Buckling of composite thin walled beams by refined theory

100 Mb/s Ethernet Transmission Over 275 m of Large Core Step Index Polymer Optical Fiber: Results From the POF-ALL European Project

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***Abstract*—We present our prototype solution for transmitting 100 Mb/s Ethernet data over large core (1 mm) step-index polymer optical fiber (POF), as one of the final results of the EU-funded project POF-ALL. The system is demonstrated over a record maximum distance of 275 m, largely outperforming CAT-5 systems and currently commercially available POF media converters. These results let us envision POF deployment for home networking and industrial automation and in general for all those environments in which ease of installation, rugged solution, low-cost and electromagnetic compatibility issues are requested.**

***Index Terms*—Industrial application, media converter, polymer optical fiber, pulse amplitude modulation.**

I. Introduction

LARGE core step-index poly-methil-meta-acrilate (PMMA) optical fibers are well known for their excellent mechanical characteristics compared to glass optical fibers (GOF), such as stress resilience, low bending radius, low bending losses, and ease of connection. The resulting key feature of these fibers is thus their ruggedness and easy installation, due to their large core diameter (1 mm) and high numerical aperture (NA $\approx$ 0, 50) [1]. For clarity, we point out that we will focus in the present paper only on this fiber type, and consequently the acronym POF will be used in the rest of the text to indicate standard PMMA, 1-mm fibers. Other types of plastic fibers will not be considered here.

POF are today largely used in some specific sectors where their characteristics are key, such as in the automotive sector [2], [3] (with several million transceivers produced per year) and in the industrial automation sector [4]. Recently, POF are being considered also for next generation home networking, thanks to their ease of handling, allowing to envision a "do-it-yourself" installation by the final users [5]–[7].

All these advantages anyway come with drawbacks in terms of optical properties such as attenuation [1] and multimode dispersion [8]. As a result, most of today commercial products have relatively low bandwidth-distance products. In fact, the most performing available Ethernet-based transceivers are able to reach 200 m at 10 Mb/s and 100 m at 100 Mb/s [9], while for what concerns IEEE 1394 S200-S400 Firewire standard [10] distances up to 50 m are covered at most. In one of our previous works, we showed anyway that these limits can be largely extended, demonstrating 10 Mb/s Ethernet transmission over more than 400 m [11].

Extending the bandwidth-distance product over POF is the focus of the European Union research project titled "POF-ALL" [7]. This 2.5 year long, 2.6 MEuro project started in 2006 and ends in 2008. It is coordinated by the authors' team and is specifically focused on two main transmission goals on POF:

— 100 Mb/s over long distances, targeting 300 m;

— 1 Gb/s over intermediate distances, targeting 100 m [12].

Both goals have currently (middle of 2008) been reached through an extensive work on the optimization of the components and transmission formats. This paper focuses on the first of these two goals, showing the results on a 100 Mb/s transmission system prototype running over a record distance of approx. 275 m and using very low cost LEDs at the transmitter side. The developed prototype is a media converter fully compliant with the Fast Ethernet standard. We believe that the importance of this results is two-fold.

- From a scientific point of view, we have introduced the idea that advanced modulation formats and signal processing can largely extend the bandwidth-distance product over POF. This idea, originally introduced by our team in 2004 [13], is today investigated by several other research groups [12].
- 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 hundred meters of access networks [4].

The paper is organized as follows. In Section II, we describe the POF transmission channel, including optoelectronic components in terms of bandwidth, noise and linearity, and we derive how these limitations drove our choices for the transmission

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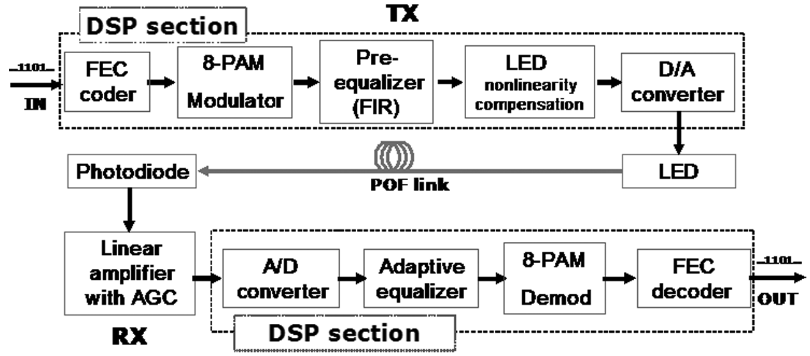

Fig. 1. Block-diagram of the implemented transmission system.

system architecture, which is thus presented in details in the following Section III. The experimental prototype and its characterization is presented in Section IV, while some comments and conclusions are drawn in Section V.

II. POF Channel Constrants in Terms of Bandwidth, Available SNR, and Linearity

In our system, we consider transmission distances ranging from 200 to 300 m over POF. The two key limitations in such a panorama are limited bandwidth and high attenuation. Regarding available bandwidth, as we showed in [10, Fig. 1], the POF 3 dB is limited to about 15–20 MHz for the considered length: this is due to POF high multimodal dispersion. As shown in [1], it is estimated that approximately 2 million modes propagates on a standard POF, resulting in a large time spread on the received impulse response and a subsequent limited bandwidth. The multimode effect is stochastic in nature, since it strongly depends on POF fabrication process and on the mechanical micro-stresses applied to the POF in a realistic installation; as a consequence, adaptive equalization is a must, as shown later in the paper. Regarding the second limitation, POF loss is very high, resulting in an unacceptable loss in the typically used red wavelength region, where the average attenuation value is around 0.18 dB/m. In the green wavelength region (520 nm) the attenuation is reduced to 0.08 dB/m [1]. Considering a target 300-m distance, we opted for the green wavelength region, where the fiber total loss results in about 24 dB, so that a reasonable power budget from the TX to the RX should be set to at least 27 dB, considering a typical 3-dB system margin. For optoelectronic devices suitable for low cost applications, such as green LEDs and large area PIN photodiode, the typically available power budget cannot be much higher than this; in fact, best commercial green LEDs can couple 1–2 dBm at most in the fiber, and typical large area photodiode sensitivity is rarely better than -30 dBm over the required bandwidth. As a result, our target 100 Mbit/s transmission systems is both band-limited and signal-to-noise ratio (SNR) limited, and the traditional binary on-off keying (OOK) modulation cannot reach our goals.

Consequently, in our project, we focused on advanced transmission techniques in order to overcome these limitations. As it will be better pointed out in the following section, we found that a good compromise between complexity and performance is based on:

- 8-PAM Multilevel (baseband) amplitude modulation at the transmitter side;
- adaptive equalization at the receiver, based on standard feed-forward FIR filters [14];
- Reed–Solomon forward error correcting (FEC) codes.

The decision to use 8-PAM modulation was key in order to reduce by a factor of three the required bandwidth with respect to binary modulation. It should be noted here that our decision was also related to these other constraints.

- 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.
- Sticking with IM-DD, it is still in theory possible to envision the use of a higher performance modulation format, such as OFDM. Anyway, as discussed later in Section V, we opted for the simpler baseband 8-PAM to keep digital signal processing complexity to a minimum, an important requirement for low-cost, short reach applications.

The decision to move to a multilevel modulation format introduces additional requirements in the full transmission chain in terms of overall linearity. In this respect, POF is a virtually perfect medium, since its nonlinear Kerr effects are absolutely negligible for any reasonable launched power, due to POF very large core diameter. Anyway, the linearity issue arises with the optoelectronic transmitter and receivers. Usually, in standard binary IM-DD system, linearity is not required, in fact, most often the receiver is completely nonlinear since it includes a limiting amplifier. With respect to this commonly used solution, moving to multilevel requires both a linear transmitter and a linear receiver. The technical consequences of this are addressed in the next section, while its component costs will be dealt with in Section V.

III. Transmission Solution

In this section, we describe the digital transmission system that we have designed to match the transmission constraints presented in the previous Section. We start by introducing the block diagram of the system, shown in Fig. 1.

The input digital data stream is first sent to a FEC encoder. We selected a RS(511, 479) Reed–Solomon code [14]. This code works with 9 bits words, that is easily matched with the 3 bit

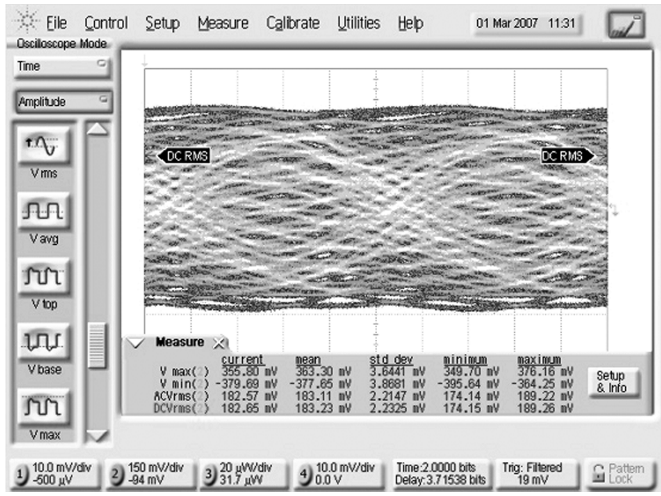

Fig. 2. 8-PAM transmission after 200 m of PMMA-SI-POF propagation: the eye is completely closed.

per symbol required by the following 8-PAM encoder. Moreover, its coding gain, of the order of 5 dB, is useful to balance the intrinsically higher SNR required by 8-PAM with respect to pure binary modulation. By extensive simulation, we found 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 digital stream at the output of the RS coder is sent to a 8-PAM modulator, 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 directly 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.

We start by noting that even when using 8-PAM, the resulting eye diagram after 200 m is still completely closed, as shown in Fig. 2, so that we had to resort to strong pre- and postequalization.

Similarly, the LED intrinsic nonlinearity would generate a completely unbalanced eye diagram even in the back-to-back case, as depicted in Fig. 3, upper graph, showing that a nonlinearity compensation is key.

The system block diagram, shown in Fig. 1, is clearly divided in two sections: one is the optoelectronic part, that is very similar to a standard IM-DD diagram with the exception of the AGC feature at the receiver; the other section is all based on digital signal processing (DSP) that, in the prototype, has been implemented over a commercial FPGA board.

Some of the key building blocks are presented in further details in the following Subsections.

A. Pre-Equalizer

Without any form of linear equalization, the resulting eye diagram after 200 m is completely closed, as shown in Fig. 2. Even though we will demonstrate later that in principle this eye diagram can be largely compensated by an adaptive postequalizer at the receiver, the task of clock recovery would be hard to achieve on such a distorted eye diagram. Thus, we analyzed the option of a (fixed) pre-equalizer block at the transmitter side. This was implemented by a standard FIR filter structure according to the following heuristic rule: let $H_{\rm tot}(f)$ be the whole transmission system transfer function for 200 m of POF and for the transmitter and receiver optoelectronics pair; the pre-equalizer transfer function $H_{\rm pre}(f)$ was selected so that the product $H_{\rm tot}(f) \cdot H_{\rm pre}(f)$ gives a raised cosine global transfer function with a roll-off factor of 0.8 and 3 dB cut equal to the transmission baud-rate. It is well know that this option ideally compensates intersymbol interference (ISI) and at the same time gives a good eye diagram in terms of tolerance to receiver clock jitter [14]. In the prototype, we have chosen to compensate for a typical 200 m span, considering it to be an average value within the possible installations range. In Fig. 4, we show the resulting pre-equalizer transfer function and its implementation with a 20 taps FIR filter. The two curves match nearly perfectly, showing that the approximation of the ideal transfer function with a 20 taps FIR is sufficiently good. The filter has been implemented with a transposed and pipelined structure, working at twice the baud-rate.

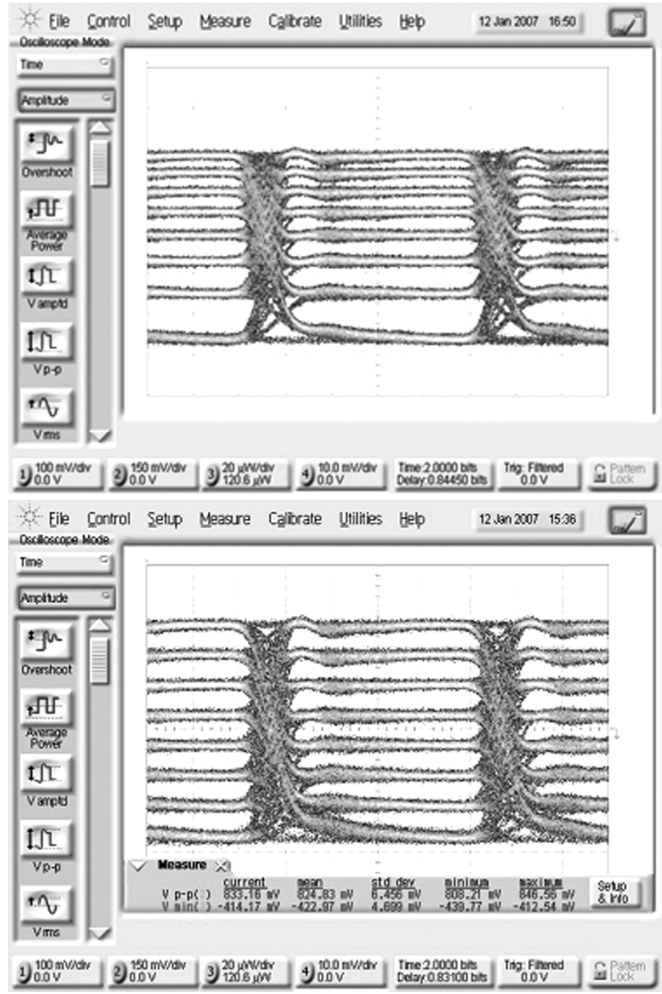

Fig. 3. Upper graph: 8-PAM signal directly applied to the LED. Lower graph: same, after nonlinearity compensation.

We note here that the resulting transfer function $H_{\rm pre}(f)$ clearly has a high-pass characteristics, with 5.5-dB gain at

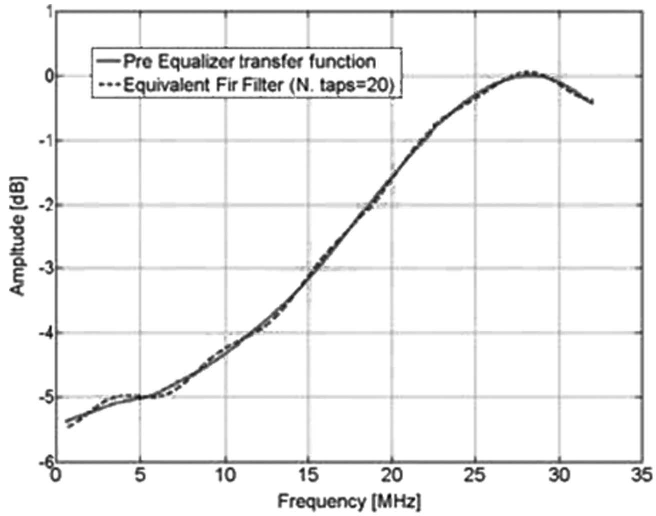

Fig. 4 Pre-equalization filter PT(f) for a link-length of 200 m, and its implementation through a 20-taps FIR filter. The overall transfer function $\mathrm{PT(f)} * \mathrm{GT(f)} * \mathrm{C(f)} * \mathrm{GR(f)}$ results in a raised cosine with roll-off factor of 0,8.

about 30 MHz with respect to the low frequency response. In the time domain, the 8-PAM signal will thus have strong overshoots. Their effect on system performance is further discussed in Section IV, where it will be shown that the addiction of pre-equalization worsens absolute performances, in terms of bandwidth limitations, with respect to a system where only an optimized adaptive postequalizer is adopted. The resulting (small) penalty gives anyway an advantage when clock recovery is concerned, as discussed in Section IV.

B. LED Nonlinearity Compensator

Optical communications systems employing directly modulated LED must face the well-known distortion due to the LED nonlinearity in its input current versus output power curve (indicated as P-I curve in the following). Usually, this phenomenon does not affect the overall performances when binary NRZ modulations are used, so LED nonlinearity compensation is not usually perceived as an issue in this context, and literature is quite poor about this topic ([14]). A completely different scenario appears when employing LEDs in systems based on multilevel modulations, such the 8-PAM that we needed to adopt in our system. As an example, we showed in Fig. 3 the eye diagram resulting at the output of the green LED used in our system, when driving its input with an ideal 8-PAM signal. In this curve, the baud rate was limited to 10 Mbaud just to avoid mixing LED nonlinear effects to bandwidth limitations. This result shows that some form of nonlinearity compensation is strictly needed.

We have addressed this problem in detail. We started by characterizing a set of several green LED (all belonging to the same production batch) measuring their P-I characteristics. We found that all these P-I curves, after a simple normalization described in detail in [16], become virtually identical. As a result, all LEDs belonging to the same production batch can be linearized using the *same* nonlinear law. We also check that this property persists over a wide temperature range. This was an extremely important results, since it allowed to program a single nonlinearity law in the DSP part of the transmitter chain, which was anyway able to compensate different LEDs in different operating conditions. Thus, we derived an analytical expression for this (normalized) LED P-I law, and found by numerical fitting that it had an excellent match in the nonlinear expression $f_{LED}(x) = a_0 + a_1 \cdot x^c$, with the experimentally fitted parameters $a_0 = 0,8777$, $a_1 = 0,1441$ and $c = 0,5492$. The compensating function $g(x)$ programmed in the DSP part of the transmitter was then simply set as $g(x) = f_{LED}^{-1}(x)$. The effect of the linearization is shown in Fig. 3, lower graph.

C. Optoelectronics

The optoelectronic setup used in the prototype was quite straightforward, low cost and similar to those used today in many POF commercial transceivers. At the transmitter side, we employed a green light emitting diode (LED) by Diemount, giving a peak output power of the order of $+2$ dBm and a 35-MHz modulation bandwidth.

At the receiver side, we used a large area (800 μm diameter) Hamamatsu S6468-02 photodiode with integrated transimpedance amplifier, with a bandwidth of 26 MHz. This device showed good noise performance with respect to other similar devices. It was followed, in the setup, by a further amplifier equipped with an AGC circuit, that was set in order to match the input range of the following A/D converter for a wide range (approx. 20 dB) of input optical power dynamic range.

D. Adaptive Equalizer

In the receiver section, after A/D conversion, the signal is sent to an adaptive postequalizer. In order to find a good compromise between performance and complexity, we opted for a relatively simple least-mean square (LMS) fractionally-spaced adaptive equalizer [14]. We implemented it using a pipelined systolic FIR filter architecture, working at twice the baud rate. We used ten taps and a gradient algorithm for taps' coefficients optimization.

In particular, for what concerns the coefficients computation algorithms, a first step at the system startup is implemented via Blind Equalization [14], quickly leading to a small LMS error. Blind equalization solves the start-up phase and at the same time avoids complex handshaking procedures to derive preliminary channel parameters. A control unit monitors the LMS errors, and makes the system switch to a decision-directed algorithm [14] once that the error gets below a properly chosen threshold.

IV. Prototype and Experimental Results

We describe in this section the experimental prototype and its characterization. The DSP part of the system was prototyped on a commercially available XILINX VIRTEX-4 FPGA board equipped with D/A and A/D converters. They both have a quantization of 14 bits, of which anyway only 9 have been used to reduce computational complexity. The optoelectronic was already described in a previous section.

The experiments presented in this Section were carried out on a system including all blocks represented in Fig. 1 and described in Section III. They have been performed on a single FPGA board that implemented both the transmitter and the receiver, so that clock recovery was not required. In fact, clock recovery is the only missing block in our current implementation with respect to a full-fledged system.

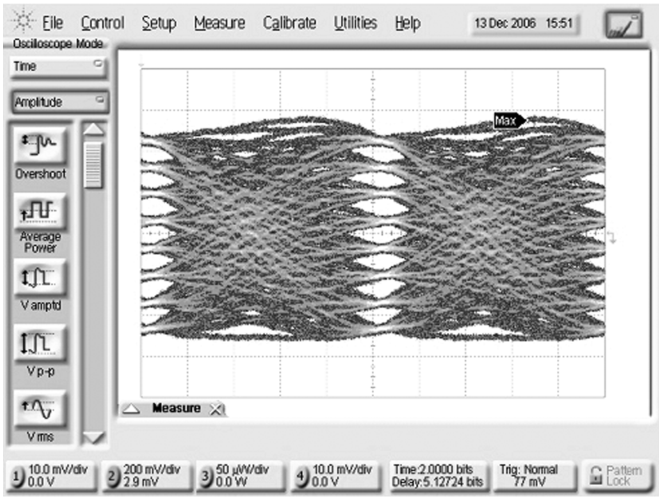

Fig. 5. 8-PAM transmission after 200 m of PMMA-SI-POF propagation, with LED linearization and pre-equalization filter: the eye-diagram is now open.

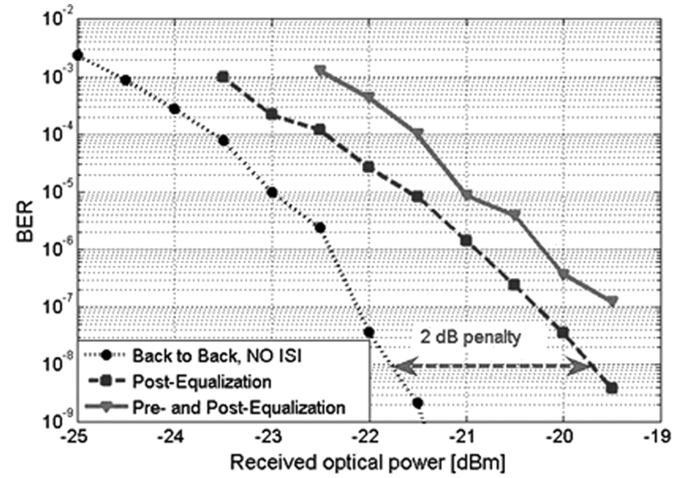

Fig. 6. BER versus received optical power: back-to-back condition in dense dashed line, with postequalization only in spaced dashed line, with pre- and postequalization in solid line.

The prototype was fed by an input pseudo-random digital sequence (PRBS $2^{15}-1$), while at the receiver side an internal bit error rate (BER) Tester was implemented in the FPGA, in order to proceed to standard BER measurements.

Regarding POF, we have access to a POF LAN-like test-bed, organized in several rings with lengths of 25 m, 50 m and 100 m, allowing to test our systems over different spans in a real life environment.

As a first result, we show in Fig. 5 the effect of LED linearization combined with the pre-equalization filter, for a 40 Mbaud 8-PAM transmission over a distance of 200 m with intermediate connector splice: the effectiveness of our linear and nonlinear countermeasures is quite evident when comparing this figure to Fig. 2, since the eye diagram is now well open. After this preliminary result that qualitatively shows the good overall performance of the system, we present in the following subsections a more quantitative characterization through BER measurement.

A. BER Versus Received Optical Power

A first reference evaluation has been performed in a back-to-back condition, simply inserting a variable optical attenuator (VOA) in the optical path, in order to evaluate system performances in absence of ISI; then, a different setup has been employed, inserting in the optical path a 200-m fiber link (two cascaded 100-m rings in our test-bed) and a VOA. We characterized our system in two different modalities: with postequalization alone and with both pre- and postequalization active. These results are shown in Fig. 6 for BER values ranging up to $\mathrm{BER}=10^{-3}$, this level being the typical FEC failure level for the employed RS code [11]. The transmitted average power in this setup was $+1$ dBm, while the attenuation introduced by the fiber was 17 dB. Fig. 6 shows a comparison between the back-to-back case and the 200-m situation for the same attenuation. This Figure shows how equalization is effective in reducing the strong ISI that is present in our system. We remind that, as was shown in Fig. 2, the eye diagram after 200 m is completely closed and, if no equalization is used, transmission is absolutely impossible. Fig. 6 shows that indeed reliable transmission can be obtained after postequalization with relatively low penalty. In particular, with the 200-m span and after equalization, the remaining penalty with respect to the back-to-back case at low BER (around 10^{-8} shown in the figure by an arrow) is approx. 2 dB. This results shows that adaptive postequalization is able to highly restore eye diagram, i.e, to reduce the effect of intersymbol interference, while the introduced penalty is due to the fact that its filtering action implements an high-pass transfer function, generating a noise enhancement. The presence of the noise enhancement penalty is a well known result for equalization theory for the so-called "minimum mean square error (MMSE) feed-forward adaptive equalizer" used in our work (see for instance [14]). Moreover, Fig. 6 shows that the FEC failure level $(\mathrm{BER}=10^{-4})$ is met for a received optical power of -23.5 dBm, less that 1 dB from the back-to-back case.

Fig. 6 also shows the results when pre-equalization is inserted in the system. The overall results are slightly worse than for postequalization alone. For instance, the FEC failure level is reached at -22.5 dBm, thus giving a 1-dB penalty when compared to the previous case (postequalization only). This penalty gets smaller for lower BER values, resulting in only approx. 0.5 dB at $\mathrm{BER}=10^{-7}$. The differences between the two considered systems (postequalized and both pre- and postequalized) are relatively small, but are somehow counterintuitive and thus are worth further commenting. First of all, pre-equalization produces an eye-diagram at the receiver side that is at least partially open, a feature that can greatly ease clock recovery algorithms (an issue that is not specifically addressed in this work, but it is further mentioned in next Section V). Secondly, we used a very simple pre-equalization technique, to keep DSP complexity low, thus getting a penalty. Much more advanced techniques are available in the literature to completely eliminate this penalty, such as the Tomlinson–Harashima (TH) precoder used in [19]. Both topics (clock recovery and TH precoder) will be investigated in a new EU-funded project, titled "POF-PLUS" that is the natural prosecution for years 2008–2011 of the work presented in this paper.

TABLE I
BER VERSUS 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	$\sim 10^{-3}$	$\sim 10^{-2}$

B. BER Versus Fiber Length

We then evaluated the performances of the system in terms of fiber lengths, cascading different rings from our test-bed. The results are shown in Table I, where the measurements are referring to links longer than 200 m with an increase step of 25 m, this being the shortest span at our disposal; interconnecting POF spans causes extra losses due to intermediate connector splices: from one in the case of the 200-m span to three in the case of the 275-m span, with an average attenuation of 1.3 dB per splice.

This table shows that, considering a Reed Solomon FEC operating threshold equal to a precoded $\mathrm{BER} = 10^{-3}$, the maximum reachable distance is 275 m.

C. Long Term, Real Traffic Tests

The characterizations shown in the previous sections were done at the lowest physical layer by measuring the actual "line" bit error rate, i.e., the BER before FEC decoders. We also performed detailed high-level system characterization using our prototype as a "UTP-to-POF" media converter configured as full duplex 100 Mbit Ethernet. In particular, the system was tested by Fastweb (the biggest Italian FTTH and xDSL alternative Telecom operator) using their standard triple play test & measurement procedures. The most important output of this long-term characterization was the so-called "Fastweb video-test". This is a 36 h continuous test involving the transmission of high-definition video and the measurement of the incorrectly received (video) frame-per-second (fps). The system successfully passed Fastweb internal test. In particular, after 36 hours, all measurements were below the "video acceptance threshold" fixed by Fastweb to 24.93 successful fps (average value over a 15-min time window), which correspond to an acceptance level of 99.72%. This shows that the systems was basically error-free after FEC.

V. COMMENTS AND CONCLUSIONS

The experimental results shown in this paper demonstrate, for the first time to the best of our knowledge, that Fast Ethernet data transmission is possible for distances well over 200 m on 1-mm plastic optical fibers. This result was obtained by a proper choice of multilevel modulations and digital signal processing (DSP) techniques. A picture of the full solution is shown in Fig. 7. The system we currently propose has shown capabilities of a BER below 10^{-3} over 275 m, with some power margin. This is a record result for PMMA-SI-POF. In terms of distance, it greatly

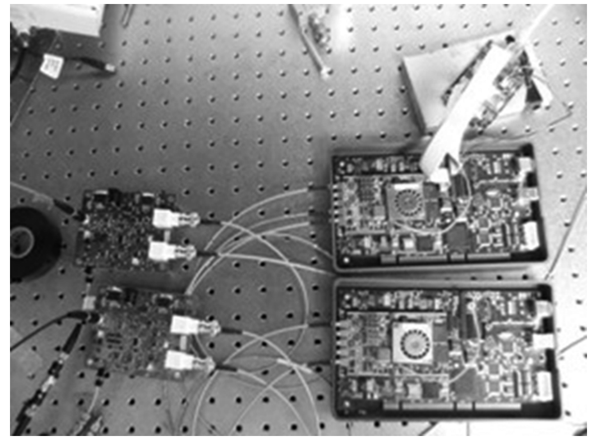

Fig. 7. Photograph of the full system.

outperforms current Fast-Ethernet over CAT-5 and CAT-6 specifications. At this moment (May 2008) we have already included in the system a fully compliant fast-ethernet interface. This required the introduction of a proper framing procedure, not described in this paper for space limitations. Our prototype can thus 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-C. Clock and data recovery (CDR) is today the only missing part of the system toward a complete Ethernet transmission. This was not due to an overwhelming technical difficulty, but simply to lack of available development time and resources inside the POF-ALL project. CDR techniques for multilevel PAM are well known in the literature and can be directly applied to our system [18]. For instance, the IEEE standard 10 Gbase-T uses 10-PAM and has to handle a completely distorted eye diagram at the receiver before CDR and equalization [19], a situation that is extremely similar to ours.

We conclude by giving some techno-economic comments that have been carried out in parallel to the scientific work inside the POF-ALL project.

1) The transmission techniques presented in this paper have been prototyped on an FPGA platform. An actual product will require the development of a proper ASIC. Preliminary studies showed that the translation into an ASIC project would be quite straightforward, but would clearly be economically viable only if a mass market for these transceivers will emerge in the following year.
2) Comparable performances (Fast Ethernet over 200 m) have been shown by other POF-ALL partners using commercial VDSL2 chipset based on DMT modulation [17]. This solution has evident advantages in terms of development costs since it does not require the design of a new ASIC.
3) The 8-PAM approach has anyway a competitive advantage with respect to DMT since its DSP complexity is significantly lower. This may in turn be a key point in terms of low power consumption, a fundamental requisite for any datacom solution.
4) Moreover, the approach shown in this paper has very low latency compared to a typical DMT solution. In fact, during

the system tests described in Section IV-C, latency measurements showed a maximum value below 110 μs. A low latency is a key parameter in several applications, and in particular in industrial automation, where maximum acceptable latency is usually set to 1 ms.

As a final conclusion, we believe that the idea of extended reach POF systems has been largely demonstrated inside the POF-ALL project 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 outlined in the introduction 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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