Ethernet transmissions over large core polymer optical fibres: demonstration of an extended reach (425 m) LAN system

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Abstract: Optical community has expressed a wide consensus over the idea that 1 mm poly-methil-meta-acrilate step-index fibres (PMMA SI-POF) can be a good candidate in future domotic networks and in edge networks, that is in the last part of access networks, due to their better mechanical behaviour and lower installation and handling costs with respect to conventional 50/125 or 62.5/125 multi-mode glass fibres. Current applications are anyway limited by relatively low transmission performances: up to now, the best performing commercial Ethernet transceivers using PMMA SI-POF are able to reach at the most 200 m at 10 Mb/s or 70 m at 100 Mb/s, thereby keeping these fibres in the niche of very-short reach applications, such as in the automotive market. A Prototype of a media converter for fully compliant 10 Mb/s Ethernet transmissions over PMMA SI-POF experimentally demonstrated the feasibility of >400 m long link, this length may open new applications to PMMA SI-POF. The 425-m record distance presented here has been achieved by both introducing a proprietary protocol implemented over a field programmable gate array platform and by a careful selection of (commercial) optoelectronic components. The prototype is to be considered as a proof-of-concept that PMMA SI-POF can be introduced in new areas such as the last part of access/edge networks or datacom applications in industrial automation or aircrafts/ships cabling. The 400-m distance is, for instance, the specification of an Italian fibre to the home operator for the last part of its access network architecture.

1 Introduction

Among all the different types of polymer fibres currently available [1], we decided to concentrate our research activities on the 1 mm poly-methil-meta-acrilate step-index fibres (PMMA SI-POF), since they are the ones that exhibit the most differences with respect to glass fibres for communications and thus they can be a perfect complement in which UTP5 cable's performances are to be targeted. PMMA SI-POF are characterised by good mechanical behaviour, such as high stress resilience, low bending radius and low bending losses, mainly because of their large core, their high numerical aperture and the elasticity of polymers. Drawbacks for these advantages are high attenuation and strong multi-modality [1], which usually limit the usage of PMMA SI-POF to a very-short reach and low speed applications. In fact, the current market in which these fibres are most widely deployed is the automotive sector, where it is estimated that they are, at present, installed in >8 million cars for the internal infotainment network [2, 3]. We believe that PMMA SI-POF can find other significant applications, with respect to its characteristics, in all those cases in which conventional multi-mode glass fibres are very expensive, in particular, those that concerns the installation and handling costs and with respect to the actually needed performances, such as in the domestic environment.

In some of our previous works [4–6], we theoretically investigated and then experimentally demonstrated how PMMA SI-POF can achieve interesting performances using information theory and improving the electronic complexity; in such work and because of the *M*-pulse amplitude modulation scheme (M-PAM) implemented with digital logic, we were able to reach high bit rates such as 150 Mb/s over 50 m of PMMA SI-POF (with 8-PAM) and 100 Mb/s over 100 m (with 4-PAM) [4] (with components working in the red region of the visible spectrum). We noticed, as well, that the system could have a significant improvement on account of the introduction of error correction methods, without any change in the architecture but just by reprogramming the digital circuits. Later, as a preliminary result, a 4-PAM eye diagram obtained by an AC-coupled receiver after 200 m at 50 Mb/s was improved with the introduction of DC-balancing coding for a 4-PAM transmission [5, 6]. Currently, we are still improving these systems, keeping the complexity in the digital domain.

In this work, we concentrated on the specifications of an Italian fibre to the home (FTTH) services provider that delivers 10 Mb/s Ethernet at the customer premises with multi-mode glass fibres – from the statistics of their current installations, it emerged that >90% of their last-mile connections are within a distance of 400 m, which became our target performance for projecting and prototyping a 10 Mb/s Ethernet UTP5-to-POF media converter.

Current commercial Ethernet transceivers working with PMMA-SI-POF are, in fact, 10BASE-T to 10BASE-FL converters, but they simply use PMMA SI-POF as transmission media instead of multi-mode glass fibre; we noted that 10BASE-FL uses a Manchester coding that doubles the signal's bandwidth. Their technical specifications usually state that they can reach up to 200 m; for making a comparison with our prototype under the same conditions and same optical components, we used one of these commercial transceivers to transmit Ethernet data using the optoelectronic components chosen for our system. The maximum distance, in this case, was 225 m (including two connectors); if a single spool was used, this distance would increase up to ≃270 m. The improvement in reach from ≃270 m to 425 m achieved by our prototype can be qualitatively explained as follows:

- Our prototype works at ≃14 Mbit/s, whereas because of the Manchester coding, commercial 10BASE-FL transceivers basically work at the equivalent of 20 Mbit/s. As shown in Fig. 1, the available bandwidth at 400 m is ≃9 MHz, making 20 Mbit/s transmission impossible. We remind here that, unless strong equalisation techniques are used, a standard optical NRZ transmission requires a 3 dB bandwidth of at least 60% of the line bit rate in order to avoid excessive inter-symbol interference. Thus, a 20 Mbit/s line rate would require at least 12 MHz, where as only 9 MHz are available in our scenario.
- Our prototype has 5–6 dB gain in minimum acceptable signal-to-noise ratio because of forward error correction (FEC) coding.

2 System architecture

The media converter we designed and prototyped is based on two independent blocks: an optical transceiver made of commercial optical and electronic components, and a logical media converter based on a proprietary protocol (Patent Pending, [7]) implemented on a commercial field programmable gate array (FPGA) development board (XILINX SPARTAN3). The full system converts a standard 10BaseT Ethernet packet stream into a suitable format for high-performance optical transmission over large core POF.

2.1 Optical constraints and optoelectronic sub-system

The need for a 400 m distance to be overcome suggested a green-window (520 nm) operation in which PMMA SI-POF exhibits its minimum attenuation (0.08 dB/m) for an estimated optical loss of ≃40 dB, considering two connectors. A previous experiment in the green window for analogue video transmission [8] reports good results for fibre links up to 300 m, whereas for greater distances (up to 400 m) a worsening of the image quality was observed. ISDN data transmission at 846 kb/s [9] has also been carried out earlier for distances up to 500 m at a wavelength of 560 nm (which has approximately the same attenuation as 520 nm). Even if those systems had less bandwidth requirements than ours, we might note that a link at our goal distance seems to be feasible. We then decided to use commercially available optical components suitable for our application: an already pigtailed green LED (DieMount) with a bandwidth of 35 MHz and high output power (1 dBm) and a photodetector with integrated trans-impedance amplifier (Hamamatsu S6468-02) with a bandwidth of 25 MHz and low output noise voltage (28 nV/Hz$^{1/2}$) – the cascade of these two elements has a bandwidth more than sufficient for 10 Mb/s Ethernet transmission. Moreover, a quantiser is inserted at the receiver side as decision device, after the photo-detection circuit.

Concerning the fibre itself, for the first time ever, we experimentally measured a bandwidth for a 400 m link of 9 MHz (Fig. 1) which as mentioned before is not enough for transmitting 20 Mb/s line rate because of the Manchester encoding needed for the 10BASE-FL standard.

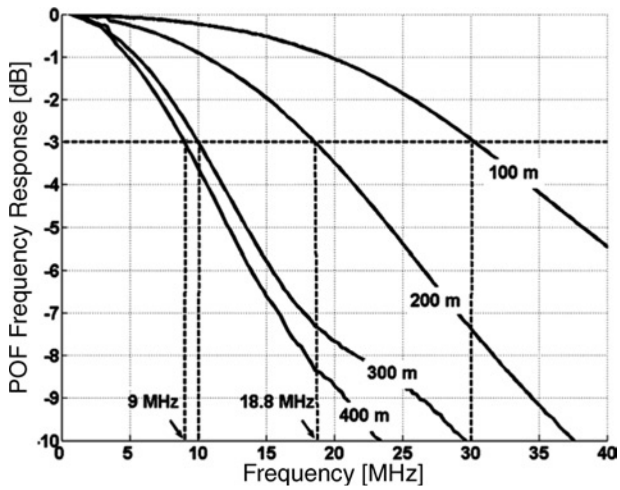

Fig. 1 *PMMA SI-POF frequency response for different link lengths*
9 MHz bandwidth is measured for a 400 m link

2.2 Electronic sub-system and protocol description

Both the optical constraints, previously mentioned, suggest the use of electronic conditioning for performances improvement, in particular,

1. the power budget requires the introduction of a FEC technique, in order to gain 4–6 dB of affordable optical loss;
2. bandwidth limitations can be overcome in two main ways: electronic equalisation or line-coding replacing – this second option seemed to be the most easily viable.

The studied proprietary transmission protocol was, thus, developed in order to overcome these limitations. In particular, as shown in Fig. 2, the protocol is based on the following actions:

- Pad data (PD) insertion via a PD Unit: special bytes are added to manage situations in which there is no Ethernet packet transmission [inter-frame gap (IFG)]; this is necessary to avoid large modulation of the IFG or Ethernet frame

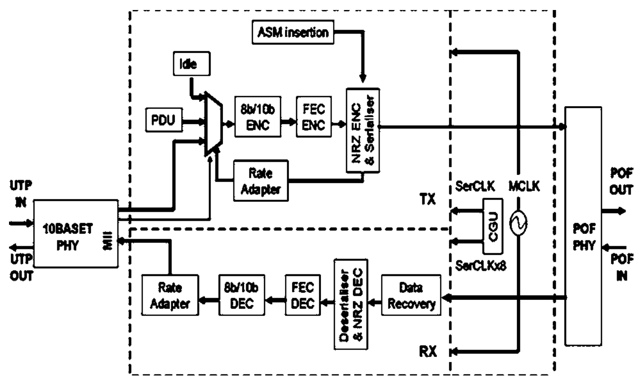

Fig. 2 *Basic architecture of our setup*
For simplicity, block diagram is shown in one direction only, the full system is actually completely full duplex

breakings at the receiver side. The PDU works at a fixed rate of 10 Mb/s.

• DC balancing via a standard 8B/10B encoding: necessary since the optimised electronic circuits have a typical AC cut-off around 30 KHz, which when joint with NRZ encoding would produce systematic errors in a 10 Mb/s transmission, especially in case of large strings of equal bits. 8B/10B also adds some special words for transmission monitoring, such as idle word, not needed for data coding.

• FEC to improve the power budget: Reed-Solomon FEC codes are conventionally used in optical transport networks; in our case, a Reed-Solomon RS(1023, 959) code has been chosen on account of its 10 bit words, which matches the parallelism at the output of the previous block. The correction capability of the selected code is up to 32 words (10 bits each) for each 1023 word FEC block. In terms of BER performance, when the incoming BER at the receiver side (before error correction) is $<10^{-3}$, the system gives quasi-error-free operation ($<10^{-12}$), whereas when the BER is $>10^{-3}$, the code cannot give a significant improvement on the performance, and there arises a condition indicated in the following as the 'FEC_Fail condition'. The FEC unit also drives the serialiser, described in the following, to insert non-coded words properly, (referred to as ASM) needed to discriminate different FEC blocks at the receiver side.

• Balanced NRZ Encoding to fit the available estimated bandwidth in the 400 m of fibre (the Ethernet 10BaseT Manchester encoding would exceed the available bandwidth);

• Data serialisation and feedback rate adaptation: the media converter, at the serial unit interface, must be able to transmit serial data at a constant bit rate, notwithstanding the Ethernet traffic that is received in bursts and can be silent for long periods. Taking into account all the mentioned codings, the resulting line rate is $\simeq$14 Mb/s (13.64 Mbit/s), which turns out to be perfectly compatible with the available POF bandwidth, as shown later; because of the difference among incoming (10 Mb/s) and outgoing (13.64 Mb/s) data rates, a feedback mechanism properly drives the insertion of coded 'idle' words, upon need, to really implement a continuous transmission.

In Fig. 3, we show how incoming Ethernet data are modified at the output of the transmitter unit. Idle, ASM and PD words and check data from the Reed-Solomon encoder are added to the initial symbols to build one FEC block made of 1023 words; in the particular example, two Ethernet frames are involved, with the second one divided between two subsequent FEC blocks.

At the receiver side, a fully-digital data recovery algorithm is implemented before going through the previously described operations in reverse order. The architecture chosen for data recovery uses an over sampling of factor 8. Fig. 2 shows that the Data Recovery block works

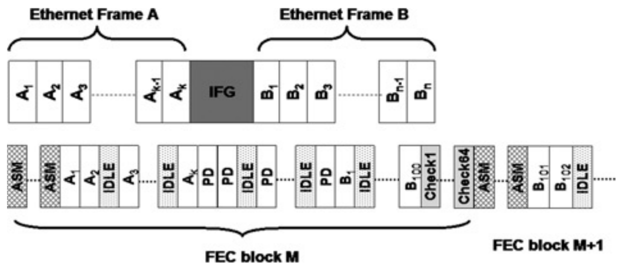

Fig. 3 *Example of conversion from Ethernet frames into FEC blocks*

with a clock eight times faster than the transmitter's. Eight enable signals at the same nominal frequency but shifted each other by 1/8 of the bit period are created, defining eight different time domains; these signals are used to sample the incoming data. The eight enable signals locally generated could be slightly faster or slightly lower than the incoming data stream (transmitter clock): the data recovery unit will take this issue (and clock jitter) into account, implementing in this way a bit synchronism process.

Once the bit synchronism has been satisfied, we should also carry out synchronisation at a frame level. When establishing a link between two nodes, the two media converters involved have to be 'transparent' to the Ethernet communication done by media independent interface (MII) between the two 10BASE-T PHY located at their edges, Fig. 2 shows one of these two media converters. We will call these two 10BASE-T PHY as sending and receiving nodes to differentiate from the words: transmitter and receiver, which constitute the nomenclature used inside a single media converter. Since PD symbols have been inserted whenever there is an IFG, in case of a slight mismatch between the sending node MII's clock and the receiving node MII's clock, it will eventually result in an overflow or underflow condition that could lead to data loss or inner breaks on the original Ethernet frames. To avoid these problems, the RXU (Receiver Unit) not only needs to remove from the received data ASM, idle and FEC check symbols, but also to implement an efficient algorithm for IFG modulation that detects overflow or underflow conditions, previously mentioned, every time a new FEC block is received and, if needed, adds or removes PD symbols. The algorithm has also to take into account that the IFG cannot be shortened less than 9.6 μs, in order to respond to the Ethernet rules. In Fig. 4 a non-detailed principle flow-chart of the receiver algorithm is depicted.

The full system has been completely implemented as a prototype over an FPGA commercial board in a full duplex configuration, and is completely compatible with standard Ethernet network cards.

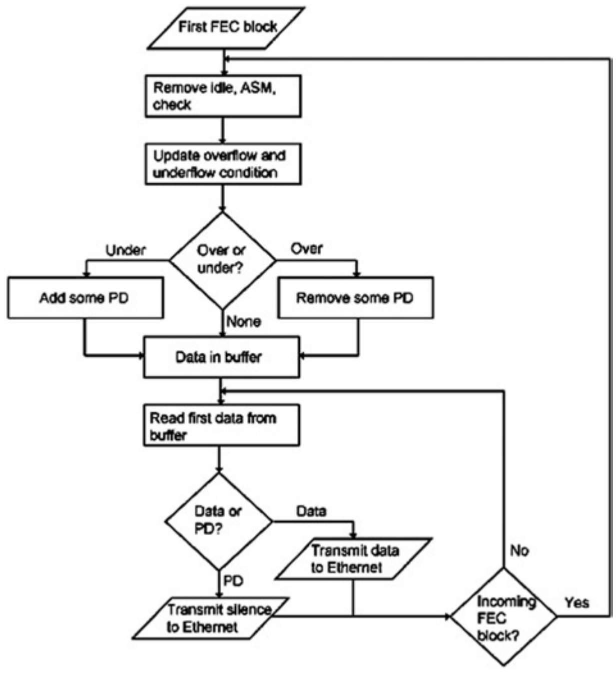

Fig. 4 *Simplified flow-chart of the receiver protocol algorithm*

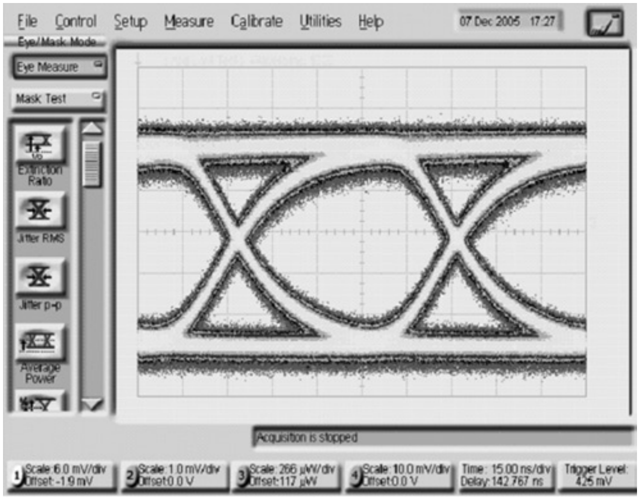

Fig. 5 *Eye diagram with 300 m of PMMA SI-POF in a single spool: the eye is widely open*

3 Experimental results

First of all, we characterised the system via eye diagram measurements for several link lengths. For instance, in Fig. 5 we report the diagram obtained with a single 300 m fibre spool, where a wide eye opening can be seen, whereas the diagram of Fig. 6 refers to 400 m of PMMA SI-POF obtained with two spools and a connector among them. Here, a clear eye diagram worsening can be noted; this situation was investigated in detail, and we saw that the eye-closure is mainly because of the low signal-to-noise ratio available at the receiver at this distance, whereas the distortion because of intersymbol interference is small, demonstrating that even after 400 m the available POF bandwidth is still sufficient for the considered system, as also confirmed by the bandwidth measurements reported in Fig. 1. Globally, as we will show later, the system at 400 m is still error free after the FEC decoding.

A first experimental network-connection demonstration of the system has been an Ethernet stream transmission over up to 425 m long fibre. The system was fed with real traffic coming from the commercial transmission of an Italian FTTH operator. The test was done over standard video-streaming experiment, where we achieved perfect quality video transmission without any service interruption.

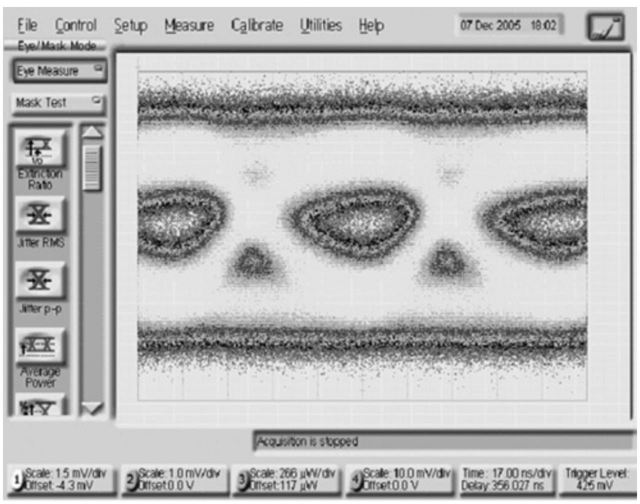

Fig. 6 *Eye diagram with 400 m of PMMA SI-POF and one connector: the eye is partially closed*

The final experiment was performed over a SI-POF LAN test-bed available in our premises (fibre provided by Luceat S.p.A.); the POF cables run in standard LAN ducts, and they reproduce a realistic LAN test-bed. The system showed good operation up to a record distance of 425 m subdivided in three spools, thus including two connectors with their additional attenuation.

We also performed a BER measurement test, directly using inner properties of the FEC coding, such as the capability to measure the incoming BER. In Fig. 7, we show the resulting BER against received power obtained in two different configurations: back-to-back and after 300 m of fibre. The FEC fail condition is also shown as a reference. It can be seen that the 10^{-3} BER level needed to let the RS(1023, 959) code to work properly is achieved for a received power of −37 dBm; this power level can be interpreted as the receiver sensitivity of our system. Since the transmitter's mean power is $\simeq$+1 dBm, the available power budget is $\simeq$38 dB. Considering that the PMMA attenuation in the green window is of the order of 0.08 dB/m [1], the results obtained confirms that our system is able to overcome the 400 m target distance. Moreover, Fig. 7 also shows that the power penalty induced by a 300 m fibre with respect to the back-to-back condition is <0.5 dB, demonstrating that the intersymbol interference introduced by the POF modal dispersion at a line rate of 14 Mb/s is nearly negligible even after 300 m.

3.1 Stability testing

In order to evaluate the reliability of the system and of the protocol, we carried out several long term tests. In particular, first of all we performed a 12 h transmission test over the previously described 425 m test-bed. The results of this long-term campaign are reported in Fig. 8, in which we plotted a histogram of the number of occurrences of the error-affected words for each FEC block. Here, it should be recalled that the code can completely correct up to 32 words per block. The histogram has, thus, been zoomed around this value in the inset of Fig. 8. It can be seen that the 32 error threshold, which would trigger a FEC failure condition, was never reached during the 12 h; in fact, the maximum number of error-affected words per block was 27, showing that the system still has some little operational margin.

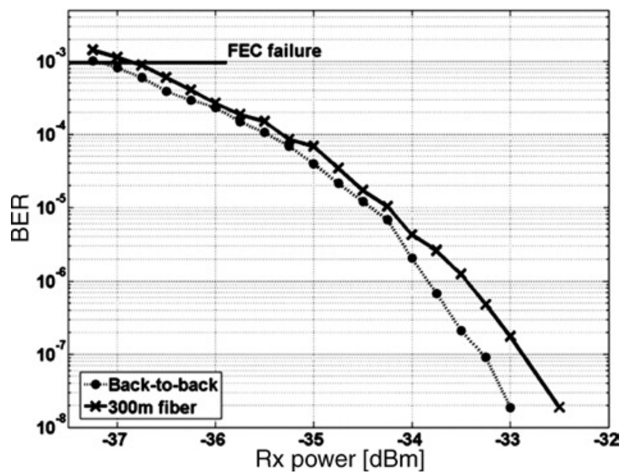

Fig. 7 *Sensitivity measurement: pre-FEC BER against Received power, in the back-to-back condition and after 300 m of fibre*

As a reference, the FEC_Fail condition level, corresponding to an input BER = 10^{-3} is also shown

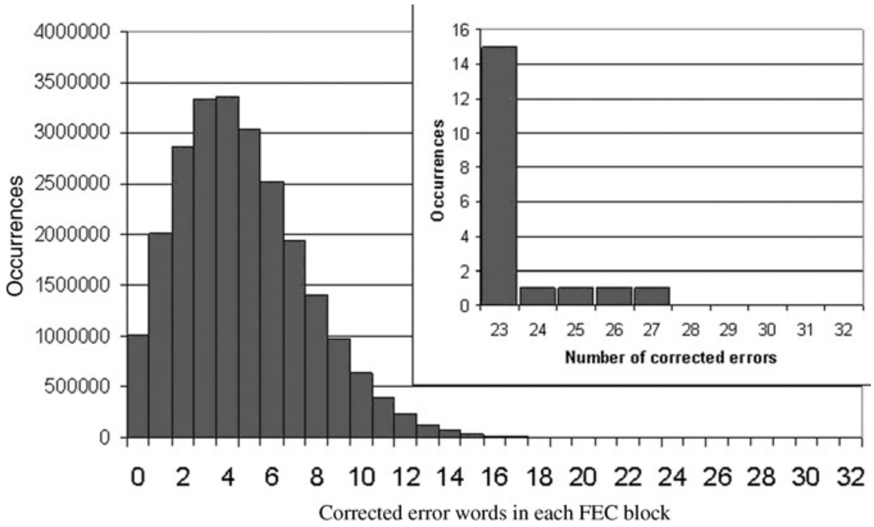

Fig. 8 *Histogram of word errors occurrences in a 12-h stability test over a 425 m link with two connectors*
Zoom reports the tails of the distribution over higher error number

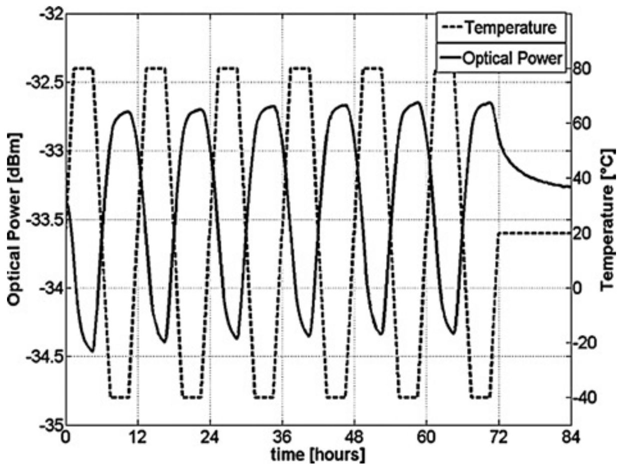

Fig. 9 *Received power against temperature: temperature increase produces an attenuation increase and thus a power diminution at the receiver side*

On account of the PMMA material being sensitive to temperature variations, attenuation worsening could occur in particularly challenging environments; we then performed a thermal stability campaign making a 300 m fibre spool undergo several thermal cycles, from $-40\,^{\circ}\mathrm{C}$ to $80\,^{\circ}\mathrm{C}$, inside our environmental chamber, simultaneously measuring the received power. The results of this campaign are reported in Fig. 9, showing that the optical power, in the above specified range, varies with a linear inverse law to temperature (that means: with temperature increase, the PMMA attenuation increases linearly) and consequently we have a worsening of the performances in terms of measured incoming BER (Fig. 10). The measured power variation is <2 dB, causing the BER to have a highest value of 4×10^{-5} in the worst conditions with temperatures much higher than those found in the typical environments we targeted, such as in-building installations or buried fibre plants.

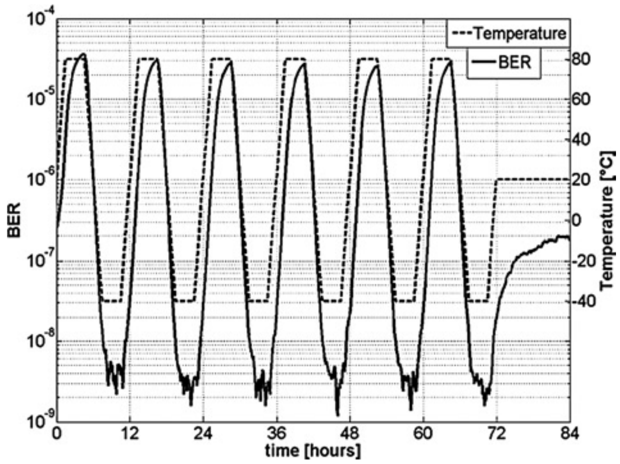

Fig. 10 *BER against temperature: temperature increase affects the system margin*

4 Conclusions

We prototyped a fully transparent 10 Mb/s Ethernet media converter from UTP5 to PMMA SI-POF, demonstrating a record distance of 425 m, using low-cost optical components and a commercial FPGA development board, into which a proprietary protocol has been programmed. In the field, a long-term test and environmental tests have been carried out, showing the high reliability of the system. We believe that this constitutes a proof-of-concept for the usage of these large core fibres for several areas, such as the last part of the FTTH networks (edge networks), domotic and local area networks, or in any datacom applications with relevant EMI problems. In all these cases, large core POF ease of installation can be a key element for cost reduction.

We believe that this prototype is ready for industrialisation with an ASIC implementation of the proprietary protocol; further optimisation actions could investigate the chance of adapting the transmitted power for avoiding saturation within low distance application, or to exploit adaptive equalisation for further performances improvement.

Future developments of our work will investigate higher bit rates for LAN or VSR applications as a main target of the EU STREP project 'POF-ALL' (IST-FP6).

5 Acknowledgments

The authors would like to thank Mr. Alessandro Nocivelli (Luceat S.p.A.) for the fruitful technical discussion with him, and Fastweb S.p.A. for sharing with us their approach to FTTH networks. This work was partially supported by the EU FP6 NoE e-Photon/One, WP3.

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