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Home Networks - they have to work standard compliant, very fast and reliable

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Introduction:

About 2/3 of the German households have access to broadband internet. Most of them have access to ADSL connections with a capacity of only a few Mbit/s. In the very next years VDSL and fiber optic links will offer bandwidths of 100 Mbit/s or even more.

In premises, only wireless technologies like W-LAN or PLC (Power line Communication) are available right now. Polymer Optical Fibers (POF) can be installed by laymen and will allow for fast, reliable and electromagnetic interference-free point-to-point connections. Ethernet media converters with more than 100 Mbit/s and even more than 120 m link length are available even now.

In these times the research on POF systems with 1 Gbit/s is ongoing. To achieve wide acceptance, new standards need to be developed and lots of technical challenges need to be solved.

In the new working group 412-7-1 (www.dke.de/ak412-7-1), established by the German standardization organization DKE (German Commission for Electrical, Electronic & Information Technologies of DIN and VDE) a wide range of manufactures and research institutes join to fill the gap in POF standardization. This paper describes the actual results of the discussion inside this group. The main questions are the choice of the fiber, the modulation format, and the optical transmitter type.

It is the objective of the team to design a robust and easy-to-install transmission system for datarates of 1 Gbit/s over up to 50 m transmission distance. This range will be sufficient for appartments and most of the multi-dwelling units.

Polymer Optical Fibers and the most important index profiles

Polymer Optical Fibers (POF), often called “plastic optical fibers”, consist of a PMMA-core (Polymethylmethacrylate; typically 1 mm in diameter) and a thin optical cladding (10 µm). Often a protection sheath (1.5 - 2.3 mm) of different polymer materials surrounds this fiber.

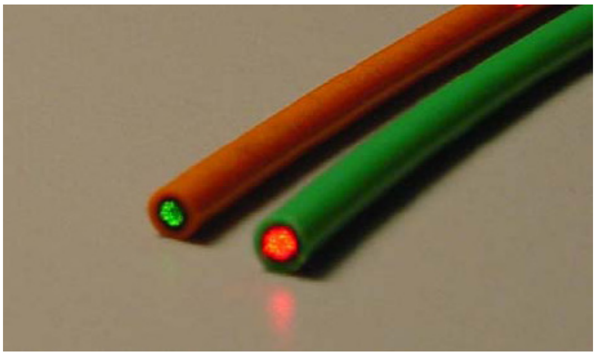

Fig. 1: 1 mm standard polymer fiber

The main differences between the available polymer fiber types are the used materials (determining the attenuation and the temperature range) and the index profiles (responsible for the bandwidth). By far most POF are made of PMMA.

In all optical fibers the bandwidth depends on its refractive-index profile. The simplest version is the step-index profile (SI, figure 1, left). A homogeneous core with an index n_{core} is surrounded by a cladding with lower refraction index n_{cladd}. The difference in the refractive index leads to the numerical aperture and the maximum light propagation angle α_{max} accordingly:

$$NA = \sqrt{n_{core}^2 - \mathrm{n}_{\mathrm{cladd}}^2}; \quad \alpha_{\max} = \arccos\left(n_{cladd}/n_{core}\right)$$

Glass optical fibers typically show a refractive-index difference of approx. 1%. Hybrid glass/polymer fibers have a maximum propagation angle of about 16° caused by larger refractive-index difference of 4%. In Standard-POF, the difference is about 5% and thus the maximum propagation angle about 20° related to the fiber axis.

A larger light propagation angle can descrease the bending sensitivity, but in the same time also the achievable bandwidth decreases.

Fig. 2: Step index-, multi step index- and multi core polymer fibers

The via extrusion easily and continuously produceable step-index POF (SI-POF) is cheap and available in good and stable quality. There are lots of compatible components and measuring instruments as well as experimental data available, e.g. life-time data. Unfortunately, due to its large numerical aperture and their step-index profile modal dispersion limits the achievable bandwidth length product to about 40 MHz × 100 m.

This effect can be alomost entireley compensated for by a so-called gradient-index-profile instead of a constant refractive index. When achieving a nearly parabolic profile, the bandwidth can be nearly 100 times higher than with the SI-POF. As a compromise between the easy-to-produce SI-POF and the high-bandwidth GI-POF, a multi-step-index-profile (MSI-POF) can be used: The “Optimedia”-MSI-POF consists of 10 layers e.g. and has a bandwidth of approx. 1500 MHz × 100 m (Fig. 2, middle).

In another approach, the fiber can be made of many tiny cores, a multi-core POF (MC-POF). The partition of the core into many individual light guiding areas allows for very small bending radii, helping to ease the installation of the fiber. The numeric aperture and the bandwidth is nearly the same as of the SI-POF.

Bandwidth and transmission capacity

SI-, GI- or MSI- and MC-POF, being multimode fibers, generally have a large modal dispersion and therefore a limited transmission bandwidth (compared to glass multimode fibers). For that reason bandwidth-efficient modulation formats are very interesting for POF transmission links. In Fig. 3 the transfer function of a typical MC-POF is shown (NA of the light source: 0.27).

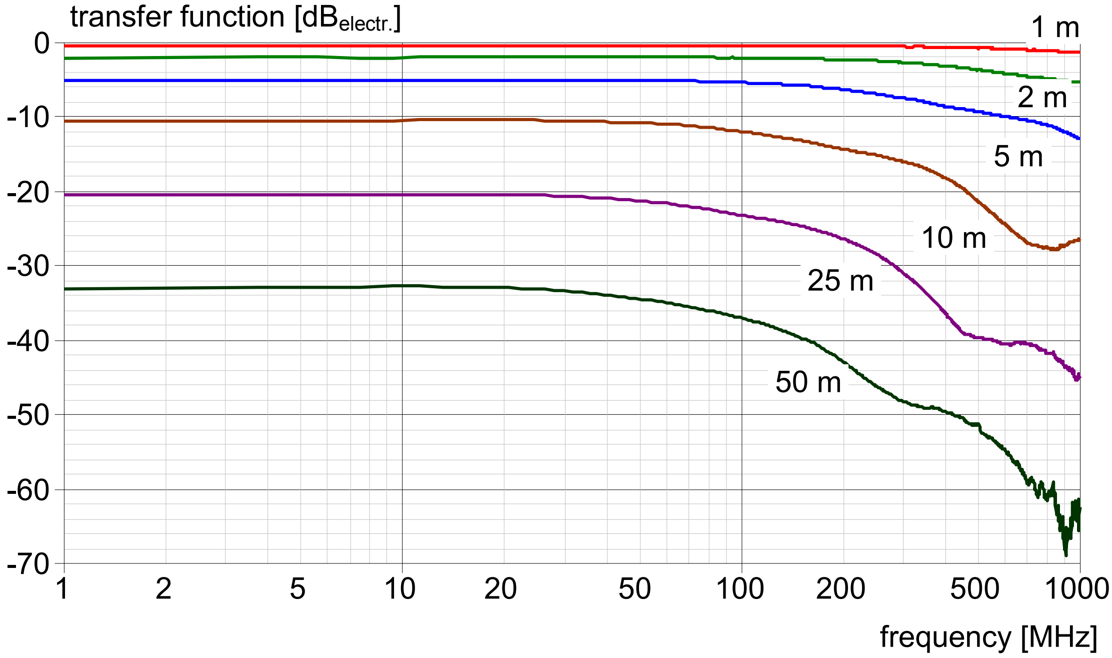

Fig. 3: transfer function of MC-POF

As shown in the diagram, the bandwidth of a 50 m POF-Link is lower than 100 MHz. This is absolutely sufficient for the transmission up to 100 Mbit/s. For datarates 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 e.g. wireless, copper cable or power line. Transmission on these media makes heavy use of signal processing to overcome the limiting bandwidth. If you employ signal processing of more efficient modulation formats, the transmission capacity of a link is not determined by the 3 dB-bandwidth only, but also by the integral signal-to-noise-ratio (SNR over the useable frequency range.

Modulation formats for Gbit/s- transmission

In the following part the most important modulation schemes get introduced, which allow for a more efficent use of the available POF link transmission capacity.

Non-Return-to-Zero (NRZ) directly

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

Error-free transmission is possible, but the eye diagram is obviously closed then. To compensate for this, a higher SNR shall be realized. This modification is called power penalt. It is shown in Fig. 4 that even in a system with only 10% of the theoretical required bandwidth (related to the bit-rate) error-free transmission can be realized (but SNR has to be increased by about 20 dB due to the more and more closed eye).

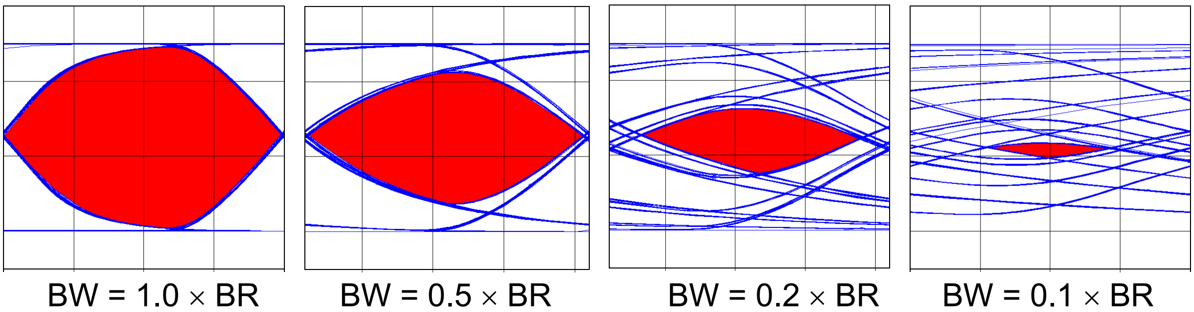

Fig. 4: Eye diagrams for different bandwidths (BW) vs. bit rate (BR) conditions, simulated without noise

Pulse Amplitude Modulation (PAM)

In pulse-amplitude modulation there are more than two levels possible. Usually 2^n are used, e.g. four or eight. Measurements of typical PAM signals are shown in Fig. 5.

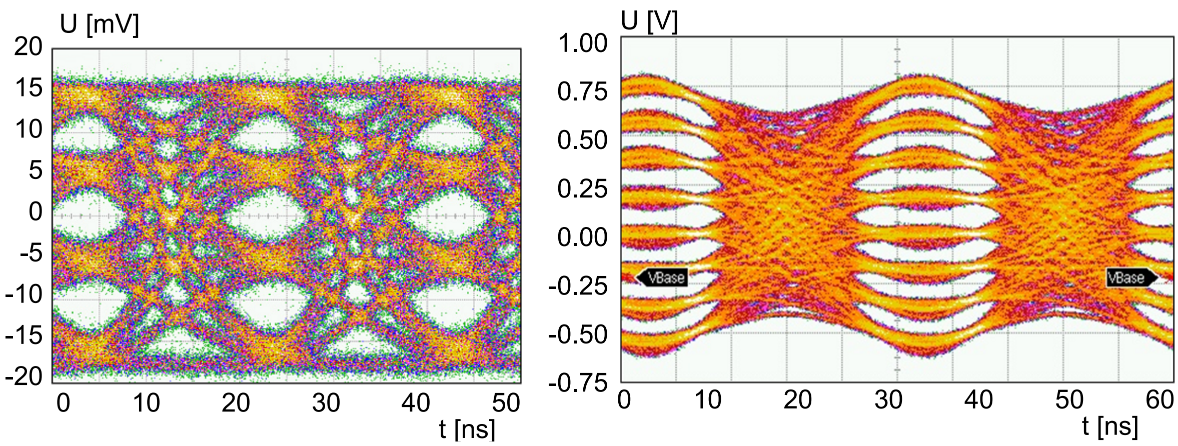

Figure 5: 4- and 8-level PAM-modulated signals

Due to every symbol transmitting n bit, the required bandwidth is reduced by a factor of 1/n and thus the noise as well. A lower noise level is required because the many signal levels are much closer spaced. The advantage of PAM is its flexibility and adaptability to the actual SNR. The more SNR is available, the more bits per symbol can be transmitted to raise the transmission capacity.

Discrete Multi Tone (DMT)

Using DMT the existing spectrum is split into many sub-channels (sub-carriers). Each sub-carrier can now be modulated separately (best with QAM: quadrature amplitude modulation, using the sub-carriers' phase and amplitude). An example is shown in Fig. 6 showing a transmission of 2 Gbit/s via a 100 m POF-link. The allocated bandwidth is 700 MHz. QAM64 is used at the low frequencies, the higher carriers only allow QAM4 (2 bits per symbol).

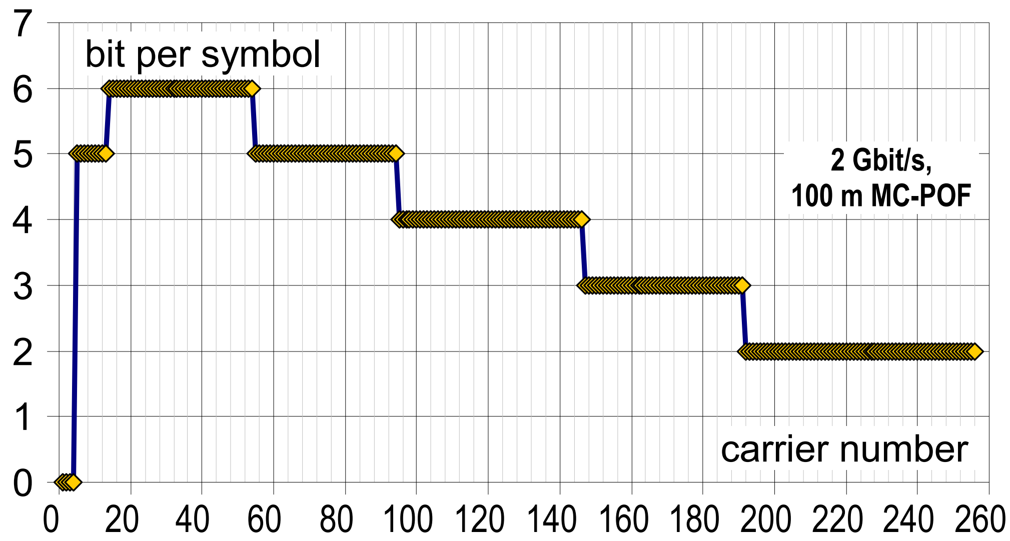

Fig. 6: Example for DMT-transmission via a 100 m MC-SI-POF

A big disadvantage of DMT is the substantial effort in signal-processing. A fast analog-digital converter is required. A forward error correction (FEC) is needed for DMT almost any time. 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 W-LAN, because the existing transmission capacity according to the available SNR can be exploited more efficiently using this method.

NRZ with filtering

When transmitting NRZ through a channel with a bandwidth much smaller than half of the bit rate, earlier or later the eye will be closed totally (see Fig. 4 schematically), and no data will be receivable. Setting a high-pass-filter with a transfer function (in amplitude and phase) according the inverse channel response behind the receiver, the eye can be opened again.
This filter can be constructed using analog technology only (1.39 GBit/s over 100 m SI-POF, POF-AC 2007, [1]). Using tuneable components, such a filter can be adaptive. A digital filter (FFE - Feed Forward Equalizer, DFE - Decision Feedback Equalizer) is more efficient and more adaptable. With these measures, a bit rate of 2 Gbit/s over 100 m POF could be achieved already.

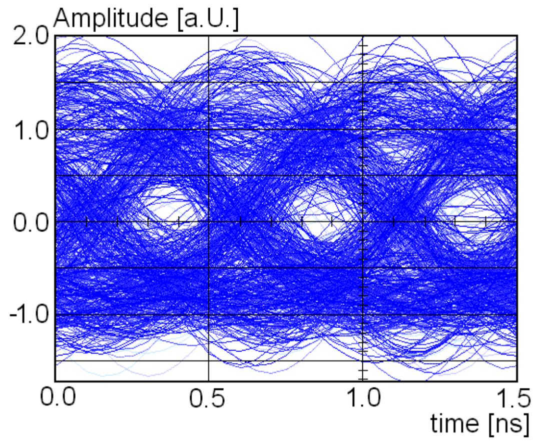

Fig. 7: Transmission of 2 Gbit/s over 100 m POF with FFE/DFE-regenerator

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 (ADC, clock recovery aso.) is detrimental, however.
In all equalizing processes using some sort of high-pass filters have in common that the higher frequencies are weighted with a higher level. Not only the signal level, but also the noise-level is increased. If parts of the signal are muted to the background noise level, these parts cannot be recovered any more. The SNR will be decreased compared to a non bandwidth limited channel (penalty).

Comparison of the frequency efficiency

In the first step the described methods shall be compared according to their usage of the channel capacity. This is shown schematically in Fig. 8. The noise level and the signal after the receiver are shown. The marked areas are described as followed:

- NRZ: only the 3 dB-bandwidth is used, independently from the available SNR
- NRZ with penalty: uses a higher bandwidth at a larger SNR
- PAM: only the 3 dB-bandwidth is used according the available SNR
- DMT: uses the whole bandwidth according the available SNR
- NRZ with filter: uses the whole bandwidth

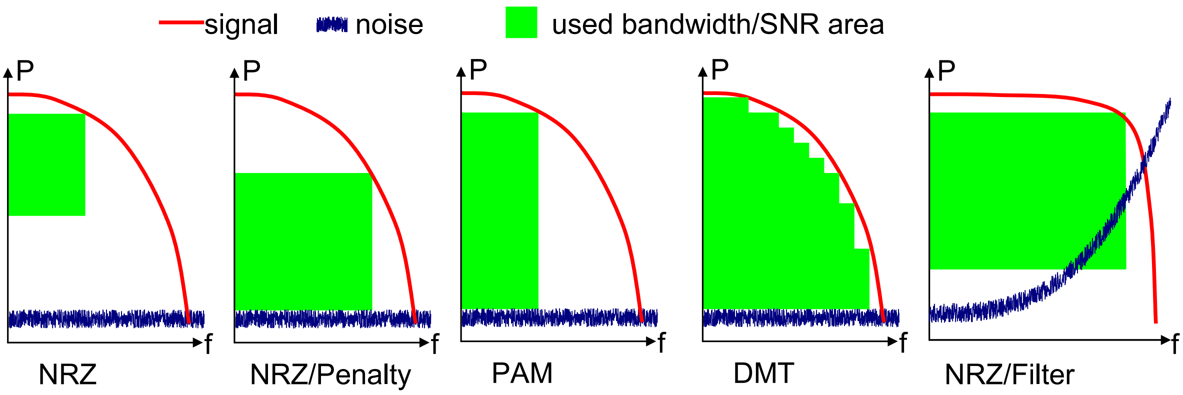

Fig. 8: used channel capacity of a POF (typical POF-transmission channel)

It is obvious that DMT and NRZ with equalization are the most efficient methods to use the capacity of a typical POF channel. DMT is even better in theory because the phase of the carrier is used as information. Otherwise NRZ works only as long as at least a small part of signal will be in the frequency range smaller or equal to half of the bit rate. The bandwidth required with the use of DMT is only a small fraction of the bit rate (related to the level of modulation). But these are the most complex methods because they need an AD-conversion and digital signal processing.

Power and Signal

For all optical systems using amplitude modulation there is a specialty to be kept in mind using POF. Optical sources (LED, Laser) are limited in power. The limitation in home networking is described in IEC 60825-1 e.g. Typically only few mW are allowed.
Using NRZ modulation the source is switched between maximum power and nearly zero in bit rate. The average power is then nearly half of the maximum power. All the energy carries information. With DMT the amplitude of the signal is Gaussian distributed. Because there cannot be negative light, a modulation is used having approximately half of the optical power. Only a small part of the signal carries information (in difference to copper or radio transmission where the electrical field can have different potentials with a total average of zero). Since Gaussian curves are unlimited in theory, the signal can adopt very large and very small values, which are very unlikely on the other hand. In order to use a significant part of signal energy the so-called clipping is used cutting the maxima and minimal of the of the signal in order to keep a fixed range of values. Each time the signal is clipped, errors are likely to occur. These errors must be corrected using FEC. The relations are shown in figure 9.

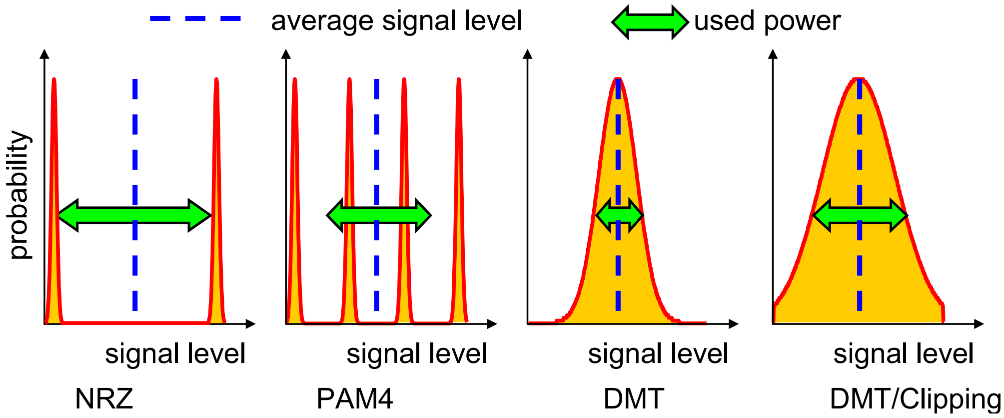

Fig. 9: Ratio of average and used optical power

6. Laser or LED

Not only the optimum fiber and the best modulation format are important, but also the used optical source. POF is working with visible light (at least PMMA), as shown in Fig. 10.

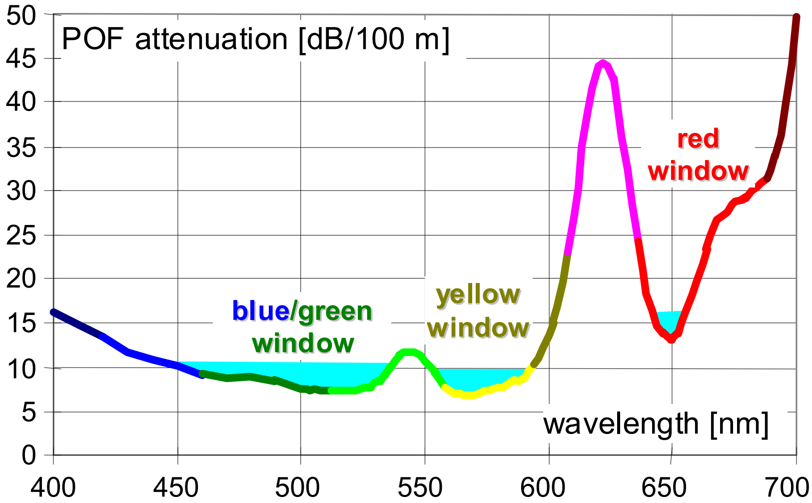

Fig. 10: attenuation of PMMA-POF

The loss of POF has its minimum at around 570 nm. Unfortunately, only few and slow LED are available in this wavelength range. The second-best wavelength is between 450 nm and 530 nm. Theses LED are working very efficiently and fast, but there are nearly no (affordable) Laser diodes available today. The loss minimum in the red spectral range is very small (changes in transmitting wavelength according temperature difference cause high differences in attenuation) and not at such a low level as at the other both. There are efficient LEDs and resonant-cavity (RC) LEDs as well as lasers and VCSEL at 650 nm wavelength. The status quo of available sources for POF systems is summarized in the following table 1.

Table 1: available sources for POF in 2010

	Note	**typical parameter**
LED	• surface emitting • very cheap • simple mounting • long lifetime	• available at 650 nm • from UV up to 530 nm • typ. 50 MHz bandwidth • useable up to 85°C • wide spectral width
RC-LED	• special form of LED with bragg mirrors • already in use for POF	• available at 650 nm • typ. 150 MHz bandwidth • useable up to 85°C • small spectral width
LD	• edge emitting • very efficient • very fast (» 1 Gbit/s) • relatively expensive (1 US$) • difficult mounting • high temperature dependency	• available only at 650 nm • very spectral width • typ. 2 GHz bandwidth • 10 mW at 40 mA current • typ. 25 mA threshold current
VCSEL	• surface emitting Laser • extremely fast (10 Gbit/s) • efficient • simple mounting	• typ. 665 nm wavelength • 1 mW power • typ. 5 GHz Bandwidth • low threshold current (2 mA)

	• (still) rel. expensive	• usable up to +40°C

It is almost obvious that actually LD are the only source to come into consideration for NRZ 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 possibility to offer a sufficient bandwidth for PAM or DMT under some circumstances. Most users are to shy to use edge emitter, because of the difficulties in mounting and their high and temperature-dependent threshold current. The conclusion might be the LED (more or less the RC-LED) with a bandwidth-efficient modulation?

Table 2: Future possible better transceivers for POF

	present disadvantage	**possible solution**
red VCSEL	Not usable at high temperatures	The advancement of the heat dissipation of the active layer, can expand the operational range (e.g. [2])
blue/green LED	Not fast enough	Blue and green LED made of GaN are inherent fast. Declining the active layer and a HF-compliant design they can be applicable for Gigabit with NRZ
blue LD	Much to expensive	As these blue laser will be used in data drives in high lots, prices may reduced in time

And the Winner is…

Unfortunately the answer to the question of what is the optimal method is not that clear. Depending on the point of optimal channel exploitation the winner is DMT. On the other hand NRZ is the easiest method using the optical power at its best. Experimental results show only marginal differences, keeping in mind that the different experiments are not always done with the same components. In the following Table 3 some disadvantages and advantages are put together (without being exhaustive).

Table 3: Advantages and disadvantages of different modulation methods

	Advantages	**Disadvantages**
NRZ + filter	• very simple system • optimal use of the optical power	• high bandwidth transceiver and receiver
DMT + clipping	• optimal usage of the channel capacity • adaptive • low bandwidth required	• inefficient use of the optical power • FEC absolutely necessary • complex signal processing
PAM 2^n	• relatively simple • small bandwidths for transmitter and receiver	• influenced by transmitter-nonlinearities

Besides the question for optimal use of bandwidth and SNR there are several other technical issues to be kept in mind:

- Is the method backward compatible to other systems?
- Is it possible to implement a sleep mode (with short wake-up time)?
- How large is the power consumption?
- How complex is the IC-design and how large will be the chip?
- Can the method adapt itself to an insufficient channel (e.g. to a lower bit rate)?

The DKE (German Commission for Electrical, Electronic & Information Technologies of DIN and VDE) working group 412.7.1 set his target in examining all these questions and drafting a guideline. The joint approach of the manufacturer concerned shall guaranty that future products comply with each other. The end target shall be a standardized POF interface.

At the actual point of discussion all different modulation formats are taken ito consideration. As an example NRZ shows a surprisingly good performance. It proved its performance in experiment and simulation to be as efficient as the other methods, but less vulnerable to non-linearities in the component structure.

In lab experiments, 2 Gbit/s over 100 m have been demonstrated. We aim at a minimum link length of 50 m at 1 Gbit/s for the final customer product. This transmission distance will be sufficient for at least all of the residential cabling, stating Gigabit Ethernet to be the most important link protocol in home computing networks. With these reduced requirements the need for SNR decrease s by approx. 15 dB compared to the lab experiments stated above. This should be sufficient to fulfill all the additional needs for bends, additional connectors, aging and manufacturing tolerance but to have a rugged system.

In near future, complete integrated transceivers, as they will be invented right now, will be available, will show more and more performance imporvements, while cost reductions can be expected ([5], [6], [7]).

The most important question to be answered is the expectation in transceiver development. To restrict ourselves to the today available LED, maybe we limit ourselves too much and choose the wrong transmission method.

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