Real-time Gigabit Ethernet bidirectional transmission over a single SI-POF up to 75 meters

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Abstract: In this paper we demonstrate 1Gb/s bidirectional transmission over a single SI-POF, over the record distance of 75m. We successfully tested our system running real time Gigabit Ethernet traffic generated by a router tester.

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1. Introduction

This paper focused on bidirectional transmission over 1 mm step-index Plastic Optical Fibers (POF) based on Poly-Methyl-MethA-Crylate (PMMA), as standardized by IEC in category A4a.2. The pros and cons of POF with respect to other solutions for home networking have already been reported in deep in other papers ([1]) and will thus only be shortly remembered here:

– *compared to glass fibers*: simpler installation thanks to a much larger core (1mm for POF, 50μm for multimode glass fibers); use of visible light rather than infrared, resulting in simpler "visual" check of the integrity of the connections; higher mechanical robustness and tolerance to bending and dusty environments. Overall, glass fiber requires skilled technicians for the installation, while for POF do-it-yourself approach for the final user can be envisioned;
– *compared to copper solutions* (UTP cables): possibility to be deployed in power ducts, thanks to a complete galvanic and EMI isolation; POF connectorization is even easier than 4-pair UTP cables; UTP Cat.5 cable is typically 5mm thick or more, while POF diameter is significantly smaller.

This last point is one of the key motivations for developing a bidirectional system over POF: using a single fiber would make for a cable with an overall diameter, including the typical jacket used for POF home networking, of approximately 2mm, significantly smaller than a UTP Cat.5 cable. This can be a significant advantage in brown-field home networking installations.

At the OFC conference 2010, we presented ([2]) a very preliminary experiment of bidirectional 1Gb/s transmission over POF, where we demonstrated a 20 meters reach in an off-line processing experiment. In this new work we significantly extend the result of [2] as follows:

– we significantly extended the reach, showing a reliable transmission over 50 meters with an optical power margin of 6dB and 75 meters a margin of 2.3dB;
– we moved from off-line processing to real-time Gigabit Ethernet transmission, either using a router tester (Agilent N2X) or actually connecting two PCs via their Gigabit Ethernet transmission interface.

These upgrades have been made possible by:

– the optimization of the optical components (in particular, the transmitter and the splitters), thanks to the work performed inside the EU project "ALPHA";
– the use of a physical layer (PHY) transmission protocol particularly designed for POF and developed inside EU project "POF-PLUS". This new PHY has been presented in details in [3], and it is briefly described in the next paragraph.

While the previous work ([2]) was a preliminary proof-of-concept with significant limitations, we believe the present work extends the demonstration of Gigabit bidirectional transmission over POF up to a level that may become of interest for practical home-networking devices.

In the rest of this paper, we present the proposed experimental system and a detailed characterization of its performance in terms of both bit error rate and packet error rate.

2. Experimental setup

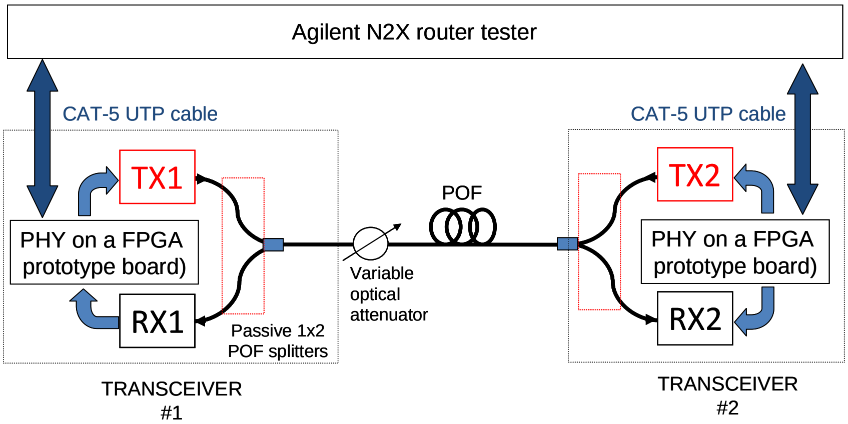

Fig. 1: Experimental setup

The experimental setup is shown in Fig.1: two workstation equipped with Gigabit Ethernet cards are connected to our prototype, which acts as a media converter from copper (RJ-45 1000Base-T) to POF. A very low cost directly modulated red laser has been used for the transmitter (from UnionOptronics Corp. SLD-650-P10-RG-03, 665nm emission, 7dBm peak output power). The laser output is coupled to the POF link by a prototype 1x2 POF splitter (1.8dB insertion loss when used as coupler). At the other end of the link (50m or 75m of Step-Index POF), another splitter (4.3dB of insertion loss) is used to connect the receiver (a commercial receiver from Graviton, model SPD-2). In the experiment, both lasers were simultaneously active and modulated with uncorrelated traffic. The isolation between the two ports of used POF splitters is almost 34dB. In order to reduce the optical reflections at the interconnections we used an index matching gel. The received optical power without extra-attenuation is equal to -11.4dBm for the 50m system and -15.2dBm for the 75m system.

The core of the newly developed PHY is implemented on an FPGA platform, and it is based on:

- traditional binary on-off modulation at the transmitter: this solution has the advantage of being much more resilient to the nonlinearities that always arise when trying to modulate a laser with a high OMA with respect to more advanced modulation formats;
- efficient line coding (64B/66B to 65B), allowing to keep the signalling overhead much lower than, e.g., 8B/10B;
- standard Reed-Solomon codes;
- blind and adaptive DFE at the receiver.

The developed prototype accepts real time traffic from regular Gigabit Ethernet cards and thus acts as a fully-compatible Gigabit Ethernet media converter from 1000-BaseT to the custom POF-PHY. We developed internal monitoring features that allow to estimate the PHY-level bit error rate (BER) before and after FEC decoding at the receiver.

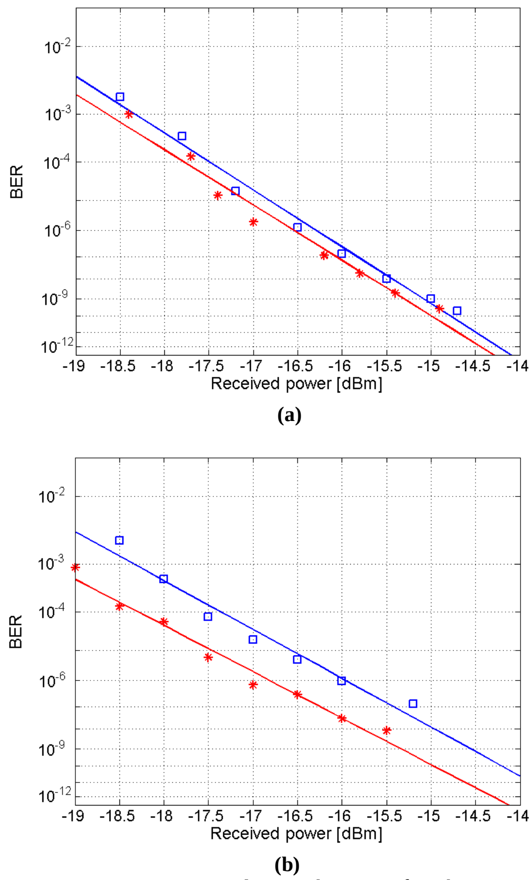

Fig. 2: BER vs. received optical power for the 50 meters bidirectional link (a) and 75 meters (b). The square markers are the BER values measured at the receiver when both channels are turned on, while the star markers are the BER values measured when only one channel is working.

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3. Experimental measurements

The full system was tested under real traffic conditions, using an external router tester (Agilent N2X). We performed a first set of measurements at the PHY level, estimating the bit error rate before FEC decoding as a function of the received optical power at the output of the 50 and 75 meters system, and the results are given in Fig.2. The variable optical attenuator indicated in Fig.1 is simply built by a free-space gap between two POFs; we placed it at the transmitter side, in order to obtain the worst-case condition in terms of mode excitation. We evaluated the resulting BER vs. the receiver optical power for two different cases: full bidirectional transmission (both lasers were turned on, square markers in the figure) and unidirectional transmission (only one laser turned on, star markers in the figure). As depicted in Fig.2, the finite isolation between the two input ports of the splitter introduces a penalty, which is negligible for the 50 meters system, and approximately 1dB for the 75m system. In this last case, the received useful power is smaller, and thus the effect of reflections from the other direction of propagation is more relevant. The available system margin is anyway good in all cases; in fact, considering that the FEC threshold is approximately 10^{-4}, we can estimate a system margin greater than 6dB for the 50 meter system and almost 3dB for 75 meters even when both lasers are on.

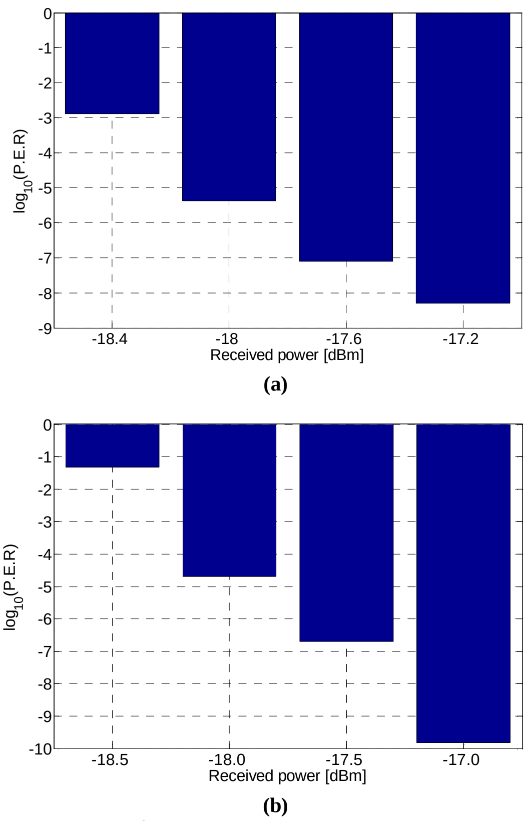

Fig. 3 Ethernet frame error rate (Packet Error Rate) vs. received optical power after 50 meters (a) and 75 meters (b).

We then repeated the measurement campaign using real bidirectional Ethernet traffic, estimating the Ethernet frame error rate. Results are shown in Fig.3. The correct operation of the FEC is effective until -17.5dBm, which approximately corresponds to a packet error rate of 10^{-7} and a raw bit error rate (before FEC) of approx 10^{-4}. Since the actual received optical power in the 50 meters case, without any extra attenuation, is -11.4dBm, we can thus estimate a margin of almost 6dB, as a further confirmation of the previous measurements. In the same way, we can estimate a margin of 2.3dB for the 75 meters case.

4. Discussion and conclusions

We have experimentally demonstrated, for the first time to the best of our knowledge, a fully bidirectional 1Gb/s system over a simplex POF cable that is running with real Gigabit Ethernet traffic. The paper demonstrates the feasibility of this architecture using low cost optical components and with good power margin up a distance of 75 meters. The only critical element in the system is the implementation of the PHY described in [3], specifically tailored for POF Gigabit transmission, and a key element to achieve the performance presented in this paper. In this work, the PHY is implemented on a prototype FPGA platform that clearly has exceedingly high cost for the applications envisioned in this paper (home networking and industrial automation). The development of the proposed PHY on a (mass-produced) ASIC chip would be fundamental in achieving a reasonable price level.

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