# Evaluation of a discrete 4-PAM optical link for future automotive networks

W. Soenen,[1] R. Vaernewyck,[1] A. Vyncke,[1] J. Verbrugghe, [1] J. Gillis, [1] and J. Bauwelinck,[1]

[1] INTEC/IMEC, University of Ghent, Sint-Pietersnieuwstraat 41, 9000 Ghent, Belgium

*A comparative study is presented between NRZ and 4-PAM to investigate the feasibility of Gigabit transmission in automotive optical networks. The system utilizes a SI-PCS fiber and an 850 nm VCSEL as transmitter. Laser driver and receiver are realized with discrete transistors at board level. Eye diagram measurements reveal that 4-PAM outperforms NRZ using 1m and 6m of fiber. Bitrates of 2 Gb/s are achieved at a BER $\leq 10^{-5}$. Covering longer distances shows that SI-PCS introduces severe dispersion. Therefore, GI-PCS fiber is suggested as optical link for future automotive networks.*

## Introduction

Recently, a lot of research is invested in determining a new high speed infotainment standard (MOST) for the automotive sector which for now is limited to 150 Mb/s [1]. The next MOST-standard will have to make a challenging leap forward up to the Gigabit region in order to be economical and sustainable for a significant amount of time. The automotive communication link consists of an optical fiber which is lightweight and immune to electromagnetic interference. Until now, polymer optical fiber (POF) was used as link but this is characterized by a high attenuation and strong modal dispersion. An alternative fiber named polymer-clad silica (PCS) is suggested which can cover longer distances at higher data rates [2]. The most popular modulation format for short-reach optical networks is Non Return to Zero (NRZ) because of its compact and robust system architecture. As the bitrate increases, NRZ poses significant demands on the (expensive) opto-electronic components. Since cost reduction is a primary target for car manufacturers, it can be very advantageous to consider alternative modulation formats which enable high data rates with low-speed components and multi-mode fibers (MMF) such as PCS. A potential candidate is 4-PAM modulation which allows a bitrate twice as high as NRZ for the same system bandwidth. In the following sections, we will describe the trade-offs associated with 4-PAM modulation and compare the theoretical remarks with experimental results.

## Battle of the fittest: NRZ vs. M-PAM

Optical NRZ signals consist of 2 levels and are created by steering a modulation current through a laser. To enhance the speed, the laser is typically biased slightly above threshold. A high and low optical level are equivalent to a logical ‘1’ and ‘0’. Because only the intensity of the signal is manipulated, the receiver can be implemented with direct-detection photodiodes which simplifies the architecture. The frequency spectrum of an ideal NRZ-pulse is a sinc function. To preserve the quality of the eye diagram, the bandwidth (BW) of the transmitter must be equal to approximately the bitrate $R_b$. At the receiver side, a compromise must be made between eye height and sensitivity. A popular

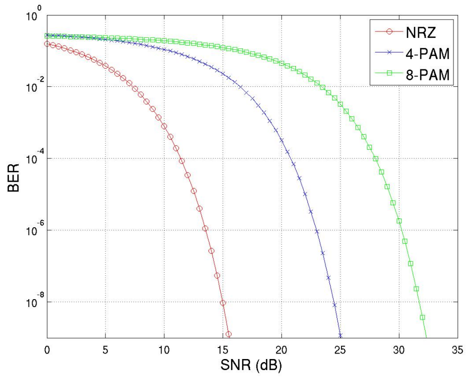

**Figure 1:** Relationship between BER and SNR assuming white Gaussian noise for different modulation formats

rule of thumb is $BW = 0.7 \cdot R_b$. This condition must also be satisfied by the optical fiber in order to limit intersymbol interference (ISI) caused by modal dispersion. Increasing NRZ bitrates poses significant challenges on the complete system and eventually leads to a technological limit. Therefore other modulation formats must be studied and evaluated in order to surpass this limit.

Automotive optical networks are of the short-reach type in the order of 1 to 20m. To minimize the system cost, information must be (de)modulated similar to NRZ by manipulating the intensity of the optical signal. A potential candidate to realize this is the M-PAM format. This format will divide the dynamic range (DR) of the signal into M-1 subregions resulting in M levels. Each level, also called a symbol, then represents a combination of $\log_2$M bits. An M-PAM pulse is thus characterized by a signal bandwidth of $\frac{R_b}{\log_2 M}$. Increasing the modulation factor M eases the bandwidth requirements on the components, but on the other hand degrades the signal-to-noise-ratio (SNR). The Bit Error Ratio (BER) is calculated using equations derived in [3] and plotted in Figure 1. It can be observed that a higher M leads to more errors for the same SNR. To obtain a BER of $10^{-9}$, the SNR of 4-PAM must be 9.5 dB larger than for NRZ. The difference in SNR between 8-PAM and NRZ even amounts to 16.8 dB. Choosing M equal to 4 thus seems to deliver the best trade-off between bandwidth reduction and required signal quality. The SNR cannot be influenced much given a maximum average transmit power of -1.5 dBm to satisfy eye safety regulations [2]. Therefore, the receiver must have a better sensitivity to achieve the same BER using 4-PAM compared to NRZ, e.g. 4.7 dB at a BER of $10^{-9}$ [3].

## 4-PAM architecture

Due to the multi-level optical signal, the architecture of a 4-PAM communication system is quite different from an NRZ system as shown in Figure 2. First of all, the laser diode must be operated in its linear region to guarantee uniform level spacing. The 4 levels can be created by 2 current mode logic (CML) differential pairs with tail currents $I_M$ and $2 \cdot I_M$ operated from 2 independent bitstreams. To obtain high linearity under a large DR, the transimpedance amplifier (TIA) in the receiver must be implemented with automatic gain control (AGC) [4]. The post amplifier (PA) will then perform an amplified single-ended to differential conversion in order to drive the 2 bit differential flash ADC of the

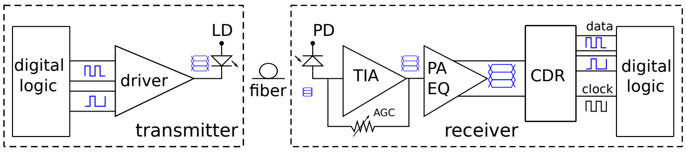

**Figure 2:** Architecture of a 4-PAM optical communication system

clock and data recovery (CDR) circuit. Because the amplitude of the detected signal is unknown, the ADC must have an adaptive input circuit [5]. A phase-locked loop extracts a clock signal from the data to synchronize the ADC and retime the data. To compensate dispersion introduced by the channel, the PA can be cascaded with an equalizer (EQ). The system chain ends with the digital logic performing decoding and additional processing.

## Experiments

A 4-PAM system is built at board level which can also produce NRZ-signals. An 850nm Vertical Cavity Surface Emitting Laser (VCSEL) is chosen as laser diode because of its many advantages suited for the automotive sector [2]. The bandwidth limitation is found at the receiver side because discrete photodiodes at 850nm with an active area of 400$\mu$m are limited to approximately 1 GHz. For simplicity, no AGC and CDR were implemented. The receiver has a measured bandwidth of 700 MHz which is the maximum that could be realized with the available discrete transistors. According to the rule of thumb, the bitrate should be limited to 1 Gb/s NRZ for optimal performance. The system is pushed above its limits by pursuing a bitrate of 2 Gb/s to illustrate the advantages of using 4-PAM. Two uncorrelated data streams are generated with a $2^7$-1 PRBS generator from Agilent. An estimate of the BER is calculated based on eye diagrams measured with a 4 GHz Tektronix oscilloscope. The maximum distance that must be covered according to the MOST-standard measures 20m [2]. Table 1 lists three fibers suited for automotive optical networks. POF is the fiber currently used by MOST150, but is not applicable for Gigabit data rates. SI-PCS is suggested by [2] as an alternative because of its higher transmission capacity. GI-PCS is an enhanced and more expensive version of the SI version and allows longer distances at the same speed. This experiment uses a SI-PCS in combination with a passive equalizer to extend the link distance.

**Table 1:** Specifications of optical fibers suited for automotive optical networks [6]

| Parameter | SI-POF | SI-PCS | GI-PCS |
|---|---|---|---|
| optimal $\lambda$ (nm) | 650 | 850 | 850 |
| core diameter ($\mu$m) | 980 | 200 | 200 |
| transmission capacity (MHz·km) | 1 | 20 | $> 20$ |
| attenuation (dB/km) | 160 | 6 | $< 12$ |

The closed NRZ eyes in Figure 3 reveal that the bandwidth of the receiver is insufficient for 2 Gb/s transmission. However, this data rate becomes possible by using 4-PAM modulation which is illustrated by the lower BER. When the distance of the SI-PCS fiber is increased to 6m, modal dispersion degrades the eye and increases the error rate. The signal quality can be recovered by inserting an equalizer in the receiver chain. When the link

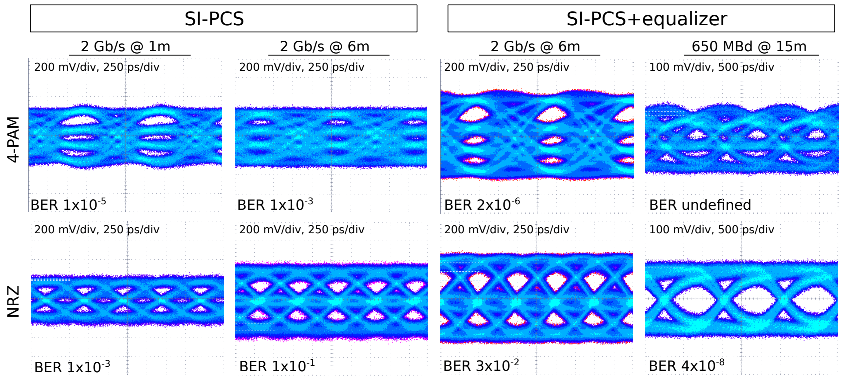

**Figure 3:** Measured eye diagrams for different lengths of SI-PCS with and without equalizer

length is altered to 15m, channel dispersion reduces the eye height significantly despite the use of an equalizer and a lower data rate. This phenomenon can be observed in the last NRZ eye diagram. The 4-PAM eye diagram at the same baudrate is now completely distorted because the spacing between the levels is more sensitive to amplitude degradations compared to NRZ. The system delivers better results with NRZ because the bitrate is now low compared to the receiver bandwidth.

The obtained results clearly show that 4-PAM modulation is preferred above NRZ when the bandwidth of the system including the fiber is approximately half the recommended bandwidth. This is typically the case when the system is driven above its technological limit. The measurements also reveal that SI-PCS introduces too much dispersion to enable operation at 2 Gb/s over a distance of 20m. An alternative is to use a fiber with a higher transmission capacity such as GI-PCS mentioned in Table 1.

## Conclusion

An experimental opto-electronic setup using a SI-PCS fiber is presented to demonstrate the trade-offs between 4-PAM and NRZ modulation. Test results reveal that 4-PAM outperforms NRZ when the system is operating above its technological limit to achieve a certain data rate. 4-PAM thus makes it possible to maintain the current technology when pursuing higher bitrates. This reduces the system cost while delivering a higher performance. Eye diagrams also show that SI-PCS introduces severe dispersion at Gigabit speeds over distances larger than 10m. GI-PCS is therefore recommended as optical link for future automotive networks because of its higher transmission capacity.

## References

[1] MOST Special Edition, `http://mostcooperation.com/publications`, 2012.

[2] T. Kibler and S. Poferl, ”Optical data buses for automotive applications”, *JLT*, 2004.

[3] W. Soenen, ”Design of a 4-PAM gigabit optical front-end for PCS fiber”, *Master Dissertation at University of Ghent*, 2012, pp. 34-38.

[4] M. Atef, R. Swoboda and H. Zimmerman, ”An integrated optical receiver for 2.5 Gbit/s using 4-PAM signaling”, *ICM*, 2010.

[5] M. Hsieh and G.E. Sobelman, ”SiGe BiCMOS PAM-4 Clock and Data Recovery Circuit for High-Speed Serial Communications”, *SOC Conference*, 2003.

[6] LEONI Fiber Optics, Product catalogue, `http://www.leoni-fiber-optics.com`, 2012.