A STANDARD FOR GIGABIT ETHERNET OVER POF.
PRODUCT IMPLEMENTATION

R. Pérez de Aranda (1), O. Ciordia (1), C. Pardo (1)

1: Knowledge Development for POF (KDPOF), Ronda de Poniente 12, Tres Cantos. Madrid. Spain

Corresponding author: o.ciordia@kdpofo.com

Abstract: The first standard for Gigabit Ethernet transmission over POF (GigaPOF) will be published shortly. A team of leading European companies and research centres on the POF networking market led by VDE/DKE, have been working for more than a year to come up with a commercial standard that will help the POF home/office networking market to develop. The company KDPOF will put into the market the first integrated circuit that complies with the standard during 2012. The standard and the silicon development have taken special care to become a flexible, robust, efficient and affordable product well suited for the high volume consumer market.

Key words: POF, Gigabit, Standard, Home networking, Industrial environment, Automotive infotainment, Silicon, Integrated Circuit, Flexibility, ABR, Low cost implementation.

1. Introduction

Current Ethernet over POF solutions rely on existing low speed optical standards such as IEEE 802.3u 100BASE-FX, achieving data rates of 100 Mbps. While this technology reuse facilitates a fast development of POF solutions, it limits their speed. To achieve higher speeds over POF, a new physical layer that is optimized for POF must be designed. This is the main goal of the GigaPOF initiative VDE/DKE WG 412.7.1.

This paper describes the GigaPOF standard and discusses its benefits for POF systems. The new standard provides a flexible physical layer that enables high-speed transmission over POF for different channels. This is key as a single solution can be used for many POF applications, from car networks to home networking achieving good performance in all of them.

The standard specifies a link at speed of 1 Gbps over standard IEC 60793 A4a.2 SI-POF. In addition, it defines optional native Adaptive Bit Rate (ABR) capabilities to go over and under the nominal speed, so extending the range of installations that can be covered by the standard.

The standard specifies also, in one of its addenda, transmission modes especially suitable for long reach applications like industrial environments at typical speeds of 100 Mbps, improving any Fast Ethernet solution currently available in the market.

Green energy focus is also present in the design of the standard thanks to the specified low power modes of operation.

2. Standard overview

POF systems have a wide range of configurations in terms of the POF used (different manufacturers provide different characteristics while A4a.2 requirements are fitted), channel length, channel impairments and optical components in both the transmitter (i.e. different light sources like LED and RCLED) and receiver (i.e. different photodiode and trans-impedance amplifier (TIA) designs).

In order to achieve a data rate that is close to the channel capacity in each configuration, one option would be to specify a different physical layer in each case. This option has a major economical issue, the development cost of a high-speed physical layer is very large and to achieve a low unit cost, a mass market is needed. As an example the unit cost of a 1000BASE-T (Gigabit Ethernet over UTP) physical layer device is below one dollar while the development cost is of tens of millions of dollars. Therefore, from an economical perspective it is more beneficial to have a single physical layer that can cover the different channel configurations. Another drawback of having a different physical layer for each configuration is that if some parameters change over time, e.g. a different light source is used, then another physical layer has to be used. In that case, the use of a single physical layer that is flexible enough to cover the different configurations is also beneficial. This is precisely the approach of the GigaPOF standard and the challenge is to ensure that the flexibility does not result in data rates that are much lower than the channel capacity.
2.1. The challenges of the GigaPOF standard

When is used for high-speed data transmission, POF present a large amount of Inter Symbol Interference (ISI) and attenuation. The use of low cost optical components such as LEDs and RCLEDs introduce further impairments in the form of non-linear distortion. The main noise sources are the TIA and the effect of the electrical capacity of photodiode when photocurrent is amplified.

All these factors make high-speed transmission over POF challenging. As an example, Fig. 1 shows the variation of POF bandwidth (in black) as a function of the fiber length, as well as the bandwidth-length product (in red). The considered fibre is SI-POF Mitsubishi Eska GH4001, and the light source is a RCLED with launching condition FWHM NA of 0.3, a wavelength of 658 nm and a FWHM spectral width of 20 nm. This would correspond to a typical home networking application.

![Fig. 1: Bandwidth and bandwidth-length product for SI-POF with RCLED as light source.](image)

As can be seen a good flat response for the required 1.25 GHz baud rate (assuming a simple NRZ scheme, e.g. IEEE 802.3z 1000BASE-X) is only possible in the very first meters. For laser sources the bandwidth in function of length is very similar. Therefore the bandwidth bottleneck is produced by POF independently of how fast is the light source, because the limiting factor is the modal dispersion of the fibre itself.

In any case, the use of advanced Digital Signal Processing (DSP) is required to achieve data rates close to channel capacity. This is similar to what happens in high speed Ethernet PHYs that use twisted pairs (UTP) as the transmission media [1], [2].

2.2. The GigaPOF solution

POF is a power peak limited communication channel. Therefore, it is very different to other channels like copper or wireless, where the transmit signal is constrained to fit a given Power Spectral Density (PSD) and average power. The peak power limit is because the transmit signal is subject to non-negativity constraint of the optical power, and the electrical intensity is limited in light sources to extend the device life.

This means that, under similar used bandwidth and channel conditions, the optical communication system is able to provide more SNR in the receiver (i.e. better sensitivity) when the crest-factor of the transmit signal is lower. This was a very important constraint during the selection of the modulation scheme to be used in the standard. Time domain schemes, e.g. NRZ, M-PAM, and frequency domain schemes, e.g. Discrete Multi-Tone (DMT), were evaluated by the VDE/DKE group.

In general, DMT schemes present very important capacity loss because the crest factor of the transmit signal is very high. Indeed under controlled clipping the capacity penalty is high [3]. Other important practical issue is the excess performance loss produced by the non-linear distortion in the frequency domain equalization carried out after the FFT in the receiver.

On the other hand, the modulation technique that minimizes the crest-factor providing maximum average Optical Modulation Amplitude (OMA) injected to the POF is the M-PAM. This is because the several levels of the transmit signal are uniformly distributed, therefore the crest-factor is minimum and the average energy of sym-
bol (considering a zero mean constellation before electrical to optical conversion) is minimum for a given minimum distance of the constellation. As conclusion, high spectral efficiency encoded PAM modulation and THP [6] equalization were selected as the best options for a flexible, robust, efficient and affordable product [4].

To provide the flexibility to adapt to different configurations, the GigaPOF architecture supports a variable number of bits per symbol, different degrees for error correction coding and multiple symbol frequencies. This is done using a Multi-Level Coset Coding (MLCC) scheme [5] based on binary Bose, Ray-Chaudhuri, Hocquenghem (BCH) component codes.

BCH codes, under hard decision decoding, provide high coding gain for high code-rates without error floor. However, for mid and low code-rates, they lose coding gain. Based on this, it was decided to not support BCH codes with configurable code-rate at each coding level. For improving the bit rate adaptability, the use of multidimensional lattices was agreed. By using 2 dimensional lattices does the adaptive bit rate resolution 0.5 bits/symbol, equivalent to 1.5 dB of receive optical power. A finer receive optical power resolution of 0.75 dB (equivalent to 0.25 bits/symbol) is possible, but by using more expensive 4 dimensional lattices. Resolution of 1.5 dB was considered the best trade-off between complexity and bit rate adaptability.

The VDE/DKE working group also evaluated the suitability of other channel coding schemes, as Binary Interleaved Coded Modulation (BICM). This was rejected due to excessive latency, non-uniform coding gain for adaptive bit rate and performance loss in mid and high spectral efficiencies.

Finally, more advanced binary probabilistic codes, as Low Density Parity Check (LDPC), were studied as component codes of the MLCC structure. This was discarded due to the high decoding complexity, which translates into more silicon area and power consumption, and because the marginal improvement provided by LDPC for an optical communication system is negligible in terms of link power budget. The potential decoding error floor of the LDPC codes was also an issue considered in the decision.

In comparison with other encoding schemes, the MLCC scheme allows to reduce the latency and the computational complexity. This is because both, interleaver is not required and each encoded level operates over simple constellations of up to 1 bit per dimension. In addition, the MLCC scheme was designed such that each component BCH code works at symbol rate. This enables to reduce the number of operations per clock cycle required for encoding and decoding.

The MLCC scheme is illustrated in Fig. 2. The incoming data is divided into blocks that are partitioned in up to three levels with different degrees of coding and then mapped to a two dimensional constellation. The bits in the first level are protected with a (2016, 1994) BCH code that provides powerful error correction while the second level is protected with a (2016, 1664) BCH code and the last level is not coded. The bits are then mapped such that bits from levels two and three are far apart (i.e. coset partitioning).

![Fig. 2: Scheme of the encoding process using the Multi-Level Coset Code of the standard](image)

Going in more detail, the first level is always enabled, by using QPSK modulation. The second level, depending on the bit rate configuration, uses BPSK or QPSK modulations. For BPSK, the BCH code is shortened to 1008 bits length. The third level directly maps the information into configurable size modulations over $Z^2$ or $RZ^2$ lattices. After mapping, 2D lattice transformations are used to implement the coset partitioning. Finally, the M-PAM symbols are generated by time multiplexing from 2D symbols.

The previous process is illustrated in Fig. 3 for a configuration in which the numbers of bits in each level are 1, 1, 1.5. This corresponds to 16-PAM modulation and bit rate of 1 Gbps, with symbol frequency of 312.5 MHz.

By using different numbers of bits at each level, multiple speeds can be obtained depending on the channel conditions. This results in a flexible scheme that can adapt to many POF channels.
The transmission of data is structured in frames that are sent continuously. The frame structure is illustrated in Fig. 4. Each frame contains 112 data blocks (MLCC code words) and also additional information related to the physical layer. This information is two pilot signals (S1 and S2) and the physical header (PHS). The pilots are intended to aid the receiver in performing the linear and non-linear equalization and timing recovery. Non-linear equalization is implemented in the receiver while the linear equalization is implemented in part in the transmitter using Tomlinson-Harashima Precoding (THP) to avoid error propagation issues and in the receiver using a feed forward equalizer. The physical header is used for physical layer signalling. This includes the selection of the MLCC configuration and the transmission of the THP coefficients. The GigaPOF scheme also provides good energy efficiency. A scheme similar to that used in Energy Efficient Ethernet (IEEE 802.3az) that enables the PHY to enter into a low power mode when there is no data to transmit is incorporated in the standard.

2.3. Key performance parameters

The link power budget is the main figure of merit of an optical communication system. This gives the maximum attenuation that is able to resist the communication system guaranteeing a given data rate with a Bit Error Rate (BER) less than a target (10^{-12} for GigaPOF standard) under a defined conditions of noise, distortion, temperature, etc.

As explained before, it was mission of the VDE/DKE team to select and develop the more suitable telecommunication techniques that lead to the maximization of the link power budget. Fig. 5 shows the link power budget for providing 1 Gbps using a LED with wavelength width FWHM of 20 nm, numerical aperture FWHM of 0.3 and OMA of 0 dBM. Several analogue -3dB electrical bandwidths of LED devices are considered in order to show how the link budget depends on. The link budget is given for 50 meters of POF. A commercially available inte-
grated large area optical receiver is considered. The trans-impedance is adjusted to optimize the noise-bandwidth trade-off as a function of the symbol rate and modulation levels.

Fig. 5 shows the link budget (dBo) as a function of the symbol frequency ($F_s$). As can be seen the symbol rate that maximizes the link budget is around 300 MHz, for LED bandwidths between 50 and 100 MHz, and something more than 350 MHz for higher bandwidths. Therefore, the 16-PAM modulation and the intermediate symbol rate of 312.5 MHz were selected for 1 Gbps, using a spectral efficiency of ~3.3 bits/symbol.

![Fig. 5: Link power budget for 1 Gbps as a function of the symbol rate and the number of PAM levels](image)

3. Product implementation

The first integrated circuit complying with the Gigabit POF standard will be released to the market during 2012. This silicon will be the first member in a row of a family of products from KDPOF, aimed towards the main POF markets: Home and small office networking, Industrial and automotive.

The product requirements for KDPOF’s chip have been carefully taken into account considering the needs and projections of key customer segments. After thorough market research activities, and thanks to the power and flexibility of the standard, this first silicon release for the home and small office networking market will incorporate key features that will enable the final products to offer, in addition to Gigabit true data speed, key customer demanded features like daisy chain networking and smart power consumption. Fig. 6 shows the block diagram of a system that integrates the first KDPOF’s chip.

![Fig. 6: Block diagram of a system integrating the KDPOF’s KD-PHY 1000 IC](image)

KDPOF’s KD-PHY1000 IC is a standard compliant PHY with standard and flexible host interfaces like GMII, RGMII, SGMII and SERDES MAC interface for an easy connection to any Ethernet MAC chip. On the other side the chip interfaces with the analogue transmitter and receiver optoelectronics, composed by the driver, LED,
photodiode and the TIA. The analogue interfaces have been carefully optimized for leader supplier optoelectronics component vendors ensuring the optimum performance of the overall system.

KDPOF’s leading technology has been able to offer all these functionalities without trading off key objectives like cost and ease of implementation required by OEMs. A comprehensive set of reference designs, application notes and on-line technical support will also be in place to ease the integration of KDPOF’s product in final chipsets and reduce the overall NREs. The long experience on integrated circuit development of KDPOF technical team, its thorough development process and the manufacturing technology and partners selected have been key on achieving the cost and size targets competing head to head with other alternatives like the 1000BASE-T Ethernet mass market products.

Thanks to the close collaboration of KDPOF with the VDE/DKE standardization team, strict compliance with the standard is ensured giving to the market a clear signal on product compatibility and mass market development, avoiding past situations with other home networking technologies were the lack of a unified standard has jeopardized customer acceptance. Being the originator of the set of technologies supporting the standard, KDPOF enjoys a strong position in the future market. There is already being acknowledged worldwide by key players, either customers or prescriptors, in the market like telecom operators, OEM vendors and optoelectronics suppliers seeking to adopt KDPOF products.

KDPOF commitment with the future development of the Gigabit POF market will translate into a comprehensive product line that will attend the future market needs. New features like packet switching capabilities, industrial and automotive grade compliance as well as specific application tuning will be offered without losing the strict power, cost, size and robustness performance which is KDPOF’s distinction.

4. Conclusions

We have reviewed briefly the main features of the first standard for Gigabit Ethernet transmission over POF that will be published shortly. This team effort, led by VDE/DKE will be the first step to future international standards around Gigabit communication over POF.

The company KDPOF will put into the market the first integrated circuit that complies with the standard during 2012. It has been shown how, during the silicon development, special care has been taken to come up with a robust, efficient and affordable product well suited for the high volume consumer market. We hope that this product will greatly contribute to develop the home and office networking market based on POF and take profit from this strongly growing market.

Acknowledgements

The authors would like to thank Pedro Reviriego for fruitful discussions and help in the standard development.

References