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A. Nespola
S. Abrate, Member, IEEE
R. Gaudino, Member, IEEE
C. Zerna
B. Offenbeck
N. Weber

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A. Nespola,[1] S. Abrate,[1] *Member, IEEE*, R. Gaudino,[2] *Member, IEEE*, C. Zerna,[3] B. Offenbeck,[3] and N. Weber[3]

(Invited Paper)

[1]Photonlab, Istituto Superiore Mario Boella (ISMB), 10138 Torino, Italy
[2]Dipartimento di Elettronica, Politecnico di Torino, 10129 Torino, Italy
[3]Fraunhofer Institute for Integrated Circuits, 91058 Erlangen, Germany

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Abstract: This paper focuses on high-speed cabling using polymer optical fibers (POF) in home networking. In particular, we report about the results obtained in the POF-ALL European Project, which is relevant to the Sixth Framework Program, and after two years of the European Project POF-PLUS, which is relevant to the Seventh Framework Program, focusing on their research activities about the use of poly-metyl-metha-acrilate step-index optical fibers for home applications. In particular, for that which concerns POF-ALL, we will describe eight-level pulse amplitude modulation (8-PAM) and orthogonal frequency-division multiplexing (OFDM) approaches for 100-Mb/s transmission over a target distance of 300 m, while for that which concerns POF-PLUS, we will describe a fully digital and a mixed analog–digital solution, both based on intensity modulation direct detection, for transmitting 1 Gb/s over a target distance of 50 m. The ultimate experimental results from the POF-ALL project will be given, while for POF-PLUS, which is still ongoing, we will only show our most recent preliminary results.

Index Terms: Communications, Ethernet, home networks, polymer optical fibers (POF).

1. Introduction

Polymer Optical Fibers (POF) based on Poly-Methyl-Metha-Acrilate with 1-mm core diameter have garnered much attention in recent years for their interesting properties compared with better-known glass fibers. These fibers has been standardized by IEC in 2008 as A4a.2. POF can be a disruptive technology in some specific scenarios for the following reasons:

- Its large core diameter (1 mm) allows do-it-yourself installation and termination using a common cutter, requiring no specific manual or technical skill.
- Its use of visible noncollimated light makes it intrinsically eye-safe and easy to troubleshoot, as the signal can be seen by the naked eye.
- Its robustness makes it possible to step on it and even tie it. POF can actually be immersed in salt water, and it is commonly used in several rugged environments.
- Being an electrical insulator, most national regulations allow POF to be laid down in power ducts. This apparent minor detail is seen by some national Telecom operators as actually a key advantage in brown field domotic installations.

From a system point of view, simple optical links up to 100 Mb/s can be designed with off-the-shelf ICs, LEDs, and photodiodes, while better performances can be achieved using lasers and enhanced modulation formats.

The drawbacks to these advantages are a limited bandwidth and high attenuation, preventing POF from being an alternative to GOF, where limited data rates and distances are required. POF performances are actually comparable with those of UTP Cat. 5e cables, although with a disadvantage in term of standardization and mass-market availability.

The overall POF market has been evaluated at $1.2 billion in 2008 and is expected to grow to $1.7 billion in 2010 [1]. Currently, the main market for POF is in the automotive industry, where they replace copper wires to communicate information between the radio, navigation system, CD player, and mobile phone system. The history of using Plastic Optical Fibers for automotive started in 1998, when the Media-Oriented Systems Transport (MOST) cooperation was founded by BMW, Daimler, Harman/Becker, and OASIS Silicon Systems (Audi joined the consortium in 2000) with the aim to define an optical bus for in-car media applications [2]. The market volume for infotainment systems in the car is expected to increase from €3.5 billion in 2005 to more than €9 billion in 2010, while the Compound Annual Growth Rate (CAGR) for Automotive Electronics will increase from 21% in 2005 to 25% in 2010 (source: MOST cooperation).

Another current market for POF is in the industrial automation, were POF links are used for their mechanical resilience, ease of installation, and complete EMI isolation.

The continuously growing bandwidth demand at the domestic customer premises lets us envision home cabling as a possible killer application for a huge deployment of POF in sectors other than automotive.

The most promising and future-proof solution for broadband access is Fiber-To-The-Home (FTTH) that will allow (or is already allowing in some countries) an unprecedented high-quality connection up to the customer's premises. However, Telecom operators are currently realizing that this is true only as long as quality-of-service (QoS) and data rates can be guaranteed end-to-end throughout the network, right up to the end terminals (i.e., set-top-boxes, media centers and PCs). It is impossible for a telecom operator to market a high access bandwidth if this bandwidth is not also available inside the home network.

These network edge limitations become apparent if we think of the rising importance of Internet Protocol Television (IPTV), particularly in its next-generation high-definition incarnation; almost all European telecom operators are currently rolling IPTV services, and according to Research and Markets [3], the worldwide IPTV service revenues is forecasted to reach $38 billion, servicing 53 millions subscribers, by the end of 2010. Recent offers of bundles of products and services by Telecom operators typically include a home gateway with a set-top-box plus a connectivity enabler such as a WiFi access point/extenders or power-line/POF-based communication modules.

Possible physical media to route the IPTV signal from the modem box to the STB include wireless, UTP Cat.5 (or higher version), and power lines. However, wireless and power-line technologies present major QoS and cost issues [4]; moreover, they are both intrinsically shared media in an uncontrolled environment. While UTP provides the ideal solution in premises that have been previously networked, it is nevertheless unacceptable for self-installation purposes since it is bulky, it cannot be inserted in existing power ducts for regulatory reasons involving safety, and it cannot be terminated by the customer. Since the vast majority of European homes do not have an installed network, a rugged foolproof self-installation solution is essential. Plastic Optical Fiber (POF), although a wired medium, offers an inconspicuous low-cost installation that can be undertaken by the customer while guaranteeing a rugged error-free link. New consumer-friendly POF connector technologies even avoid the need to use plug-terminated cable; POF can be simply cut to length with a razor blade cutter and the bare fiber inserted into the end device. The principal cost saving derived by Telco's is the avoidance of installation engineers visiting their customers' premises, sometimes referred to as the "truck-roll," which has an estimated cost of between €60 and €250 per visit. This adoption of POF is only just underway and makes use of POF well within its current specification envelope, providing dedicated links capable of delivering up to 100 Mb/s over 50 m, matching today's VDSL2 data rates (50 Mb/s). POF has been very recently adopted by some Telco's in Europe as a "self-installable" solution that allows the end user to implement a link between its modem and STB; such self-installed POF solutions are already being offered by Deutsche Telecom and Swisscom (under the commercial name "T-COM Speedport OptoLAN Pack") and are expected to be followed soon by a number of other Telco's, including Fastweb and KPN. Moreover, Swisscom has officially announced that, in some specific situations, it is already installing POF solutions inside the apartment (see [4]). However, two factors are creating pressure to develop and increase the performance envelope of SI-POF. First, the increasing roll-out of FTTH as witnessed by recent announcements in France (by Free and France Télécom) and the Netherlands (by KPN) will mean that gigabit-per-second data rates will be available up to the optical network unit (ONU) and, thus, in principle nearby the home; second, the improvement in both speed and QoS of wireless solutions, due to the advent of high-speed wireless technologies commonly referred to as Ultra-Wideband (UWB), which will be used as a high-speed replacement of WiFi; as the data rate increases, an inevitable reduction in the maximum range occurs, leading to a new concept of network architecture in which a low-cost easy-to-install wired infrastructure feeds multiple antennas distributed around the home. In the medium- to long-term perspective, both trends require POF to carry +1 Gb/s over several tens of meters between the ONU and the gateway box and between antennas, while maintaining all the ease-of-use properties that originally made it so attractive.

A rationale for building cabling with 1-mm POF then exists and is supported by economical reasons. A new model has to be promoted, in which customers and operators cooperate, sharing the expenses. The customer should be accountable for its own home or in-building network, while the operator should deploy its network up to the cabinet. This approach would also ease, from the customer's point of view, moving from an operator to another, since the final part of the network would be property of the customer himself, with no need to remove and reinstall it in case of service provider/telecom operator's change. However, it has to be pointed out that structured cabling policies and recommendations should be adopted.

It is important to notice that this is just a part of the picture. A great future in seen for new applications in home networking, and new developments involve more than just telecommunication in the usual meaning, but also for applications to entertainment systems, healthcare, security, and domotics; according to IMS Research, the home networking market will more than double by the end of 2009, reaching an installed base of nearly 100 million units, compared with 42.5 million units in 2005 [5]. A possible classification of home networking application [6], categorized in several segments, could be for example the following:

- Data-Centric: broadband data sharing, PC LAN, communications, information platforms;
- Multimedia-Centric: multiperson gaming, personalized content, on-demand content, stored/streamed multimedia;
- Home Management: home controls, energy management, security, remote applications;
- Value-added services: voice, protection, communities, upgrades.

It may be arguable how much POF access could suffer from competing technologies. While alternative wired solutions have been widely discussed, one subtle and somehow unexpected role is played also by emerging wireless solutions. As a matter of fact cheap wireless technologies, such as WiFi IEEE 802.11n, provide large bandwidth and flexible solutions; for instance, 802.11n achieves data rates up to 600 Mb/s with the maximum of four spatial streams using a double-width 40-MHz channel. In 802.11n, data rates are boosted by MIMO spatial multiplexing and several further optimizations, the result is outstanding and opens interesting networking perspectives. However, it is worth recalling that wireless channel is intrinsically shared among the users (it is closely related to the concept of broadcast and collision domain); therefore, at the current state, they can replace cables only when the applications are compatible with statistically sharing of the available bandwidth among the users. From a practical point of view, broadband wireless solutions are not envisaged as POF competitors but rather as complementary ones as drawn by mesh solutions (IEEE 802.11s), where sparse wired connection are distributed by multihop wireless mesh topologies. In our vision, then, a well-connected home in 2015 would have an optical infrastructure building a 1-Gb/s "backbone" on fiber lengths in the order or 50 m to enable a set of services that at a room level could even be wireless based (for coping with terminals increasing mobility); POF then makes for a high-flexibility, secure, and stable solution with high bandwidth.

2. POF-ALL: 100 Mb/s Over More Than 200 m

The EU-funded research project POF-ALL project started in 2006 and concluded in mid 2008, being classified among the excellent research projects of the BroadBand-For-All (BB4All) initiative of the European Commission. Its main task (among several others not reported here due to space limitations) was delivering a Fast-Ethernet-compliant data stream over a distance of 300 m, this being a specification from an alternative Italian telecom provider that states that more than 80% of its FTTH customers are located within a distance of 300 m from the Gigabit Ethernet switch placed in the basement. Among the several activities carried out over a duration of 33 months, in the following, we will briefly describe the two technical solutions that have been identified for the 100-Mb/s task: an 8-level Pulse Amplitude Modulation (8-PAM) and a VDSL-like approach.

2.1. 8-PAM Approach

This approach required to implement a set of functions and algorithms over an FPGA platform, in order to adapt the Fast Ethernet data stream to a form suitable to overcome the different impairments due to the fiber propagation: in particular, high attenuation and low bandwidth had to be compensated; in addition, components nonlinearity had to be taken into account, due to the presence of a multilevel modulation.

The 300-m distance goal required working in the "green" wavelength (520 nm), where POF exhibits its minimum attenuation ($\sim$0.08 dB/m). Low-cost green LEDs were used. Fig. 1 shows the whole transmission system. The "optical" channel can be modeled by the cascade of three elements (LED, Fiber and photodiode), i.e., the analog transmit section with transfer function $GT(f)$ (mostly set by the LED electrical characteristic), the fiber $C(f)$, and the analog receive section $GR(f)$ (photodiode + amplifier). Among the three transfer functions, the main bandwidth limitation comes from the fiber itself, with only 18.8 MHz for 200 m and 10 MHz for 275 m [7], which is not enough for standard NRZ transmission at 100 Mb/s. We thus select a baseband multilevel modulation format (8-PAM) to achieve high spectral efficiency. We assume a baud rate equal to 40 MBd to have a line rate equal to 120 Mb/s (overhead available for FEC and/or line coding). Even at this rate, intersymbol interference (ISI) is so strong that the received eye diagram after 200 m is still completely closed. We thus used linear preequalization through a FIR filter $P(f)$. We also compensated the LED nonlinearity using a suitable nonlinear function $g(\cdot)$. All these features are implemented on the FPGA through DSP techniques, and the resulting signal is sent to D/A converter and then applied to the analog optoelectronic system. At the receiver, after A/D conversion, adaptive equalization is implemented inside the FPGA. In order to efficiently monitor the performance, an embedded BER tester was included in the FPGA code.

The selected preequalizer filter $P(f)$ was designed such that the overall transfer function $P(f) * GT(f) * C(f) * GR(f)$ resulted in a fourth-order Bessel transfer function with 3-dB cut equal to the baud rate. The result is a high-pass, 20-tap FIR filter, implemented using a pipelined and transposed structure working at twice the baud rate. We chose a fixed preequalizer filter for a "reference" length of 200 m. The actual system can be longer or shorter, and the residual ISI is compensated by the post-equalizer at the receiver. This implemented a Delayed Least-Mean Square (DLMS) [8] fractionally spaced adaptive equalizer; the best solution, in terms of performance and complexity, was a pipelined systolic 10-tap FIR filter working at twice the baud rate and with a quantization of 18 bits for the coefficients and 14 bits for the data samples. In order to avoid any initial protocol between transmitter and receiver, Blind equalization was used rather than having a training sequence. We implemented an automatic control unit to monitor the LMS error, switching automatically from a Blind to a Decision-Directed method when it is under a certain, properly chosen, threshold, and *vice versa*. For that which concerns the Forward Error Correction, a

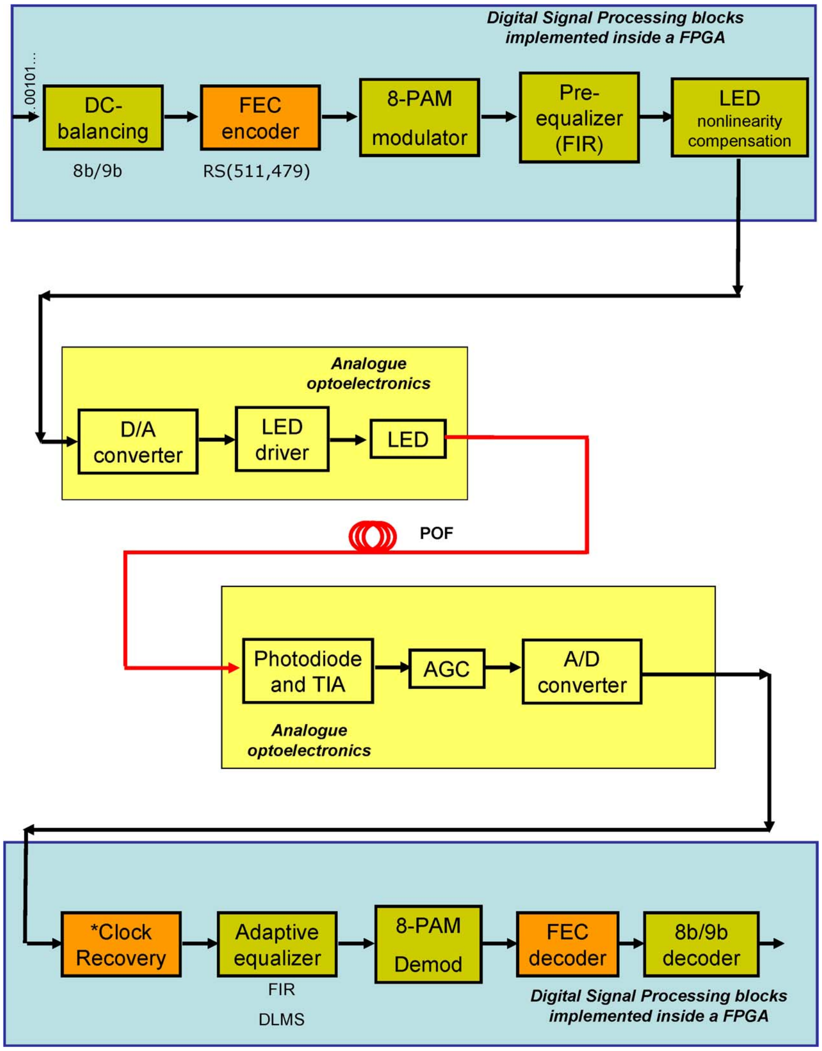

Fig. 1. POF-ALL—Scheme of the full system for 8-PAM transmission.

TABLE 1

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	˜ 10^{-6}	˜ 10^{-5}
275	˜ 10^{-3}	˜ 10^{-2}

Xilinx IP referring to a RS(511, 478) code has been chosen, since we needed to use words made of 9 bits, thus yielding to 511 code symbols in the encoded blocks.

The system was first tested on a laboratory testbed made of several rings of lengths ranging from 25 m to 100 m; the results of a long-term campaign are resumed in Table 1, from which it is evident that the better performances are obtained with the postequalization only. The data shown is

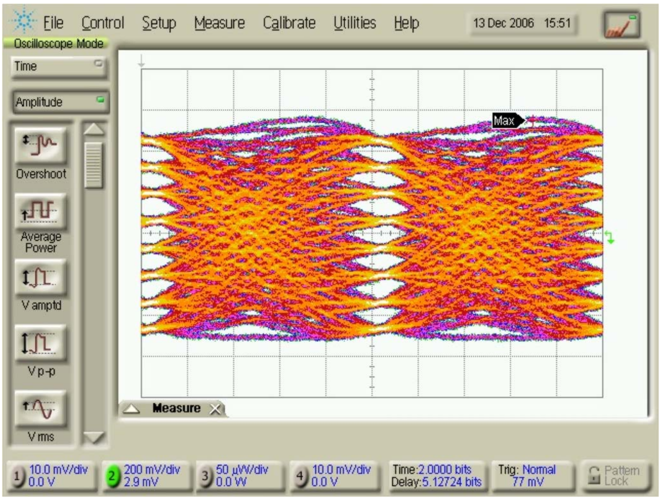

Fig. 2. POF-ALL—8-PAM transmission after 200 m of PMMA-SI-POF propagation, with LED linearization and preequalizing filter.

calculated before the FEC application, and it is obtained feeding the system with real traffic and thus estimating, and not measuring with an error tester, the BER on the basis of the number of symbols corrected by the error-correction mechanism; recalling that FEC is able to recover all errors with an incoming BER better than 10^{-3}, we can conclude that our system is able to cover a span of 275 m.

In Fig. 2, we show the eye diagram of a 100-Mb/s data transmission over 200 m of POF when LED linearization and postequalizing filter are active.

The same system has undergone a qualification test in laboratories at a telecom operator's premises, performing real traffic measurement. Again, over a distance of 275 m, the system has passed all the acceptance thresholds that the involved operator required for adopting transmission equipment in its access network.

2.2. OFDM Approach

Today, no commercial chipset is available for a highly bandwidth efficient transmission method for SI-POF in the medium range $(200 + \mathrm{m})$. The use of Multicarrier Modulation (MCM), also called orthogonal frequency-division multiplexing (OFDM) or Discrete Multitone (DMT), as a bandwidth-effective, noise-protected, and adaptive method for transmission over SI-POF has been investigated in POF-ALL. Following the analysis of the features of different MCM applications (number of tones, tone spacing; bits per tone; required bandwidth; possible spectral efficiency, etc.), the choice is to use existing VDSL2 chipsets as the basic technology for the required Fast Ethernet transmission over $200 + \mathrm{m}$. The major feature of MCM is the division of the spectral bandwidth into several thousands of equidistant tones with a Signal-to-Noise Ratio (SNR) depending on the number of bits modulated by Quadrature Amplitude Modulation (QAM). With a maximal spectral efficiency of 15 b/s/Hz corresponding to 15 bits per tone, VDSL2's theoretical maximal bit rate for a 17-MHz available bandwidth, 4.3125-kHz tone spacing, and 4096 tones is approximately 123 Mb/s for each direction. For 30 MHz, with double tone spacing and 3478 tones, 205 Mb/s per direction can be achieved. Furthermore, there are existing plans to transmit within a bandwidth of 35.328 MHz (8192 tones and a tone spacing of 4.3125 kHz). In this case, the maximum bit rate would get close to 250 Mb/s.

The idea to use MCM for Fast Ethernet transmission over SI-POF was proposed in [9]. In 2007, several demonstration activities have been carried out. The principle architecture of the demonstrator is shown in Fig. 3. First and second demonstrator generations have been based on VDSL2 evaluation boards directly put available by the chip set manufacturer, while a third generation concentrated on an optimized optoelectronic and ad hoc interfacing. All demonstrators

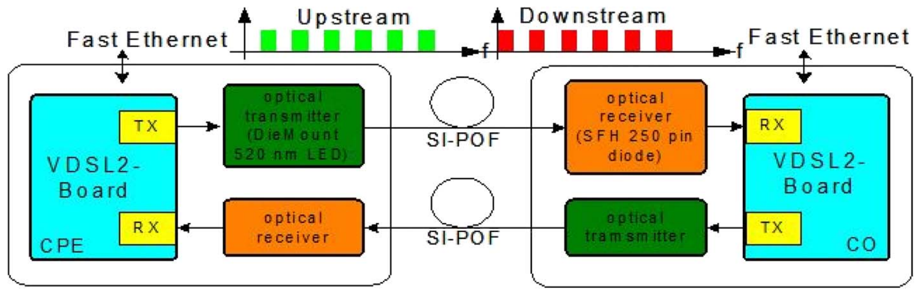

Fig. 3. POF-ALL—Architecture of OFDM demonstrator for the POF-ALL project.

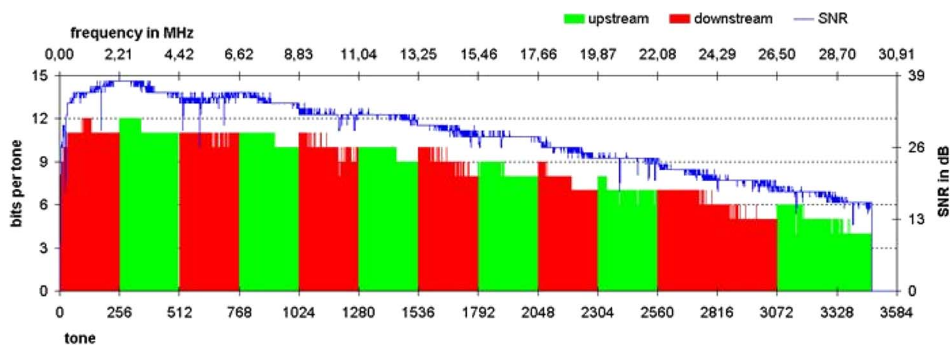

Fig. 4. POF-ALL—Bit allocation and SNR after 200 m of SI-POF.

have proved to be fully compatible with IEEE 802.3 (Ethernet 100Base-T) and RFC 2544 ("Benchmarking methodology for network interconnects"). The test results for 100-Mb/s full duplex show an average latency of around 1.1 ms, 0% packet loss, and a 100% throughput for all packet sizes.

In parallel to the practical realization of the demonstrators, theoretical investigation with the aim of finding the limits of data transmission were conducted and showed good matching with the practical results. Fig. 4 presents the SNR and bit allocation for 200-m duplex SI-POF with a specially created band plan and a resulting aggregate bit rate of 216,7 Mb/s.

3. POF-PLUS: 1 Gb/s Over 50 m

The POF-PLUS project, started on May 2008, focuses 1-Gb/s+ transmission over several tens of meters of POF, for home networking, optical interconnect, data-center, and multimedia applications. In the following, we will describe more in detail the activity related to 1-Gb/s transmission over 50 m for home networking. We decided to focus on the Gigabit Ethernet protocol in its optical version (1000Base-X), and we investigate in particular, what modifications would be needed to make it compatible with POF. The ambitious target of 1-Gb/s transmission over 50 m of SI-POF suffers of both dispersion and attenuation constraints, requiring the employment of several compensation techniques. In particular, considering our goal of using LEDs at the transmitter side, the available electrical-to-electrical bandwidth over LED + 50-m POF + Photodiode is very limited (usually considerably below 100 MHz) and strongly distorts the useful transmitted signal, thus requiring strong equalization at the receiver side.

This activity is carried out in two parallel technical activities. The first one, which we internally dubbed "fully digital implementation," aims at a completely new PHY level, including a new PCS, looking for maximum transmission performance. The second one, called "mixed analog–digital implementation," envisions keeping the existing 1000Base-X PCS and modifying only the PMD layer. The schematic of the two approaches in terms of Ethernet layering are represented in Fig. 5.

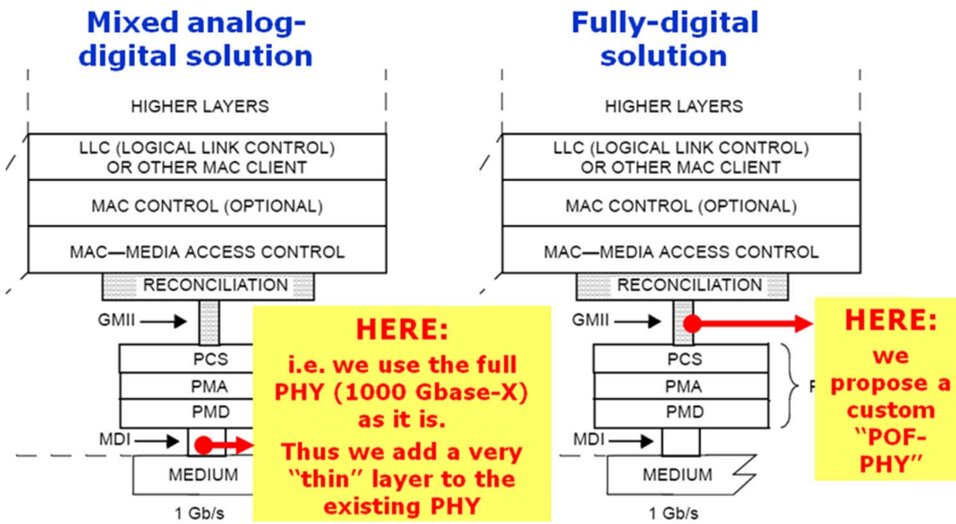

Fig. 5. POF-PLUS—Positions in the Ethernet OSI layering of the mixed analog–digital and fully digital approaches.

The first solution attaches at the GMII level, completely redefining the PHY below it, while the second reuses most of the 1000Base-X PHY. It is worth noting that both the proposed solutions for 1-Gb transmission implement amplitude modulations, which is typical of the fiber optics community, even if OFDM and DMT modulations are effective in the home market thanks to DLS and power-line communications; this choice is due to our focus on low-cost solutions, and OFMD and DMT would result in more computational complexity, affecting FPGA, and eventually ASIC, area requirement and development cost, and in worse performances, in terms of power consumption. However, some preliminary studies and proof of concept on the adoption of different modulation schemes are being worked on, and a very short description will be given at the end of this paragraph, referring to more than 1-Gb transmission.

In the first year of the project, we developed a detailed physical-layer Simulink time-domain simulator to conduct a preliminary evaluation campaign that initially let us work in parallel on several different technical options, and then, it was useful to take the architectural choices described in the following.

3.1. Mixed Analog–Digital Approach

The mixed-signal approach works on the native serial Gigabit Ethernet (1000BASE-X) data stream, with no modification on the PCS layer. The envisioned architecture, as shown in Fig. 5, plans to leave most of the 1000BASE-X PHY in its original form, just adding an adaptive equalization function at the PMD level on the receiver side. The system would thus transmit a regular 1000Base-X, 8B/10B coded digital stream using pure binary modulation (PAM-2).

This mixed-signal equalizing approach we designed applies equalization at the receiver side, dividing the structure of the adaptive equalizer in a forward path that is simply a variable high-pass analog filter and a decision-feedback path mixing analog and digital processing. The analog forward path has the advantage of avoiding a high-speed ADC at the first stage of the signal processing chain (as requires in turns by a fully digital solution), thus potentially reducing the chip power consumption, which is a key parameter in consumer electronics. Although equalizing can be done with a forward filter only, the extremely noisy environment of the POF transmission channel virtually dictates the use of a feedback section, which is known to enhance the noise on the signal much less then the forward filter section. However, the feedback section can only compensate for postcursor ISI. The precursor ISI is accounted for by the forward filter section. Hence, the combination of feedforward and feedback section is the architecture of choice.

Work has been carried out on two architectural variants, differing in the implementation of the forward filter. In the first IC design run inside POF-PLUS, the analog forward filter has been realized through an analog peaking filter. This filter has a very limited number of possible transfer functions, which are essentially controlled by the size of a digitally switchable capacitor. The advantages of this variant are the low-power properties and the ease of implementation of the analog filter. The obvious disadvantage is the lack of sophisticated control over the transfer function (i.e., its spectral shape). This architecture has already been implemented on a prototype ASIC chip based on the UMC180 technology. Three separate chips have been designed and realized, which can be combined into the target architecture or tested standalone.

The combination of analog peaking filter and digital DFE has been intensively tested in the lab. The obtained results show the capability of equalizing the SI-POF channel (using RCLED) for 1.25-Gb/s transmission for 25 m and beyond. We measured a BER of less than 10^{-13} at the output of the equalizer. The channel in the setup comprises the following components: a Fraunhofer-IIS designed driver circuit with red Firecomms RCLED (see [10]), 25 m of Toray TC-1000 SI-POF, and a custom lab receiver consisting of an 800-μm Hamamatsu S5052 and a Maxim 3266 TIA. The output of the TIA is then processed by the mixed-signal equalizer. The data transmission is below the BER threshold specified for Gigabit Ethernet. However, the experiments also showed the limitation of the performance due to insufficient control of the equalizing filter transfer function.

In the second variant of the mixed-signal equalizer, the forward filter is implemented via an analog feedforward equalizer (FFE). The analog FFE is a FIR filter, in which the delays are implemented through analog filters instead of clocked flip-flops. The advantage of this implementation is the sophisticated control over the filter's transfer function. The disadvantage is the high implementation effort and power consumption. The work on this architecture variant is still in the design phase. The development of an ASIC chip and the following experimental characterization are expected for Summer 2010. We foresee to achieve error-free transmission over the 50-m SI-POF in conjunction with the RCLED using this equalizer.

3.2. Fully Digital Approach

At the beginning of POF-PLUS, after an intensive simulation campaign, we identified 2-PAM and 4-PAM as suitable modulation schemes to be possibly adopted for this approach, in conjunction with Decision Feedback Equalization (DFE) at the receiver side.

This preliminary simulative feasibility study lead to further developments and experimental evaluations. Since we have not yet implemented all the required digital signal processing techniques at the receiver on our FPGA-based prototype, our experiments were carried out according to the conventional offline processing approach. In particular, the experimental setup is organized as follows:

- generation of 2-PAM and 4-PAM signals by means of a commercial board with integrated Xilinx Virtex-4 FPGA chip and fast A/D and D/A converters (UHAB board by BitSim). In both cases, the transmitter sequences are DC balanced. To this end, we used standard 8B/10B for 2-PAM and a custom DC-balancing technique for 4-PAM;
- use of RC-LED for the optical source. An electronic driver circuit capable of preemphasis, for compensating the LED bandwidth limitation, has been employed. We used devices from partner Firecomms, packaged inside a commercial Optolock plugless connector;
- two POF links with length 25 m and 50 m were tested, with both the amplitude modulation schemes mentioned above;
- signal detection by means of two different receivers: a Graviton SPA1 (laboratory receiver) and a Firecomms FC1000D (prototype for off-the-shelf receiver), differentiated mainly by the presence of an Automatic Gain Control (AGC) in the latter;
- signal acquisition, at the receiver side, with a 1-GHz real-time oscilloscope running at 5 GSamples/s. The memory of the instrument was able to record approximately 50.000 symbols;
- offline processing of the received data in Matlab/Simulink, applying a fractionally spaced DFE algorithm to open the eye diagram (the feedforward filter works with two samples per symbol).

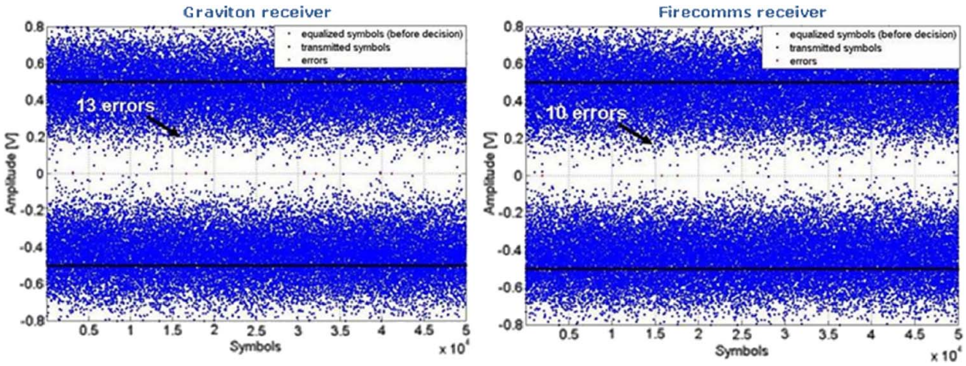

Fig. 6. POF-PLUS—2-PAM transmission over 50 m, received signal with offline DFE processing, with Graviton (left) and Firecomms (right) photoreceivers.

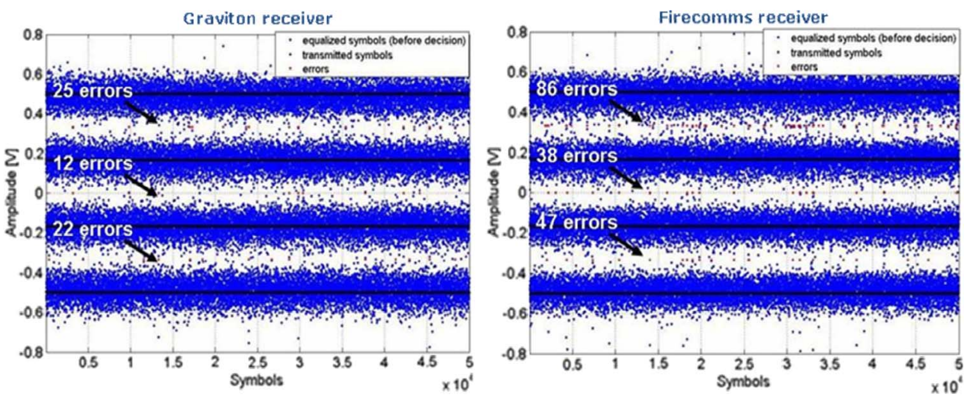

Fig. 7. POF-PLUS—4-PAM transmission over 50 m, received signal with offline DFE processing, with Graviton (left) and Firecomms (right) photoreceivers.

For the optimization (and adaptation) of the taps coefficients, we used a common gradient-based least-mean-square adaptation algorithm. This adaptive equalizer is the "core" of the digital signal processing required by the system we are proposing.

A 2-PAM 1.25-Gb/s transmission campaign over 25 m has been initially performed, and the relevant eye diagrams have revealed to be completely closed due to the extremely low bandwidth available on the overall system, measured in 54 MHz only; then, the DFE algorithm has been applied, obtaining error-free (i.e., below BER $= 10^{-12}$) transmission for both 2-PAM and 4-PAM (625 MBd) modulations, independent of the employed receiver. Due to the intrinsic characteristics of DFE algorithms, it is worth noting that only one sample per symbol (per bit in 2-PAM) can be obtained at the output of the decision-feedback section, and consequently, no eye diagram can be shown.

For that which concerns transmission over 50 m, in the case of 2-PAM, we measured a BER equal to $2 * 10^{-4}$ BER on the DFE equalized signal for both receivers, which is a value that can be recovered to BER $< 10^{-12}$ by the adoption of a conventional Forward Error Correction. Fig. 6 shows the received samples after DFE over the full received sequence (approximately 50K samples). A different, and somehow unsuspected, situation occurs in the case of 4-PAM transmission; with the Graviton receiver, a $1.2 * 10^{-3}$ BER has been measured, while the performance decreases to $3.4 * 10^{-3}$ with the Firecomms model. In particular, it emerged that the errors distribution is not homogeneous over the different power levels, mainly being concentrated on the upper levels (see Fig. 7); this leads us to conclude that nonlinearity effects due to LED and receiver are able to make

TABLE 2

BIT RATE versus POF length

Bit-rate	Length (Commercial)	Length (Research)
10Mb/s	100m	425m
100Mb/s	70m	225m
1Gb/s	N.A.	30m (mixed analog-digital) 50m (fully digital)

the 4-PAM multilevel advantages vanish in terms of performance. 4-PAM still gives, however, the advantage of a required processing speed that is halved with respect to 2-PAM. In the case of the Graviton receiver, we assume that LED nonlinearity is dominant, since a laboratory receiver is employed, while in the case of the Firecomms receiver, we assume that receiver nonlinearity is significant as well, probably mainly due to the presence of the AGC.

It is then evident that, in the considered optoelectronic setup, multilevel amplitude modulation, even if it is potentially less demanding in terms of bandwidth, gives no significant advantage for this application with respect to conventional 2-PAM, while it requires increased complexity at both transmitter and receiver side for generating DC-balanced sequences and clock recovery and needs very linear LEDs and photodiodes.

In the remaining working period of the POF-PLUS project, we will then concentrate our efforts on 2-PAM transmission and efficient DFE reception, together with a POF-optimized PCS layer.

3.3. More Than 1-Gb/s Transmission

As part of the project, very-high-speed solutions for data-center communications are being investigated as well, based on 1-mm PMMA fibers. At a proof-of-concept level, several interesting results have been achieved, employing DMT modulation schemes; this approach allows us first to obtain high bit rates and adaptive performances and, second, to investigate the adaptability of techniques used by competing technologies, such as power-line and VDSL2, to POF communications. Employing Graded Index fibers (GI-POF) and a record result of 5,3-Gb/s transmission over 50 m has been shown [11], while 10 Gb/s over 25 m SI-POF has been obtained with an high-power red laser [12]. However, both solutions suffer of problems due to the fiber; currently available GI-POF are not stable enough, and their available bandwidth can consistently vary, depending on the installation, while at 10-Gb/s, SI-POF performances can be much affected by bending radius; then, 10 Gb/s over 25 m has been demonstrated, also adopting bend-insensitive 0,5-mm multicore POF (MC-POF), showing that a 2,5-mm bending radius does not worsen the overall performance.

4. Conclusion

We have reviewed some of the results and research activities of the POF-ALL and POF-PLUS European projects, identifying technological solutions that we believe could be of deep impact for the fiber cabling of residential buildings. In particular, we believe that the delivery of 100 Mb/s to the final customer, and a 1-Gb/s distribution inside the apartment, could be important factors for a massive deployment of broadband services based on FTTH architectures.

In Table 2, we resume the latest research results in terms of distance of POF transmission at Ethernet, Fast Ethernet, and GbEthernet data rates, compared with commercially available products.

In particular, the final results of the POF-ALL project could ease telecom operator's job, reducing customer connection timing and thus costs, lowering their Return-On-Investment time. Moreover, 100-Mb transmission over 300 m can find interesting applications in industrial automation, while the (preliminary) results of the POF-PLUS project on Gigabit transmission over POF let us envision a bright future for the adoption of do-it-yourself very high-performance systems for communication, entertainment, and e-health.

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