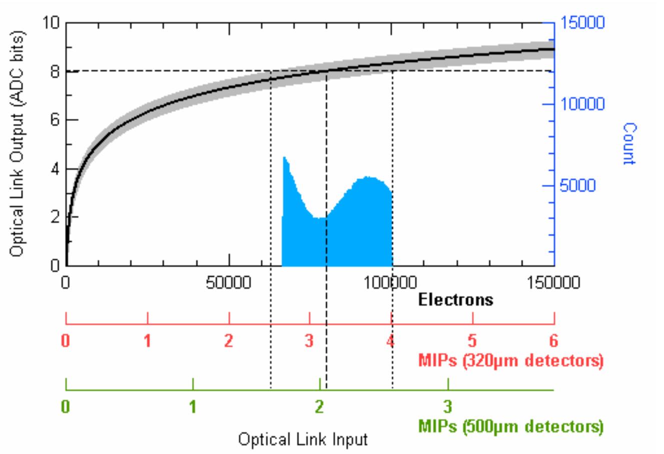

Figure 11: Showing Optical Link Output vs Input in ADC bits (left axis). The histogram (right axis) shows the spread in dynamic-range.

3) Available Dynamic-Range

The significance of the switched link gain spread on the dynamic-range of the readout system is illustrated in Figure 11. After the analog signals are transmitted through the optical links, they undergo digitization by a 10-bit, 1.024V input-range ADC on the Front End Driver card (FED) [9] in the counting room. After digitization and processing, the two MSBs of the data are discarded. It is therefore useful to look at the signal size that can be transmitted by the system using 8 bits, before clipping occurs. The signal size is in terms of electrons and is easily related to MIPs for both thin and thick detectors. Hence the dynamic-range figure of merit is in electrons/8bits.

The solid line in Figure 11 corresponds to the target link gain of 0.8V/V. Hence, at the specified gain, signal sizes up to 80 000 electrons can be transmitted in their entirety. The shaded area around this line corresponds to the full range of switched gains predicted by the simulation. The maximum signals that fit in 8bits will range from ~63 200 to 100 500 electrons.

On the same figure, the spread in dynamic-range (in electrons/8bits) is also shown in the form of a histogram. There are only a few statistically insignificant links with a dynamic-range between 63 200 and 66 500 electrons/8bits. These are the same simulated links having gains over 0.96V/V in the switched gain spread (Figure 10). Ignoring these, the dynamic-range of the links will lie between 66 500 and 100 500 electrons/8bits.

The signal sizes can also be interpreted in MIPs, assuming that 1 MIP produces 25 000 electrons in thin detectors, and 39 000 in thick detectors (see bottom axes of Figure 11). For thin detectors, the maximum signal sizes will be between 2.65 and 4 MIPs/8bits. The corresponding range for thick detectors is 1.7 to 2.6 MIPs/8bits.

4) Comparison to Previous Simulation

The results obtained can be compared to the previous study [5] which assumed uniform gain distributions within the specifications of each optical link component. The switched gain and 'single gain' spreads are shown in Figure 12.

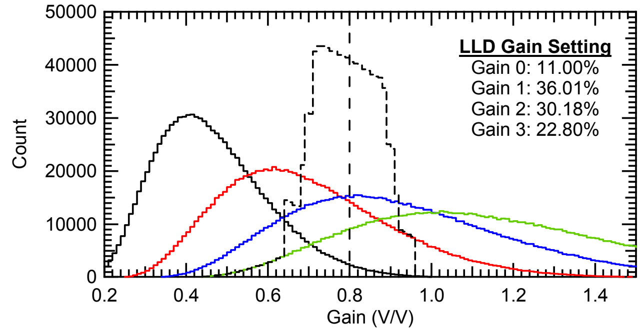

Figure 12: Switched gain distribution (dashed line) obtained by assuming uniform component gain distributions. 'Single gain' spreads are also shown (solid lines).

It is immediately obvious that the shapes of the 'single gain' distributions are different than in the current simulation. Their spreads are much larger, while their means are lower. The results led to the expectation that the links would be set mostly to gain settings 1 and 2. However, production test data show the links have higher gains than expected, and hence most have to be set to LLD setting 0.

It is worth mentioning that the larger switched gain spread is due to the low-end tail of the Gain 3 distribution. Clearly, low-gain links could not be compensated as well as high-gain links, which is the opposite of the current situation. If one ignores this tail, the extents of the switched spread would be exactly the same as those obtained with real production data (0.64-0.96V/V). In fact, if the LLD had a fifth gain setting, these low-gain links could be compensated and the tail would disappear. Therefore switching the LLD allows the final system spread to remain within the same window of gain, so long as the high-end tail of the Gain 0 distribution and the low-end tail of the Gain 3 distribution lie within this window, regardless of the 'single gain' distribution shapes. The size of the gain window depends on the resolution of settings available on the LLD. Hence, a future system could be designed so that real component gain distributions (within their specification ranges) are irrelevant; it would possible by simple calculation to determine the appropriate number of LLD gain settings and their resolution.

B. *Gain Spread in the Real System*

The CMS Tracker test beam that took place in June 2004 presented the opportunity to study the largest number of optical channels ever deployed in a single system setup. The gains of 123 analog optical links of the Tracker Endcap (TEC) system were calculated for each LLD gain setting.

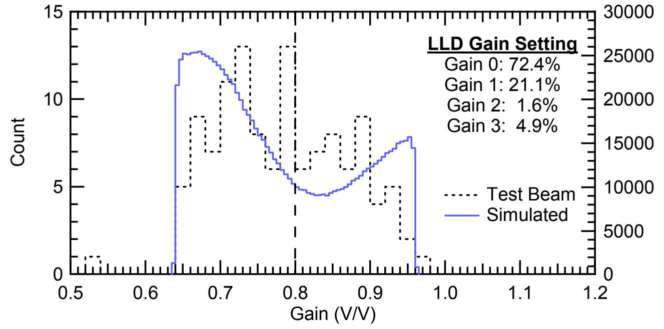

Figure 13: Switched gain distribution of TEC optical links in the test beam. The simulated switched gain is also shown.

Figure 13 shows the gain distribution obtained in the TEC system with LLD switching used to equalize the links. The limits are almost identical to that obtained via simulation (0.64 to 0.96V/V), the results of which are overlaid on the same figure.

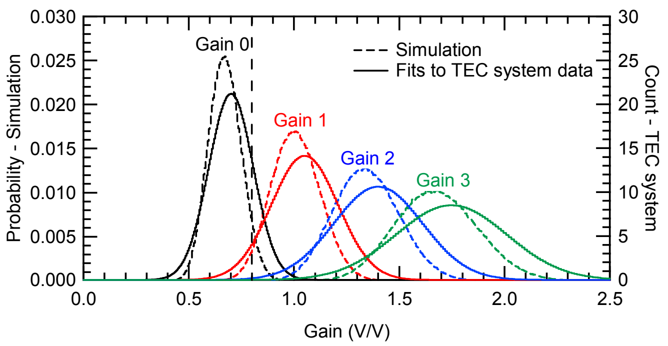

Figure 14: Comparison of 'single gain' distributions obtained from TEC data and simulation.

It is not surprising that the switched gain distribution of the real system closely matches that obtained via simulation, for the reason explained in the previous section: the extents of the spread mostly depend on the LLD gain setting resolution. The simulation's accuracy can be better assessed by looking at the 'single gain' distributions.

The statistics of the TEC system data are low; at gain settings above 0, the increased spread makes it very difficult to fit a Gaussian curve to the data. In order to make a useful comparison to the simulation, only Gain 0 data was used to perform a fit. The other distributions were then derived by multiplying by the appropriate factor, determined by the average gain values of the LLD (Figure 3). The result is shown in Figure 14, where there is strong agreement between the simulation and TEC system data. The real data shows a larger spread. This can be attributed to components that are part of the readout chain (but not part of the optical link) that were not included in the simulation (e.g. the APV25 readout chip and passive analog components present on the FED).

IV. Conclusions

A model for the CMS Tracker analog optical link has been developed and used in a Monte Carlo simulation to determine the distribution of gains that can be expected from the ~40 000 links that will be deployed in the final system. The results obtained represent the most accurate prediction yet, using data from production testing of the link's constituent components. The original specifications will be met for every single readout link in the final system. The gains calculated in a real system setup validate the results obtained by simulation.

The gains of the Tracker's 40 000 readout optical links are expected to lie within a 0.32V/V window, from 0.64 to 0.96V/V. This is 32% of the spread initially specified (0.3-1.3V/V).

The LLD and laser transmitter exhibit gain spreads on the high end of their specifications, while the connectors introduce very little insertion loss, leading to overall link gains that are higher than expected. This is where the benefit of having a switchable LLD is best demonstrated. Switching decouples the extents of the gain spread from variations of the shapes and means of the 'single gain' distributions.

It has been shown that the 'typical' LLD gain setting is 0 (5mS), in contrast to the expected setting of 1 (7.5mS). This means that there is less room for compensation of high-gain links. The simulation can be used to determine if the optoelectronic receiver load resistor should be changed. This could be set to a lower value that will shift the 'single gain' distributions so that the mean of gain setting 1 is closest to 0.8V/V (e.g. with a load resistor value of 75Ω).

V. References

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

[2] CMS Optical Links homepage, http://cms-tk-opto.web.cern.ch

[3] J. Troska *et al.*, "Optical readout and control systems for the CMS Tracker", *IEEE Trans. Nucl. Sci.,* Vol 50, No. 4, pp.1067-1072. (2003)

[4] G. Cervelli *et al.*, "A radiation tolerant linear laser driver array for optical transmission in the LHC experiments", *Proc. 7th Workshop on Electronics for LHC Experiments,* CERN/LHCC/2001-034, pp155-159. (2001)

[5] T. Bauer, "A model for the CMS Tracker analog optical link", CMS Note 2000/056.

[6] S. Eidelman *et al.*, "The Review of Particle Physics", Physics Letters B592, 1 (2004).

[7] CMS Tracker Optical Link Specification, Part 1: System. CERN/EP/CME.

[8] R. Macias, "Laser threshold current and efficiency at temperatures between -20°C and +20°C", EDMS document CMS-TK-TR-0036. (2003)

[9] J. Coughlan *et al.*, "The Front-End Driver card for the CMS Silicon Tracker readout", *Proc. 8th Workshop on Electronics for LHC Experiments*, CERN/LHCC/2002-034 pp. 296-300. (2002)