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Bit Error Rate measurements on prototype digital optical links for the CMS Tracker

C. Azevedo, F. Faccio, G. Cervelli, K. Gill, R. Grabit, F. Jensen, F. Vasey

CERN, Geneva, Switzerland

Abstract

Two prototypes of a four-channel digital optical link to be used for the slow control of the CMS Tracker detector were tested for bit error rate, at transmission rates of 40 Mbit/s and 80 Mbit/s. Both prototypes used the same transmitter and PIN photodiode, but different receiver configurations: one used COTS electronics, whilst the other used a digital receiver ASIC developed at CERN in a 0.25 μm process. Both links proved to be well within the specification limits even after the ASIC receiver was irradiated to a 20 Mrad total dose, and the PIN photodiode to a 6.5×10^{14} n/cm^2 fluence.

1 Introduction

The data acquisition system of the CMS tracker will make use of optical fibre links for analogue readout of detector signals from the front-end electronics, and for digital transmission of clock and data between the front-end and the back-end electronics. The basic technology used for the digital links is similar to the one used for analogue links: edge-emitting lasers operating at 1310nm, epitaxial PIN photodiodes and single mode optical fibres [1]. The components at the front-end will be immersed in a highly radioactive environment, resulting in high radiation doses over a long (10 years) lifetime period. This means that radiation-tolerant design will have to be used for the electronics and that all other components of the optical link in this region will have to be radiation-hard [2][3][4]. No such constraints will exist at the back-end.

The digital optical fibre links, in number of approximately 1'000, will distribute LHC clock and trigger signals. These same digital links will also act as a bi-directional channel between the Front End Controller (FEC) and rings of control modules (CCU), transmitting commands and responses to and from the front-end readout chips. A simplified representation of the CMS tracker optical control system is illustrated in Figure 1.

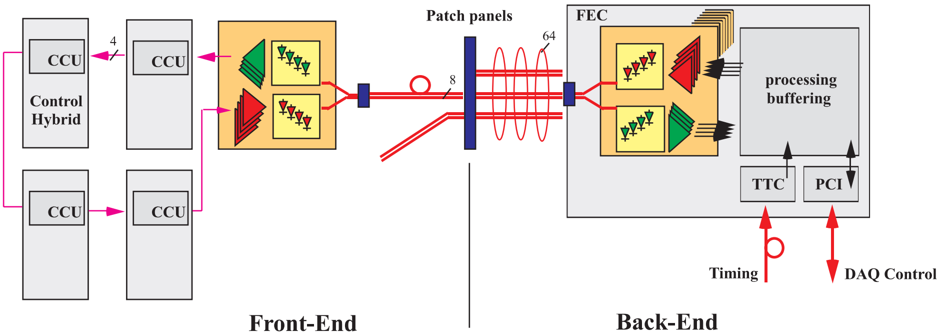

Figure 1: CMS Tracker control system.

The Bit Error Rate (BER) is the main criterion used to assess the transmission quality of a digital optical link. It is defined as the ratio of incorrectly received bits to the total number of bits transmitted, and is calculated as [5]:

$$BER = \frac{number\ of\ error\ bits}{total\ number\ of\ bits} = \frac{number\ of\ error\ bits}{bit\ rate \times time\ of\ measurement}$$

The sensitivity of the system is defined as the minimum optical power amplitude at the input of the receiver in order to achieve a certain bit error rate.

For all the investigated systems, the BER was evaluated in several conditions: individual performance of each channel (with data flow in only one channel), and with crosstalk between channels (with data flow in adjacent channels). These measurements were taken at different transmitter bias levels, and for different delays between clock and data [6]. The measurement time ranged from seconds in high BER conditions to days when operating the link in realistic conditions.

Table 1 summarises some of the target specifications that should be met for the CMS Tracker optical link. More detailed specifications can be found elsewhere [7].

Table 1: Target specifications for the CMS Tracker optical link @ 25 °C.

Operational specifications					
	min	*typ*	*max*	*unit*	*note*
Total length	60	100	120	m	
Bit Rate	2		80	Mb/s	AC coupled
Bit Error Rate		10^{-12}	10^{-9}		
Sensitivity		-30	-20	dBm	
Skew			2	ns	Between any 2 fibres coming from the same hybrid
Jitter			0.5	ns	rms
Operation rate		4000		hrs/year	

Table 1 (cont.): Target specifications for the CMS Tracker optical link @ 25 °C.

Electrical specifications					
	min	*typ*	*max*	*unit*	*note*
Input voltage range	-400		+400	mV	LVDS, differential referred to Vss
Input impedance		100		Ω	
Output voltage range	-400		+400	mV	LVDS, differential referred to Vss
TRx hybrid power supply	2.25	2.5	2.7	V	Vdd - Vss
Radiation resistance					
	min	*typ*	*max*	*unit*	*note*
Neutron	$2x10^{14}$			n/cm^2 (1 MeV)	Integrated over lifetime
Charged hadrons	$3x10^{14}$			$1/cm^2$ (300 MeV)	"
Gamma	$15x10^6$			Rad (Si)	"

2 Links Under Test

Two configurations of digital optical links were tested: the same transmitter -named Tx- was connected to any one of two receivers, named Rx1 and Rx2. For the remainder of this text, the ensemble Tx-Rx1 is referred to as "Link 1" and the ensemble Tx-Rx2 is referred to as "Link 2", where both "Link 1" and "Link 2" have 4 channels. The components used in both cases are listed in Table 2.

A comparison between the two link versions is not the aim of this paper. Although not having been tested for radiation-hardness, and being much more 'power hungry' than Rx2 (see Table 3), the receiver Rx1 allowed to have a functional link and test a full optical chain long before the ASIC was available. Furthermore, the use of non radiation-hard components can still be envisaged for the back-end electronics. Links of type 1 have been successfully used during beam tests at CERN in 2000 to transmit clock, trigger and data [8]. Links of type 2 have also been extensively tested for single event effects (SEE) in a particle beam [9,10]

Table 2: List of components used for Link 1 and Link 2.

Component	*Type*	*Candidate for use in final system*
Tx	4x Alcatel 1951 LMC pigtailed lasers	No, unsuitable package
Tx	1x quad ASIC developed in a 0.8μm BiCMOS process	No, rad-soft
Rx1	4x Fermionics FB80S-7F PIN photodiodes	Yes
Rx1	4x Philips NE5223 transimpedance amplifier with AGC	No, rad-soft
Rx1	4x Philips NE5224 limiting amplifier	No, rad-soft
Rx2	2x Fermionics FB80S-7F PIN photodiodes	Yes
Rx2	1x quad ASIC developed in a commercial 0.25 μm CMOS technology using radiation-tolerant design	Yes

The transmitter Tx is composed of four MQW semiconductor lasers attached to single mode fibres and a laser driver, which provides the dc pre-bias current (variable, via a I2C interface), as well as the modulation current proportional to the input signal [11].

The receiver Rx1, built using commercially available components, has four PIN photodiodes mounted. The photocurrent of each of the photodiodes is converted to voltage by a transimpedance amplifier with an Automatic Gain Control (AGC) and differential outputs, which are then handled by a limiting amplifier and a discriminator, resulting in the final digital signal. The AGC feature allows to handle bursty data over a range of nA to mA of signal current, therefore increasing the link performance in terms of reliability of the transferred data.

The receiver Rx2 was built around an ASIC developed at CERN in a commercial 0.25 µm CMOS technology using radiation-tolerant design. It can process up to four channels, but only two PIN photodiodes were mounted. The ASIC implements a transimpedance amplifier, a chain of limiting amplifiers and a LVDS driver [12].

Table 3: Comparison between commercial chip set(1) used in Rx1, and ASIC receiver used in Rx2.

	Philips commercial receiver	*ASIC receiver*
Channel count	1	4
DC input current compensation	+2 mA	> +200 µA
Sensitivity (for BER = 10^{-12})	≈ -33 dBm(2)	≈ -28 dBm
Dynamic range	> 40 dB	> 30 dB
Nominal supply voltage	5.0 ± 0.5 V	2.5 ± 0.5 V
Power consumption per channel	250 mW	30.6 mW
Output signal level	ECL	LVDS
Bandwidth	> 150 MHz	> 80 MHz
Radiation hardness (10 Mrad)	Not applicable	Yes

(1) Transimpedance amplifier + limiting amplifier.

(2) Obtained using a receiver similar to Rx1, but with only one photodiode mounted.

Whereas the commercial receiver chip-set is performing well beyond the CMS-Tracker digital link requirements, the ASIC receiver used in Rx2 is clearly optimised in terms of density, bandwidth and power dissipation.

3 Experimental Setup

The BER measurements were performed by feeding a repetitive pseudo-random ECL-NRZ bit sequence (2^{11} - 1 bits) into the link; this sequence was then compared to the original data stream by the bit error rate tester (BERT). An adjustable optical attenuator was inserted between the transmitter and receiver modules to stress the system and investigate its optical power margin [13][14]. The dc working point of the laser transmitters could be varied by the laser driver, controlled by an I2C interface.

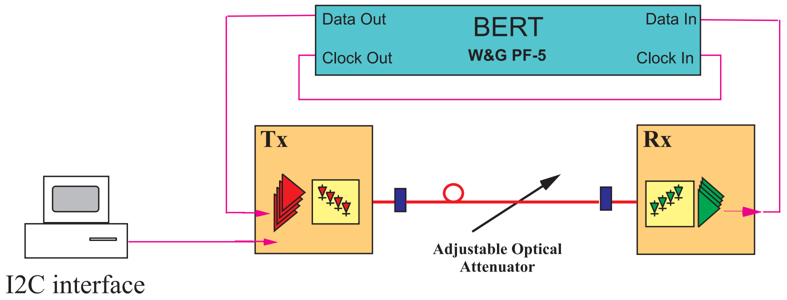

Figure 2: Experimental setup for BER measurements.

The operating transmitter was pre-biased to an optical output power level P_{DC} well above threshold. It was modulated by the input signal around this working point: $P_{Tx} = P_{DC} + P_{AC}$. The received optical power after variable attenuation was $P_{Rx} = Att^*(P_{DC} + P_{AC})$. After compensation of the DC-input current by the receiver circuit, the signal of relevance for the BER tests was $Signal = Att^* P_{AC}$.

The bit rates tested, 40 Mbit/s and 80 Mbit/s, represent respectively, the transmission rates for data and clock signals under real operation conditions.

By varying the length of the copper cable carrying the clock signal of the BERT, the data signal could be sampled at different points, thus allowing to determine the influence of the delay (i.e. skew) between clock and data signals on the BER.

To test for crosstalk influence, an additional signal was fed into one or more of the remaining Tx channels. To evaluate the power supply rejection ratio (PSRR) of Link 2, an uncorrelated signal was injected into the power supply of Rx2 to simulate noise.

4 Results

4.1 Results for Link 1

After alignment of clock and data signals, two BER measurements were taken at different dc pre-bias levels, in the optical signal power range [-42 dBm; -33 dBm]. Only one channel was active during the measurement reproduced in Figure 3.

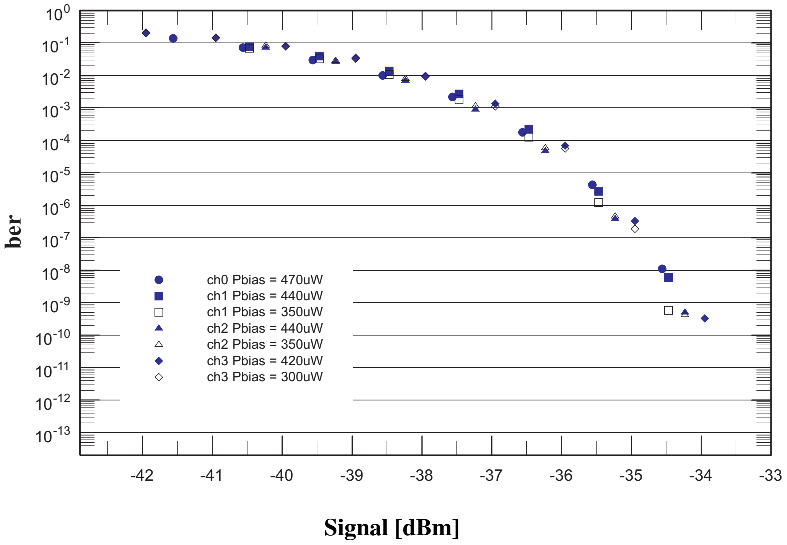

Figure 3: BER results at 40 Mbit/s and 0 ns relative delay between clock and data signals (see also Figure 5).

One sees from Fig. 3 that a BER of 10^{-9} is achieved at a signal level of less than -34dBm. When compared to the specified sensitivity of -20dBm (see Table 1), this indicates the availability of a 14dB power margin to accommodate noise and other perturbing effects not present in this measurement.

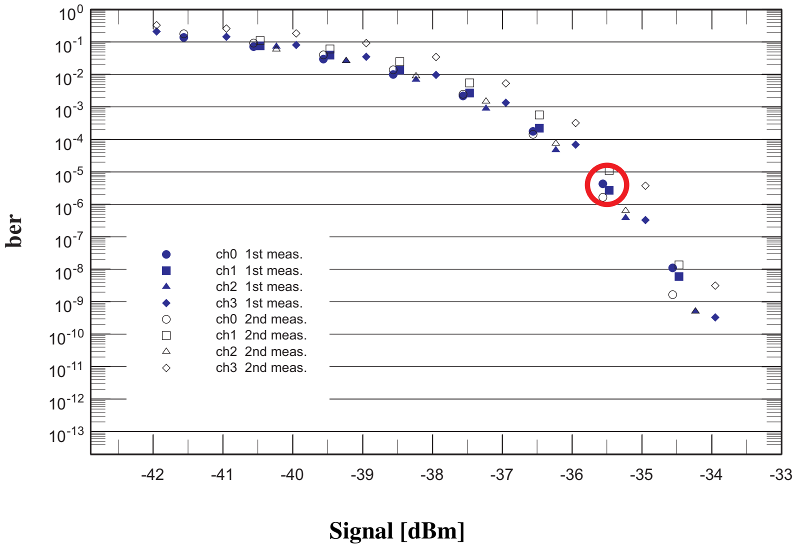

Figure 4: Comparison of BER results obtained two months apart, under the same conditions. The circled point indicates a measurement at -35.50 dBm (see also Figure 5).

A second set of measurements (represented by empty symbols in Figure 4) was taken after 2 months, under the same conditions as before, at a pre-bias level of 450 µW. The comparison between the two groups of values demonstrates a good reproducibility.

The exact BER values measured during a given test depend on the time position of the sampling point in the data stream. A time scan of the sampling point was performed on link1 at an arbitrarily chosen signal power of –35.5dBm. The BER as a function of skew between data and clock is shown in Figure 5. The delay between clock and data signals was varied by changing the length of the copper cables carrying the clock of the tester.

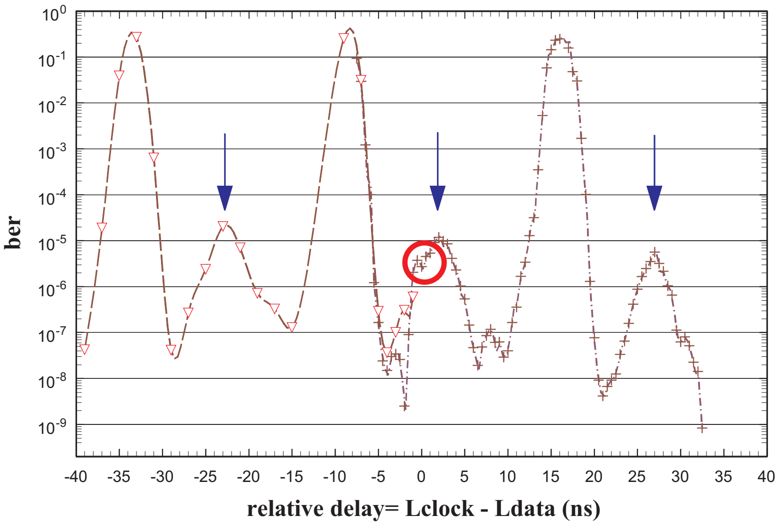

Figure 5: BER vs delay results, for Link 1 at 40 Mbit/s and -35.50 dBm signal level. The circled point indicates a measurement at the optimal delay normally used (see Figure 4).

The unexpected degradation of the BER -signalled by the arrows in Figure 5- when clock and data signals are apparently optimally aligned is confirmed by the eye diagram shown in Figure 6: the degradation of the link performance at low receiver power levels is caused by the glitches in the centre of the eye during the clock active transition. These glitches are only visible at very high attenuations. They are caused by the noise present in or around the digital Rx1 chip, boosted when the input stage operates at highest gain. They disappear when received signal levels reach about -33dBm. Nevertheless, the presence of these glitches makes the link performance sensitive to the exact phase of the clock with respect to the data, at very low received power levels. This effect is undesirable and should be investigated further if links of type 1 are to be used in the future.

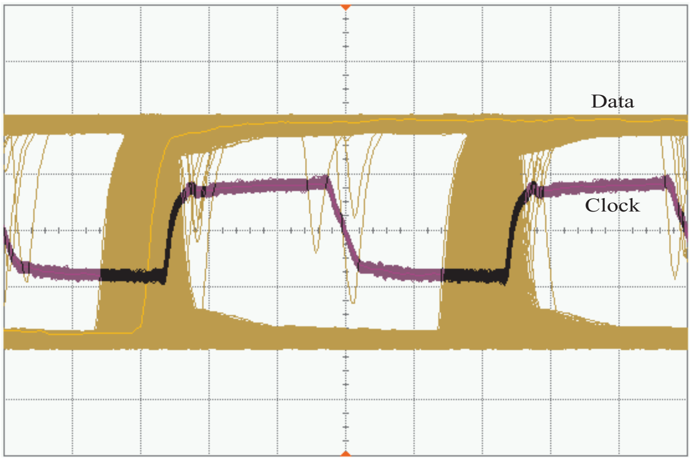

Figure 6: Eye pattern for Link 1 at 40 Mbit/s and -35.5 dBm.

A crosstalk measurement was also performed. No degradation of the BER was observed due to the presence of uncorrelated data on neighbouring channels. This is a predictable result since Link 1 handles data from each channel independently (one transimpedance amplifier and one limiting amplifier per photodiode) at the expense of a bigger circuit size and higher power consumption.

Finally, a performance test in real operating conditions was carried out with no extra-attenuation on the light path between Tx and Rx1. The long-term measurement, performed using channel 0 running for 30 days at 40 Mbit/s and –4.5 dBm signal level (pre-bias optical power ≈450 µW), yielded 0 errors, resulting in a BER lower than 9.6×10^{-15}.

4.2 Results for Link 2

4.2.1 Performance before irradiation

We measured the BER performance of the receiver Rx2 at a bit rate of 80 Mbit/s. Only two of the four channels in the chips were bonded to photodiodes. One of the two diodes had been previously irradiated with neutrons (mean energy 6 MeV) to a level of $6.5 \cdot 10^{14}$ cm^{-2}, whilst the other was new. Figure 7 shows the result of the measurement on the channel bonded to the new photodiode in three different conditions. First, the neighbour channel was kept silent during the measurement ("no crosstalk"). Then, an uncorrelated signal of maximum amplitude was applied to the neighbour channel ("crosstalk"). Finally, this last measurement was repeated while simultaneously injecting a 20 mV (peak-to-peak) uncorrelated signal on the 2.5 V power supply to simulate noise and evaluate the PSRR of the circuit ("crosstalk + noise on PS"). Even in presence of a big noise on the power supply, a BER of 10^{-12} is reached for signals considerably smaller than the minimum specified sensitivity of –20 dBm. There was no significant difference in the performance of the two channels (new vs irradiated photodiode).

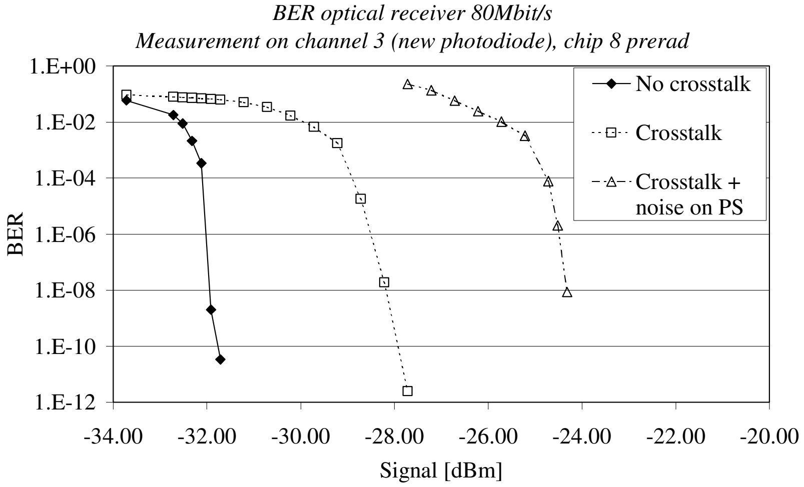

Figure 7: BER measured on the channel bonded to a new photodiode in three different conditions.

The present version of the ASIC circuit was designed to cope with a possible radiation-induced leakage current of the photodiode up to about 100 µA. Such current introduces an additional noise source at the input of the preamplifier, and the consequent penalty on the BER is shown in Figure 8 in the "crosstalk" condition. The diode leakage current was simulated in the measurement by increasing the DC optical power. Compared with the measurement performed with minimal DC input current, the penalty is less than 1 dB for the highest DC input current of 96 µA.

We made a long-term measurement to estimate the BER of the receiver in the worst-case specified operational condition. Both channels were operated, as both the clock and the data signals for the BER measurement were sent through optical lines. The channel bonded to the irradiated photodiode was chosen to receive the data, and the optical power was tuned to minimum AC power (10 µW) and maximum DC power (100 µW). The measurement was made at a bit rate of 80 Mbit/s, i.e. double the real operation rate. We stopped the measurement after 15 days and 14 hours without any error, for a BER better than $9.27 \cdot 10^{-15}$.

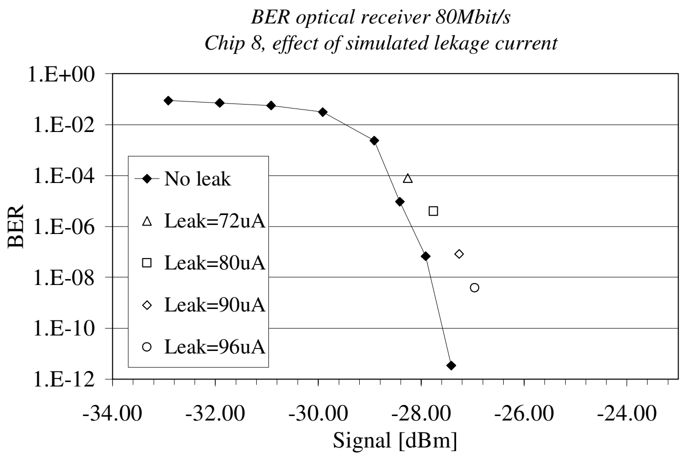

Figure 8: Influence of increasing levels of DC input current on the BER performance of the receiver. These measurements were made in the “crosstalk” condition.

4.2.2 Performance after 20 Mrad

The receiver circuit was irradiated with X-rays (10keV X-rays from a SEIFERT RP149 irradiating system) up to a total dose of 20 Mrad (SiO_2) at a dose rate of about 18.4 krad(SiO_2)/min and at room temperature. Measurements were performed first in the few hours after the end of the irradiation, then after a complete high temperature annealing (80^{o}C for 168 hours). After irradiation, the current consumption increased by about 7% to 53 mA, and the bandwidth decreased slightly, still complying with the specification of 80 MHz.

The BER measurement was repeated after irradiation and subsequent annealing. In Figure 9, the results are compared with the pre-irradiation performance. The net effect of the irradiation is visible in the measurement of the single channel, with the other channels silent (“No crosstalk”). In that case, the radiation-induced loss of sensitivity was limited to about 1 dB. When the neighbour channel is operated (“Crosstalk”), there is practically no evident irradiation effect on the receiver performance. When noise is injected in the power supply, the BER curve changes its shape, still the sharp decrease in the BER is around –24 dBm in every condition. Post-irradiation annealing did not significantly affect the BER.

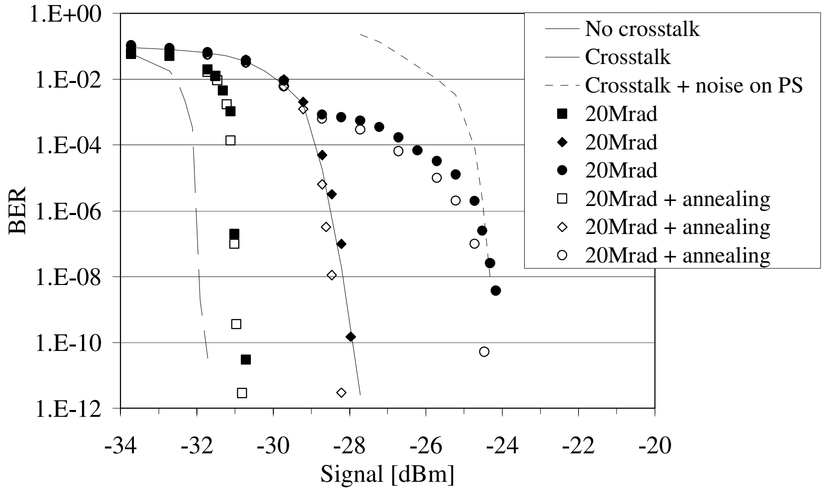

Figure 9: BER performance before and after irradiation (20 Mrad) and annealing in different operation conditions.

5 Conclusions

The results of the BER measurements performed on the digital optical link prototypes for the CMS tracker demonstrate that the specification limits are met with a good margin of confidence. The good results obtained by Link 2, with the ASIC designed for radiation hardness, allow envisaging a radiation resistant link with low power consumption and good performance throughout the lifetime of the CMS experiment.

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