



(Bild: BMW)

Breaking the Gigabit Barrier

New gigabit POF standard for home networking, new possibilities for automotive applications

Most of the commercially available POF systems for home networks operate at 100 Mbit/s. For automotive networks this used to be fast enough, but with new applications like uncompressed video transmission for surround view cameras the demand for gigabit links over large-core step-index (SI) fibers increases as well. The few available gigabit systems can only operate over a few meters of SI POF, due to the bandwidth limitation of the fiber itself.

By Prof. Dr. Christian-Alexander Bunge and Prof. Dr. Olaf Ziemann

It is well known that bandwidth-efficient modulation formats can transmit up to 2 Gbit/s over 100 m of SI POF, but the use of these methods requires a worldwide standard in order to guarantee compatibility between manufacturers.

In September 2009, the new working group 412.7.1 [1] inside the DKE

was founded in order to discuss the different related questions and to generate a common application guideline for the transmission of 1 Gbit/s over at least 50 m of SI fiber, which can also be interesting for automotive applications.

For the foreseen specification, some parameters are already set and serve as boundary conditions:

- ▶ Step-index and multi-core fibers according to class A4a.2.
- ▶ Eye-safe operation (≤ 1 mW fiber coupled power).
- ▶ 24 dB optical link budget (including two in-line connections and 5 dB margin).
- ▶ Low power consumption.

Polymer optical fibers with big core diameters and large numerical apertures have a limited transmission bandwidth. Therefore bandwidth-efficient modulation formats are very interesting for POF transmission links.

The bandwidth of a 50 m SI POF link is usually lower than 100 MHz. This is sufficient for the transmission up to 100 Mbit/s. For data rates of 1 Gbit/s this seems to be much too low. This is a general problem and also valid for other media types being used inside of buildings like for example wireless, copper cable or power line. Transmission schemes for these media make heavy use of signal processing to overcome the limiting bandwidth

and multi-level modulation formats. If one employs signal processing of more efficient modulation formats, the transmission capacity of a link is not determined only by the 3 dB bandwidth, but also by the integral signal-to-noise-ratio (SNR) over the useable frequency range. In addition, there is a trade-off between efficiency and complexity, especially in a cost-sensitive environment like home networking or automotive applications.

Therefore, several transmission formats are under discussion, including simple binary amplitude modulation (Non-Return to Zero; NRZ), multi-level amplitude modulation (m-ary Pulse Amplitude Modulation; m-PAM), and multi-carrier modulation such as Discrete Multi-Tone (DMT) modulation.

The other limiting factor is set by the electro-optical components. The loss of polymer optical fibers has its minimum at around 570 nm. Unfortunately, only few and slow LEDs are available in this wavelength range. The second-best wavelength is between 450 and 530 nm. These LEDs are working very efficiently and fast, but there are nearly no (affordable) diodes available today. The loss minimum in the red spectral range is very small, leading to a strong increase of attenuation (about 150 dB/km higher than for green and blue) for wavelength-offset or broad spectra (like the LEDs). There are efficient LEDs and resonant-cavity LEDs (RC-LED) as well as lasers and VCSEL at 650 nm wavelength.

It is almost obvious that LD are the only source to come into consideration for non-return-to-zero transmission at 1 Gbit/s. The use of VCSEL would be the ideal solution, but they are not usable for temperatures over 70 °C. LED and RC-LED are not fast enough, but may have the ability to offer sufficient bandwidth for pulse amplitude modulation or discrete multi-tone modulation under certain circumstances. They also prove a transfer function linear enough for multi-level modulation. Especially for automotive applications, many developers avoid edge emitters because of the difficulties in mounting and their high and temperature-dependent threshold current.

■ Finding the optimum transmission scheme

Non-return to zero

NRZ means that the transmitter switches from its maximum level to zero according to the bit pattern. The advantage is the very simple system design; the disadvantage is the large required bandwidth. Usually a minimum bandwidth corresponding to half the transmitted bit rate is needed (e.g. 500 MHz for a bit rate of 1 Gbit/s).

Error-free transmission is possible at higher bit rates, but the eye diagram is obviously closed then. By setting a high-pass-filter with a transfer function (in amplitude and phase) according to the inverse channel response behind the receiver, the eye can be opened again.

This filter can be constructed using only analogue technology (1.39 Gbit/s over 100 m SI POF, POF-AC 2007, [2]). Using tunable components, such a filter can be made adaptive. A digital filter is more efficient and more adaptable. The most important advantage of digital filters is that they can be part of an integrated circuit and that no bulky discrete components are required. The substantial effort in signal processing at such high sampling rates is detrimental, however. In all equalizing processes, using some sort of high-pass filters means that the higher frequencies are weighted toward a higher level. This means that not just the signal is amplified, but that the noise level is also increased. If parts of the signal are muted to the background noise level, these parts can no longer be recovered.

Pulse amplitude modulation

In m-ary pulse amplitude modulation there are more than two signal levels. Usually 2^m levels are used, e.g. four or eight. Measurements of typical PAM signals are shown in **figure 1**.

Due to every symbol transmitting m bit, the required bandwidth is reduced

by a factor of $1/m$ and thus the noise is reduced as well. But a lower noise level will be required because the many signal levels are arranged much denser. The advantage of PAM is its flexibility and adaptability to the actual SNR. The better the SNR, the more bits per symbol can be transmitted to raise the transmission capacity.

The m-PAM signal can also be equalized in the same way as explained above in order to maximize the useable frequency range of the channel. The digital filters that perform the equalization rely on a decision feedback structure. This means that, on the basis of the pre-equalized signal, it will be decided what the symbol was supposed to be, and according to this decision the feedback will be provided. This bears the advantage that the noise can be suppressed, since the clean signal after the decision will be fed back, but in the case of incorrect decisions (as likely as the error probability before error correction, approx. $p = 10^{-4}$) the feedback is also wrong and can lead to errors

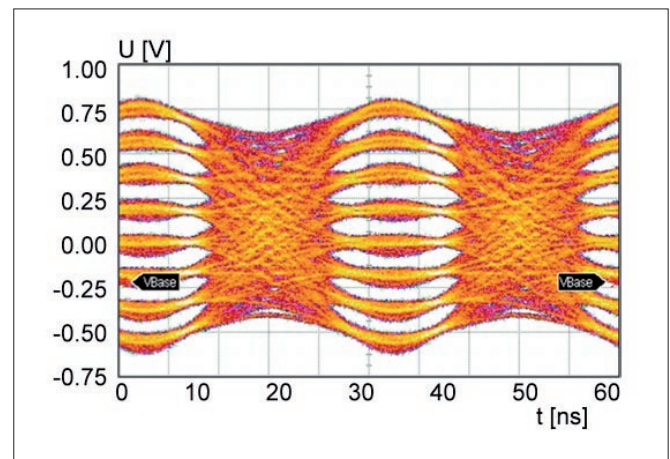


Figure 1. 100 Mbit/s 8-level PAM signal after 275 m POF transmission [3].

or even to an error burst. Therefore, the equalization can be done at the transmitter before sending the signal. Since pre-equalization usually leads to large crest factors as well, the resulting signal will be pre-coded using a modulo operation. The whole process is called Tomlinson-Harashita Precoding (THP) and can avoid these error bursts because it does not rely on a decision from a highly distorted signal, but on the transmitter where the sequence is known.

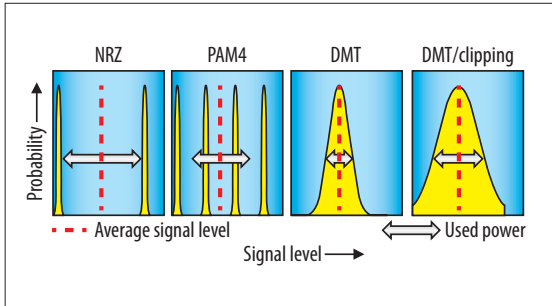


Figure 2. Ratio between average and used optical power.

Discrete multi-tone

Using DMT, the existing spectrum is split into many sub-channels (sub-carriers). Each sub-carrier can now be modulated separately according to the available SNR at that frequency.

A big disadvantage of DMT is the substantial effort in signal processing. A Forward Error Correction (FEC) is needed for DMT almost at all times. Today, many communication systems in end-customer business are using DMT or the related OFDM (Orthogonal Frequency Division Multiplexing), like e.g. DSL, PLC, LTE, Wi-Max or WLAN because the existing transmission capacity according to the available SNR can be exploited more efficiently using this method.

In contrast to electrical transmission schemes, the optical signals used are unipolar, since the intensity is used as an information carrier. This means that the average signal will not be zero as in the electrical case, but a carrier will be needed. In addition, multi-carrier signals exhibit a large crest factor, meaning that the signal shows large peaks from time to time. In order to

avoid negative peaks, the average power of the signal must be increased and clipping has to be applied. Both actions lead to worse performance compared to electrical transmission schemes.

Limitations of optical sources

For all optical systems using amplitude modulation, there is a specialty to be kept in mind when using POF. Optical sources (LED, Laser) are limited in power. The limitation in home networking is described in IEC 60825-1; typically only a few mW are allowed.

Because there cannot be negative light, a modulation of approximately half of the optical power is used. Only a small part of the signal carries information (in contrast to copper or radio transmission, where the electrical field can have different potentials with a total average of zero). Using NRZ modulation, the source is switched between maximum power and nearly zero in bit rate. All the energy carries information leading to a crest factor $\gamma_{NRZ}=1$. Using PAM4, the distribution becomes broader and some energy is lost compared to NRZ (figure 2). This effect is getting stronger when using a higher number of symbol levels. The distributions approach a uniform distribution for a sufficient number of levels. Thus the change from NRZ to more levels incurs a crest-factor penalty at the beginning and must be overcome by the better performance due to the smaller bandwidth requirements. This is usu-

ally only the case for low-bandwidth systems, but it is valid for POF.

PAM will usually be accompanied by equalization. In order to avoid error propagation in the equalizer, THP can be used. It exhibits approximately the same complexity as a conventional digital equalizer, but leads to an additional penalty since it scrambles the transmission signal into a uniform distribution with a crest factor of $\gamma_{THP}=1.73$. The additional penalty depends on the initial crest factor of the signal. For multi-level m-PAM with more than eight levels, this penalty becomes negligible.

With DMT, the amplitude of the signal follows a Gaussian distribution. Since Gaussian curves in theory are unlimited, the signal can adopt very large and very small values, which are, on the other hand, very unlikely. In order to use a significant part of signal energy, clipping is used, which means cutting off the maxima and minima of the signal in order to keep a fixed range of values. But even for the most extreme clipping, only uniformly distributed signal values could be obtained, with an even worse crest-factor penalty. Additionally, each time the signal is clipped, errors are likely to occur. These errors must be corrected using FEC.

Compromise between efficiency and complexity

Currently, three proposals are under consideration. A DMT solution has been presented, but no further theoretical or experimental results are known

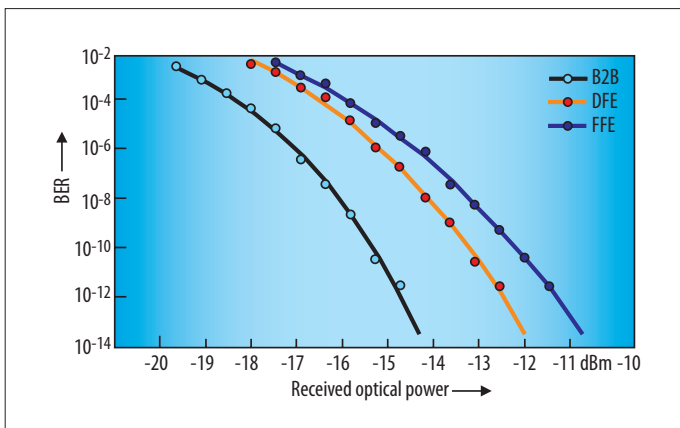


Figure 3. Experimental results over 50 m for 1 Gbit/s POF real-time transmission [4].

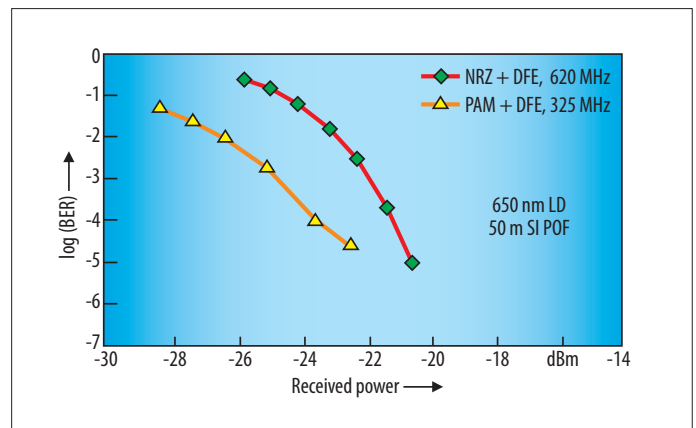


Figure 4. Comparison between NRZ and PAM4 transmission with adapted receiver bandwidth.

so far. It is unclear if this approach will be followed up in future discussions. ISMB in Torino have proposed a serial NRZ solution, for which they have developed a real-time FPGA system as an outcome of the European project POF-PLUS. With a 650 nm RC-LED, they proved a 1 Gbit/s POF transmission over 50 m with a 6.5 and 7 dB margin at a bit error ratio of $BER=10^{-4}$ [4]. **Figure 3** shows the results. Since it is a real-time solution, this proves the feasibility and the readiness of this approach.

An experimental comparison between the NRZ and PAM4 was done at the POF-AC in Nuremberg (**figure 4**). Here, the receiver bandwidth was adapted according to the symbol rates so that the lower noise and the better sensitivity of the lower-bandwidth receiver could be exploited. A3PICs receivers with a bandwidth of 620 MHz and 325 MHz respectively were used in conjunction with a 650 nm laser diode. It can clearly be seen that the bandwidth limitation of the POF link makes the PAM solution with only the half-occupied bandwidth the preferred solution. An advantage of almost 3 dB at $BER=10^{-4}$ can be observed. Unfortunately, lowering the required bandwidth even further has not resulted in better performance in terms of better sensitivity. It seems that the further reduction of the receiver bandwidth will not increase the sensitivity. Further investigation is required here.

Based on these results and the theoretical assumptions above, the application of a multi-level PAM seems to be a good compromise between efficiency and complexity. This scheme can be made more robust by THP and an adaptive choice of number of levels. The advantage will be even bigger once low-bandwidth LEDs are used instead of red lasers.

A guideline for 1 Gbit/s POF links can make the introduction of a future MOST standard at higher data rates easier. Here shorter link lengths, but more robustness may be needed. The publication of the guideline for home networks is expected for 2011. The modulation scheme and the light source will be the first decisions to be made. The development of a suitable

connector and measurement standards will follow. *sj*

Literature + Links

- [1] www.dke.de/ak412-7-1
 [2] Ziemann, O. et al: The Development of Gbps over SI-POF Systems in the POF-ALL Project. POF 2008. Santa Clara, CA (USA) August 2008.
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 [4] Nespolo, A. et al: A New Physical Layer Capable of Record Gigabit Transmission over 1 mm Step Index Polymer Optical Fiber. Journal of Lightwave Technology, Vol. 28. No. 20. 2010.



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Infotainment:

VW selects Harman for next-gen infotainment system

Harman and Volkswagen AG signed a six-year contract worth 1.2 billion Dollar. Harman will develop and deliver a new infotainment system to VW for its new vehicle platforms.

The new system will offer a sophisticated set of features including dynamic navigation, high resolution graphics, Internet access, and wired or wireless connectivity. An embedded flash memory will provide dynamic navigation data which may be updated as required for current access to routes and road information.

„We are delighted to extend our long-standing relationship with Volkswagen Group across the leading automaker's

wide range of vehicles,“ said Dinesh C. Paliwal, Harman's Chairman, President and CEO.

Harman will be the first infotainment system supplier worldwide to integrate the new Texas Instruments Jacinto 5 SOC (system-on-chip), offering MOST150 networking technology and an FPGA-less design. The highly integrated system provides a telephone module, several tuner modules, a six-channel class-D amplifier, a DVD drive and a computing module built on a Nvidia SOC. The system will fit into a 1-DIN slot and will be offered in new Volkswagen vehicles beginning in 2012. *sj*