Prototipos para transmisión de datos sobre fibra óptica plástica en cortas distancias implementados en FPGA

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Abstract — **This work describes two media converter prototypes for transmitting 10Mb/s & 100Mb/s Ethernet data over large core (1mm) Step-Index Polymer Optical Fiber (SI-POF). In terms of reach, both prototypes greatly outperform previously published results and current commercial media converters based on POF as well as CAT-5 systems. These results encourage the deployment of POF for short and medium reach communications systems such as the last part of access networks, in-house and in-building networks, industrial automation, airplane and ship cabling and in general for all those environments in which not only characteristics like ease of installation and low-cost are desired, but also the inherent advantages of fiber optic transmission systems like electromagnetic compatibility issues.**

Index Terms — **Polymer Optical Fiber, Pulse Amplitude Modulation, Media Converter, Industrial Application.**

I. INTRODUCTION

P LASTIC or Polymer Optical Fibers, as from their name, are made with polymers and thus have a different behaviour from the "usual" optical fibers made of glass (GOF). This work focuses on large core step-index (SI) Poly-Methil-Meta-Acrilate (PMMA) optical fibers which have diameter of 1mm and high numerical aperture (NA≈0,50) [1]. These fibers show excellent mechanical characteristics such as stress resilience, low bending radius, low bending losses and ease of connection; characteristics that currently cannot be found in GOF. These features are translated into a key advantage: easy installation and consequently low installation costs. From here on, the acronym POF will be used in the text to indicate standard PMMA, step-index, 1mm fibers, exclusively.

POF are today largely used in several specific sectors, some of the most important ones are the automotive sector [2, 3] (with several million transceivers produced per year) and the industrial automation sector [4]. Recently, POF are being also considered for next generation home networking since it could lead to a "do-it-yourself" installation by the final user thanks to their ease of handling [5, 6, 7].

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Unfortunately, despite POF's mechanical advantages, its use is limited due to some drawbacks in terms of optical properties such as attenuation and multimode dispersion [1, 8]. As a result, up to date, most of commercial products have relatively low bandwidth-distance products. In fact, the most performing available Ethernet-based transceivers are able to reach 200m at 10Mb/s and 100m at 100Mb/s [9], whereas distances up to 50 meters can be covered when dealing with IEEE 1394 S200-S400 Firewire standard [10]. The purpose of this work is the experimental demonstration of POF communication systems overcoming these limits; specifically, this work describes the design of two media converter prototypes carrying Ethernet/IEEE 802.3 data, with the following transmission characteristics:
- 10 Mb/s over ~400m (System 1, Ethernet compliant); and
- 100 Mb/s over 275m (System 2, Fast Ethernet compliant)

In order to overcome the bandwidth-distance product of current POF systems, an extensive work on the optimization of the components and transmission formats was done; moreover, digital signal processing techniques in real-time were applied in a Field Programmable Gate Array (FPGA).

The prototypes were designed in the framework of two research projects: the first one was entirely developed at Istituto Superiore Mario Boella (ISMB), and the second one was carried out thanks to a European Union research project titled "POF-ALL" [7], from which ISMB was the coordinating partner.

The authors strongly believe that the importance of the results shown here is two-fold: from a scientific point of view, the introduction of advanced modulation formats and signal processing can largely extend the bandwidth-distance product over POF which is today considered by several other research groups [12] due; and from an application point of view, it can open the use of POF to several niche applications, like in the industrial automation sector, in some IP video-surveillance systems and, possibly, as an alternative to copper solution for in-building cabling in the last hundreds meter of access networks [4].

This paper is organized as follows: Section II describes the POF transmission channel, including optoelectronic components in terms of bandwidth, noise and linearity, and analyzes how these limitations drove the choices made for the transmission system architecture of each prototype, which are thus presented in detail in the following Section III. The characterizations and performances of both

experimental prototypes are presented in Section IV, whereas some comments and conclusions are drawn in Section V.

II. TRANSMISSION CHANNEL CONSTRAINTS

The two main limitations of POF transmission systems are low bandwidth and high attenuation [1]. Regarding bandwidth, at the time of the experiment, all measurements available in the literature did not cover one of the link goals (~400m), they were limited to 150-200 meters, with a typical reported value of 30 MHz·100m for high NA POF [1, 8, 16]. Bandwidth measurements for POF distances greater than 200m, and up to 400m was carried out, the result is shown in Fig. 1 [11]. All measurements were done using commercial 1mm POF fiber with NA around 0.46.
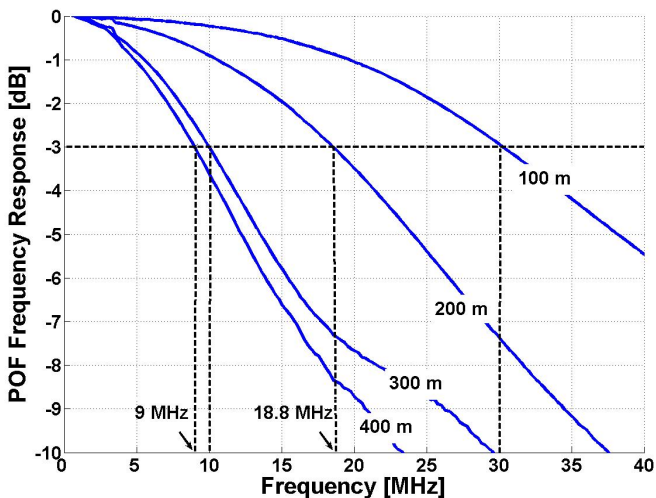

Fig. 1. SI-POF frequency response (electrical-to-electrical) for several link lengths. 3-dB bandwidths are also shown.

Table 1 shows the 3-dB bandwidth available for both transmission systems. POF has a small bandwidth since it has a high multimodal dispersion. It is estimated that approximately 2 million modes propagates on a standard POF [1], resulting in a large time spread on the received impulse response and a subsequent limited bandwidth. As inferred from the table, this issue is more critical in the system 2 (Fast Ethernet), as a consequence, adaptive equalization is a must in this case coupled with a reduction in the actual line baud rate. In the system 1, Ethernet standard considers Manchester encoding which requires a bandwidth about twice the nominal bit rate; therefore the system cannot simply take the Manchester encoded signal and modulate it optically.

TABLE I
AVAILABLE POF BANDWIDTH FOR THE DESIGNED SYSTEMS

	Bandwidth [MHz]	Distance [m]
System 1 (10 Mb/s)	9	400
System 2 (100Mb/s)	~10-20	300-200

Along aside the bandwidth problem, standard PMMA-SI-POF exhibits an attenuation of the order of 0.18 dB/m in the typically used red wavelength region (650 nm) [1]. Both systems consider instead the green wavelength region (520nm) where the attenuation is reduced to 0.08dB/m.Therefore, in the case of the system 1, this is translated into an attenuation of approximately 35 dB for the target distance, including 1-2 connectors. Considering at least a 3 dB system margin, the system 1 should tolerate about 38 dB power budget, a fairly high quantity that requires an optimization in the transmitter and receiver design in terms of average launched power and sensitivity. It also explains why FEC coding was introduced in the system 1.

In the case of the system 2, with a target distance of 300m, the total fiber loss is about 24 dB; considering a typical 3dB system margin, the power budget from TX to RX should be at least 27dB.

Regarding the optoelectronic components suitable for low cost applications, the proposed system is based on commercial components, i.e. a green LED (Die-Mount) which can couple 1-2dBm at most in the fiber, and a large area photodiode integrated with a transimpedance amplifier (Hamamatsu S6468-02). The -3dB bandwidth is 35MHz for the LED (with an optimal driving current) and 25.8MHz for the photodiode-transimpedance amplifier. It is clear that the system 1 is mainly limited by signal to noise ratio (SNR), whereas the system 2 is limited by both: SNR and bandwidth. The strategies taken in the design of the systems in order to overcome these limitations are summarized in the following.

System 1: In order to transmit the information at 10 Mb/s, it changes the line coding from Manchester to the combination of NRZ and 8B/10B, in order to overcome bandwidth limitation, while still keeping high transition density and DC-balancing. It includes a FEC to overcome SNR limitation.

System 2: Traditional binary On-Off Keying (OOK) modulation cannot reach the target 100Mb/s transmission, consequently, the system implements advanced transmission techniques such as multilevel modulation formats, FEC and equalization in a good compromise between complexity and performance.

The systems thus, implement a new data encapsulation or "protocol"; these are explained in the following section along with the systems' architectures.

III. PROTOTYPES' ARCHITECTURES

A. *System 1 (10 Mb/s)*

This media converter is based on two parts, as shown in Fig. 2: an optoelectronic part interfacing with the POF (POF-PHY, indicating with this the "physical" optoelectronic part of the system) and the logical core of the converter, implementing the proprietary protocol. This logical core part was implemented on a commercial FPGA development board (XILINX Spartan-3).
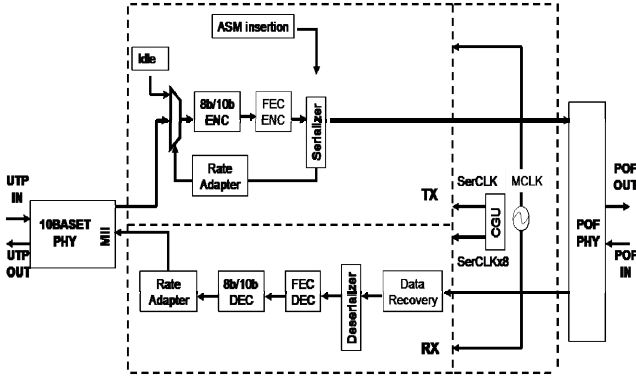
Fig. 2. System 1. Media Converter architecture

The system performs a conversion of the incoming Ethernet frames into a new framing model, based on the FEC block, i.e. the frame coincides with a FEC block. This structure was designed aiming to improve the physical layer transmission performance while keeping a reasonable level of digital complexity by developing an algorithm that can be easily implemented in digital electronics. The system thus, maps the incoming traffic into a synchronous and continuous transmission based on 8B/10B and RS-FEC. A description of the functional elements is shown below.

1) 10BASET-PHY: Via a commercial Ethernet PHY chip, which handles the full set of Ethernet physical layer specification, the Manchester encoded signal is passed to the algorithm core by means of a Media Independent Interface (MII).

2) Rate adaptation: The system forces a continuous bit transfer over the POF to allow a good optimization of clock and data recovery at the receiver side. Since input Ethernet traffic is intrinsically bursty, the rate adaptation unit inserts properly coded "idle" words in absence of incoming Ethernet data in order to guarantee a continuous output data stream.

3) DC balancing: The optoelectronic system is AC-coupled (i.e, with a zero in the receiver at null frequency) with a low cut-off frequency around 30 KHz. The system thus uses 8B/10B line coding [17] that, not only assures a good DC balanced signal, but also eases clock recovery thanks to a high transition density. Moreover, 8B/10B adds monitoring features, thanks to the availability of reserved control words (called *K*-characters in the 8B/10B standard). A subset of those *K*-characters was used for implementing the dedicated framing. As stated before, the "frame" in this system coincides with a FEC block, and is delimited by four K28.5 characters titled as "Attached Sync Mark", (ASM). Moreover, the K27.7 and K23.7 *K*-characters were used for implementing the previously mentioned rate-adaptation. As a result, input Ethernet data is mapped into a new framing structure. The use of 8B/10B adds 25% overhead.

4) Forward Error Correction: In order to increase the overall system sensitivity, the system uses Reed-Solomon (RS) FEC to increase the power budget. A RS(1023,959) code was chosen in order to match the 10 bit words at the

output of the 8B/10B coder. This code adds 64 redundant words to each 959 input data words, giving an overhead of 6.67 %. It is able to correct up to 32 10-bit words in a 1023 word block and gives quasi error free operation (BER < 10^{-12}) for an input BER < 10^{-3}. The FEC block is followed by a serializer which interfaces directly with the POF physical interface by a continuous NRZ binary stream. Taking into account the overhead introduced by 8B/10B, FEC and ASM, the resulting line bit rate is 13.64Mb/s, a compatible value with the 9MHz available bandwidth for the target 400m POF system without requiring special compensation techniques, such as adaptive equalization.

5) Optoelectronic transceiver: Composed by a LED working in the green region of the visible spectrum and a photodiode with integrated transimpedance amplifier at the receiver side as mentioned before.

6) Data Recovery: At the receiver side, a fully digital data recovery algorithm is implemented. The system uses a modified version of the data recovery over-sampling technique described in [18], and long-term PLL-like averaging in the clock recovery to minimize jitter in the sampling point in the middle of each received bit.

After recovery, the data are deserialized in order to be fast processed in a parallel format by the FEC and 8B/10B decoder. Moreover, the original Ethernet traffic, including the proper time gap between frames, is reassembled thanks the rate adaption unit which removes idle words.

B. System 2 (100 Mb/s)

As in the previously mentioned system, this prototype also consists in two main parts, a POF-PHY and a logical core implemented on a FPGA Xilinx Virtex-4 as shown in Fig. 3. This logical core includes the same or similar techniques developed for the system-1 prototype with the exception of the 8B10B coding and some others listed in the following:

a) 8-PAM Multilevel (baseband) amplitude modulation: Introduced here in order to reduce by a factor of three the required bandwidth with respect to binary modulation the line baud rate.

b) Equalization techniques: An (optional) pre-equalizer at the transmitter side and adaptive equalization at the receiver based on standard feed-forward FIR filters [13] were introduced in order to overcome dispersion limitations.
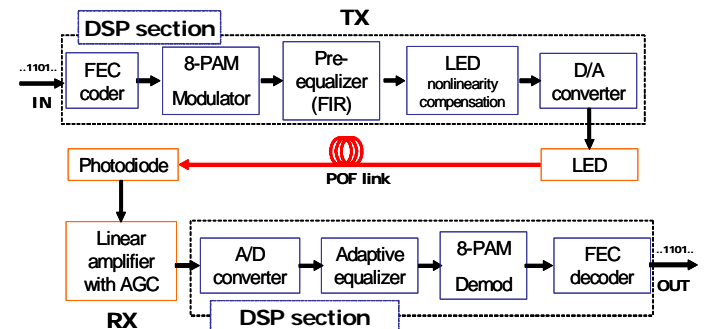

Fig. 3. System 2. Block-diagram

The decision of implementing a simple modulation format (8-PAM) was also related to the fact that most of the optically advanced modulation formats under consideration today for single mode optical fibers, such as polarization multiplexing and coherent detection, are unfeasible for POF due to its multimodal transmission properties, and make intensity modulation and direct detection (IM-DD) the only available option. Additionally, sticking with IM-DD, it is still in theory possible to envision the use of a higher performance modulation format, such as OFDM. Anyway, baseband 8-PAM is much simpler and thus keeps digital signal processing complexity low, an important requirement for low-cost, short reach applications.

In this system, the linearity issue arises with the optoelectronic transmitter and receivers. Usually, linearity is not required in standard binary IM-DD system; very often the receiver is completely nonlinear since it includes a limiting amplifier. Here instead, moving to multilevel requires both a linear transmitter and a linear receiver, an issue that was taken into account when analyzing the LED's response (non linear).

At the transmitter side, the input digital data stream is first sent to a FEC encoder, in this case a RS(511, 479) Reed-Solomon code was used. This code works with 9-bits words that are easily matched with the 3 bit per symbol required by the following 8-PAM modulator. Its coding gain of the order of 5dB is useful to balance the intrinsically higher SNR required by 8-PAM with respect to pure binary modulation. It was proved by simulation that the SNR requirement for a given bit rate of the combination of 8-PAM plus RS is very similar to pure binary without coding.

The output of the RS coder goes to the 8-PAM modulator and then to a pre-emphasis FIR filter. The resulting signal is sent to a block that compensate the LED intrinsic nonlinearity and finally to a Digital to Analog (D/A) converter, which drives the input of a green LED.

At the receiver side, a large area photodiode is followed by a linear amplifier. In order to maintain linearity over a large input dynamic range, an automatic gain control (AGC) system is required. The signal is then sent to an A/D converter and then to an adaptive equalizer, an 8-PAM demodulator and a FEC decoder.

Note that even when using 8-PAM, the resulting eye diagram after 200 meters is still completely closed, as shown in Fig. 4, confirming that strong pre- and post-equalization were necessary.

Similarly, the LED intrinsic nonlinearity would generate a completely unbalanced eye diagram even in the back-to-back case, as depicted in Fig. 5, which explains the insertion of a nonlinearity compensation block.

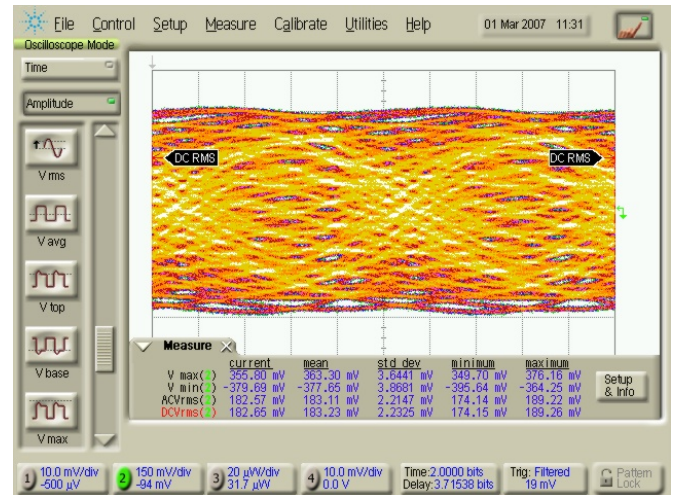The most important modules of this prototype are described in the following.

Fig. 4. 8-PAM transmission after 200m of PMMA-SI-POF propagation: the eye is completely closed.
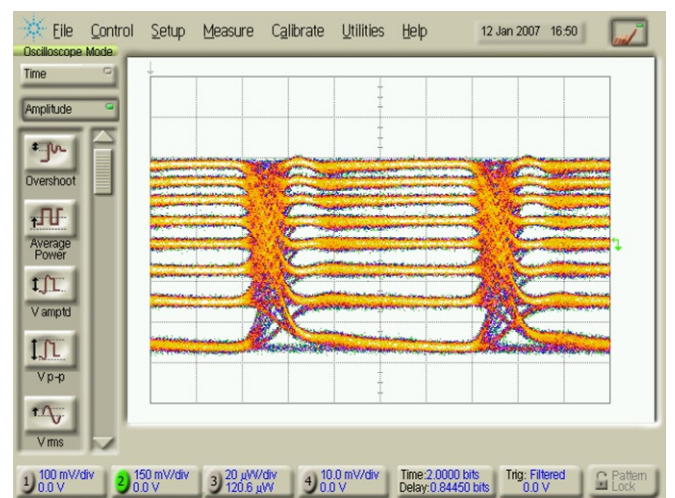

Fig. 5. 8-PAM signal applied to the LED (back-back). A compensation for this non-linearity was finally applied.

1) Pre-equalizer

Fig. 4 shows the completely closed eye diagram after 200 meters of POF without any form of linear equalization. Even though that in principle this eye diagram can be largely compensated by an adaptive post-equalizer at the receiver, the task of clock recovery would be hard to achieve on such a distorted eye diagram; therefore, the system considers a (fixed) pre-equalizer block at the transmitter side. It was implemented by a standard FIR filter structure and chosen so that the resulting transfer function of the whole system (including transmitter and receiver optoelectronics, 200 meters of POF and the pre-equalizer) had a raised cosine global transfer function with a roll-off factor of 0.8 and 3dB cut equal to the transmission baud-rate. It is well know that this option ideally compensates inter-symbol interference (ISI) and at the same time gives a good eye diagram in terms of tolerance to receiver clock jitter [13]. The pre-equalizer compensates for a typical 200m span, considering it to be an average value within the possible installations range. Fig. 6 shows the resulting pre-equalizer transfer function and its implementation with a 20 taps FIR filter in a transposed and pipelined structure, working at twice the baud-rate.
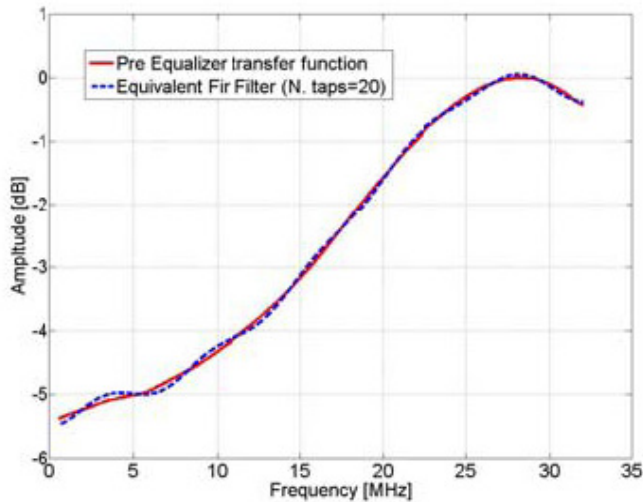
Fig. 6 Pre-equalization filter for a link-length of 200m, and its implementation through a 20-taps FIR filter. The overall transfer function results in a raised cosine with roll-off factor of 0,8.
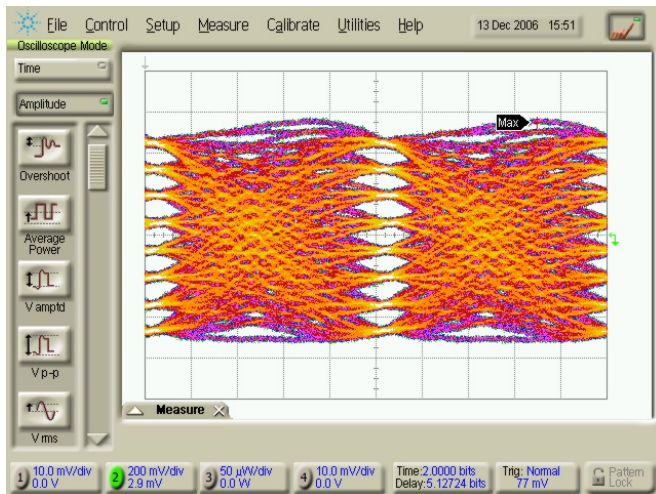

Fig. 7 8-PAM transmission after 200m of POF, with LED linearization and Pre-equalization filter: the eye-diagram is now open

As can be seen, the resulting transfer function of the pre-equalizer clearly has a high-pass characteristic, with 5.5dB gain at about 30MHz with respect to the low frequency response. This is translated into strong overshoots on the 8-PAM signal in the time domain. It will be shown that this issue worsens absolute performances, in terms of bandwidth limitations, with respect to a system where only an adaptive post-equalizer is adopted. Nevertheless, the resulting (small) penalty is worth when clock recovery is concerned as stated before. The resulting eye diagram after 200m with pre-equalization at the transmitter is shown in Fig. 7.

2) LED nonlinearity compensator

When a system employs direct modulation of a LED, it deals with the well-known distortion due to the LED's non-linearity in its input current vs. output power curve (P-I curve). This actually does not affect the performance when binary modulation like NRZ is applied; unfortunately this is not the case here since this system is based on a multi-level modulation format. Fig. 5 mentioned before shows the eye diagram obtained driving a green LED with an 8-PAM signal at 10 Mbaud. This result shows that some form of

nonlinearity compensation is strictly needed.

A characterization of a set of several green LED (all from the same production batch) measuring the P-I curve was done. These P-I curves, after a simple normalization, become virtually identical; therefore, all LEDs belonging to the same production batch can be linearized using the *same* nonlinear law [14]. Moreover, this property persists over a wide temperature range. This extremely important result, allows programming a single nonlinearity law in the transmitter chain of the logical core, which was able to compensate different LEDs in different operating conditions.

3) Optoelectronics

In addition to the green LED and the photodiode-transimpedance amplifier described previously, the system also considers an amplifier equipped with an Automatic Gain Control (AGC) circuit, which was set in order to match the input range of the following A/D converter for a wide range (approx. 20dB) of input optical power dynamic range.

4) Adaptive equalizer

After A/D conversion, the received signal is sent to an adaptive post-equalizer. The prototype implements a relatively simple Least-Mean Square (LMS) fractionally-spaced adaptive equalizer [13] in a pipelined systolic architecture of a 10-tap FIR filter, working at twice the baud rate.

Actually, the prototype considers two different algorithms for the coefficients' computation. The first step is carried out at the system startup by a Blind Equalization, which quickly leads to a small LMS error. Blind equalization avoids complex handshaking procedures to derive preliminary channel parameters. A control unit monitors the LMS errors, and switches the system to a second step, a Decision-Directed algorithm, once the error reaches a properly chosen threshold.

IV. EXPERIMENTAL RESULTS

A. System 1

The prototype of the system 1 implements a fully compliant Ethernet (10 Mb/s) full duplex link. The system was characterized first in terms of Bit-Error-Rate (BER) performance and it was tested with both, a continuous DVD quality video stream running between two PC, or by real traffic coming from a FTTH connection from an Italian operator. The used fibers are part of a real POF LAN test-bed.

Fig. 8 shows pre-FEC BER vs. received power plots for back-to-back and after 300m of POF. Since the used FEC starts to fail for a pre-FEC BER of about 10^{-3}, the figure shows that the resulting global receiver sensitivity is about -37dBm. This value is translated into a power margin is 38 dB (given an average transmitted power of 1dBm for the used green LED) which allows a 400m link including 1-2 connectors and some system margin, as explained in Section II. It can be seen also that fiber related impairments are small, e.g. for a BER = 10^{-8} the figure evidences a 0.5 dB

power penalty when 300m of fiber is used (with respect to back-back). The power penalty gets even smaller for higher BER values, demonstrating that the intersymbol interference introduced by multimodal dispersion at the operating bit rate is very low.
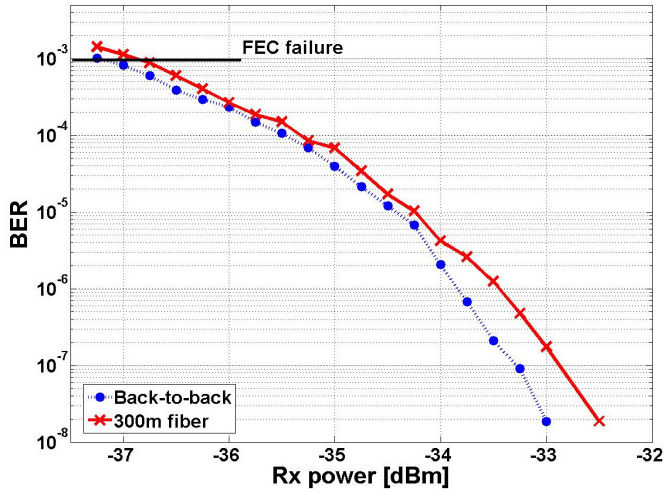

Fig. 8 System 1.BER before FEC vs. received optical power for back-back and after 300 meters. FEC failure level corresponds to a pre-FEC BER $\cong 10^{-3}$

Several long term measurements were carried out over a record distance of 425m, the system's limit. Fig. 9 shows the probability density function of the obtained BER after a continuous 105-day measurement. Note that the selected FEC fails with more than 32 erroneous words in a 1023 word block, situation that was never reached; in conclusion, no errors after FEC were observed in 105 days over 425 meters.

The system was also characterized in temperature. It was observed a power variation of at most 2 dB, resulting in no errors after FEC, when testing a 300m span with variations between -40°C to 80°C.
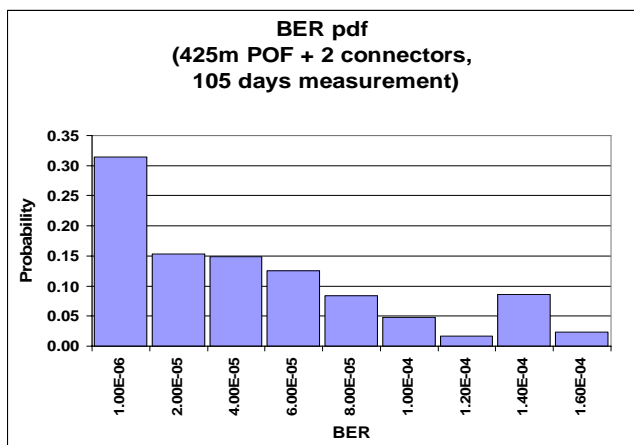

Fig. 9 System 1. BER probability density function, 105-day measurement over a 425m link

B. System 2

This system was initially tested on a single FPGA board that implemented both the transmitter and the receiver, which implies that clock recovery is not yet considered. The prototype also implements a pseudo-random digital sequence (PRBS 2^{15}-1), and a BER Tester at the receiver side.

Regarding the characterization in terms of BER, the system was tested in two different setups: with post-equalization alone and with both pre- and post-equalization active, both in a 200m link. The results, along with the back-back case, are shown in Fig. 10. The transmitted average power was +1dBm, whereas the attenuation introduced by the fiber was 17dB. The Figure shows the effectiveness of equalization in reducing the strong ISI present in the system. Remind that if no equalization is used, transmission after 200m is impossible (closed eye diagram). Note also that indeed reliable transmission can be obtained after post-equalization with relatively low penalty, e.g. approx. 2dB for a BER around 10^{-8}.
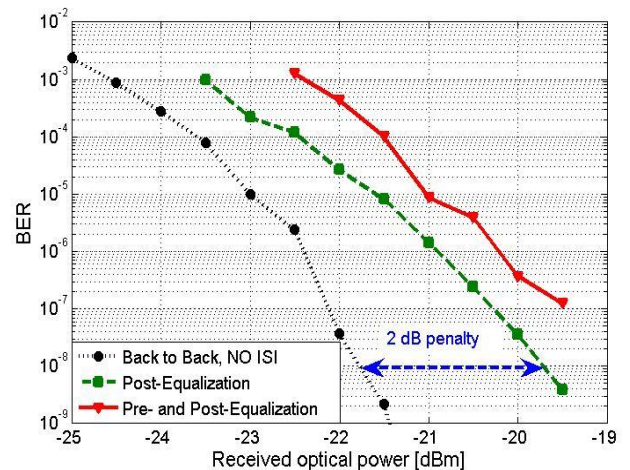

Fig. 10 System 2. BER vs. Received Optical Power: back-to-back condition (dense dashed line), with post-equalization only (spaced dashed line), with pre and post-equalization (solid line)

Figure 10 also shows that, if pre-equalization is inserted in the system, the overall results are slightly worse than for post-equalization alone, e.g. 1dB penalty compared to the post-equalization only for the FEC failure level (at -22.5dBm). This result seems to be counter-intuitive but it is explained in terms of a dynamic range of the received eye diagram. The open eye diagram obtained with pre-equalization has lower dynamic range than it would have if no ISI were present in the system. Moreover, the prototype implements a very simple pre-equalization technique, to keep DSP complexity low, thus getting a penalty.

TABLE II
SYSTEM 2. BER (BEFORE FEC) VS. POF LENGTH

Length (m)	BER with post-equalization only	BER with pre and post-equalization
200	Error free	Error free
225	$<< 10^{-8}$	$< 10^{-8}$
250	$\sim 10^{-6}$	$\sim 10^{-5}$
275	$\sim 10^{-3}$	$\sim 10^{-2}$

The system was later evaluated in terms of fiber lengths, the results are shown in Table II; note that the measurements were taken with a step of 25m, which involves also extra losses due to intermediate connector splices (average attenuation of 1.3dB per splice). The table shows that, considering a Reed Solomon FEC operating

threshold equal to a pre-coded BER=10^{-3}, the maximum reachable distance is 275m.

Finally, a detailed high-level system characterization using the prototype as a "UTP-to-POF" media converter configured as full duplex (100Mb/s) Fast Ethernet was also carried out at Fastweb premises (the biggest Italian FTTH and xDSL alternative Telecom operator) using their standard triple play test & measurement procedures, being the "high-definition video-test" the most relevant. After 36 hours, all measurements were below the "video acceptance threshold" fixed by Fastweb which correspond to an acceptance level of 99.72%. This shows that the system was basically error-free after FEC.

V. COMMENTS AND CONCLUSIONS

The works presented here constitute a proof of concept of the usage of 1mm POF not only in short reach application below 100 meters, but also on extended reach for 10 Mb/s and 100mb/s thanks to a proper choice of DSP techniques. The record distances achieved open new applications of this fiber like edge-networks, or in other niche sectors, such as in any industrial-like environment where harsh environmental conditions (dust, EMI interference, etc) make the use of other transmission media difficult or even impossible.

In terms of distance, system 2 greatly outperforms current Fast-Ethernet over CAT-5 and CAT-6 specifications. Therefore, the prototype can be considered today as a UTP-to-POF Fast-Ethernet media converter, and it was tested as such at the application layer as shown in Section IV.

Regarding the techno-economic aspect, the transmission techniques presented mainly in the system 2 were prototyped on an FPGA platform. An actual product will require the development of a proper ASIC. Preliminary studies showed that this would be quite straightforward, but would clearly be economically viable only if a mass market for these transceivers will emerge in the future.

Comparable performances (Fast Ethernet over 200 meters) have been shown by other POF-ALL partners using commercial VDSL2 chipset based on DMT modulation [15]. This solution has evident advantages in terms of development costs since it does not require the design of a new ASIC. IN any case, the 8-PAM approach has anyway a competitive advantage with respect to DMT since its DSP complexity is significantly lower which means low power consumption, a fundamental requisite for any datacom solution. Moreover, the approach described here has very low latency compared to a typical DMT solution.

Finally, extended reach POF systems have been largely demonstrated inside the POF-ALL project (also by other partners) so that, scientifically and technically, it is now perceived as completely feasible. The actual success of these technologies will thus only depend on the market requests in the several niche sectors and/or in the ever evolving residential access scenario. Here, several European operators are evaluating POF as a potential solution for in-apartment networking.

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