Noise Analysis and Multi-Gbit/s Transmission in PoF Scenarios over SI-POF

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ABSTRACT:

In this work the delivering of optical power with several mW simultaneously with Gigabit data transmission in step-index plastic optical fiber is reported. Theoretical analysis of the signal-to-noise ratio of data signal at 650 nm is presented to study the influence of the feeding power at 405 nm on the data traffic. We experimentally explore this influence on a real-time Ethernet link at a speed of 1 Gbit/s using commercial products. The system performance was tested at 650nm and a low loss designed multiplexer was used to enhance the power budget of the system. The system was able to deliver several mW of optical power in coexistence with data transmission at 1Gbit/s and BER ~ 1×10^{-10}.

Key words: Plastic optical fiber, home network, power over fiber, signal-to-noise ratio, multiplexer, gigabit transmission.

1.- Introduction

Large core step index (SI) plastic optical fiber (POF) is considered to be very useful in many applications such as home networking [1] due to many advantages such as easy installation and high bending tolerance which make it more interesting than multimode silica fibers in such application scenario. Today, short-reach network data transmission at Gbit/s rates are more requested by users due to the growth of different multimedia end-user services like high definition TV or IPTV [2].

In this framework, POF has been proposed to achieve low cost and high speed links in short-reach and in-home networks such as in [3-5]. POF is also envisioned to support future WiGig [6].

On the other hand Power-over-fiber (PoF) technology has been proposed to feed some elements in the access network portion [7] as well as to supply wireless access points (AP) that are used to process RF signals in multi services systems [8]. Graded Index POF (GI-POF) using for power delivery is also reported in [9] and other examples of PoF technology utilizing different kinds of multimode fibers capable of delivering hundreds of mW to the remote node are shown in [10-11]. An analysis of the impact of the high optical PoF power levels with simultaneous data signal transmission then becomes of prime importance [12].

Hence, in this work we experimentally test the potential of 1mm core diameter SI-POF fiber for simultaneous transmission of real time data traffic at 1 Gbit/s and power delivery. Both the signal-to-noise ratio (SNR) and bit-error-rate (BER) of the data signal are addressed at different PoF signal levels for remote power delivery. We provide some theoretical calculations to compare the impact of the noise that affects the data transmission quality due to the simultaneous transmission.

In order to multiplex the data and power signals in our experiment, a custom-made multiplexer (MUX) device with low insertion losses was used [13]. The optical cross-talk (CT) requirement for the devices at the reception stage is also discussed here based on the transmission results. As an use-case we propose an in-home POF network with 5G wired backbone for Gbit/s transmission and using PoF technology to provide energy autonomous wireless access points as shown in Fig. 1.

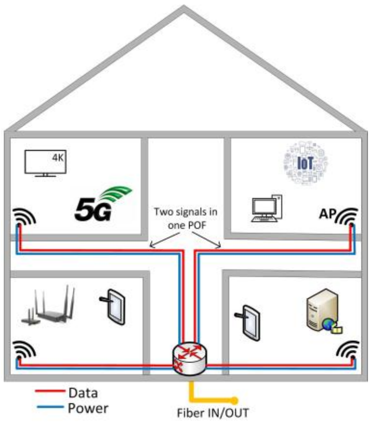

Fig. 1 Illustrative POF network for multi-standard wired and wireless transmission in the home applications with remote power delivery.

2.- Theoretical basics

In any communication link, the minimum optical power required to achieve an acceptable BER is one of the most important parameters to be designed. Hence, in this section we theoretically calculate the optical SNR (oSNR) of the data signal for our proposed system as this value is directly related to the required power and to the BER of the system. Different power levels are investigated as well as the noise that can be added if we simultaneously transmit optical power with data traffic. Based on its general definition, the oSNR can be expressed as:

$$SNR = \frac{\text{Average Signal Power}}{\text{Noise Power}} \tag{1}$$

In our calculation we consider two laser diodes (LD), one at 650nm (LD_1) for data transmission and the other at 405nm (LD_2) for the PoF channel. The optical power transmitting from LD_1 is P_1.To estimate the noise, different mechanisms that arise from different sources (laser, fiber and detector) are taken into consideration. We consider the Relative Intensity Noise (RIN) of the LD limited by shot noise. It can be given as:

$$\sigma_1 = \eta_{FO} P_1 \sqrt{\text{RIN B}} \tag{2}$$

where $$RIN = \frac{2h\upsilon}{P_1} \tag{3}$$

The η_{FO} parameter considers the fiber loss dependency of the noise transfer. For the detector, the Shot noise (σ_2), Dark current (I_D) noise (σ_3) and Johnson noise (σ_4) are added, as shown in equations (4-6) respectively:

$$\sigma_2 = \frac{1}{\eta_{PD}} \sqrt{2q\eta_{PD} P_D B} \tag{4}$$

$$\sigma_3 = \frac{1}{\eta_{PD}} \sqrt{2q I_D B} \tag{5}$$

$$\sigma_4 = \frac{1}{\eta_{PD}} \frac{1}{\eta_{Rx}} 2\sqrt{KTRB} \tag{6}$$

All above parameters are described in Table 1. The noise contribution from each term of the system and the equations used are all based on [14] to calculate the oSNR. The parameters η_{PD} and η_{Rx} are added to equations (4-6) in order to address the noise level at the input of the detector due to the optical received power (P_D, see Eq. 4). The oSNR now can be expressed as follows:

$$SNR = \frac{P_D}{\sqrt{(\sigma_1)^2 + (\sigma_2)^2 + (\sigma_3)^2 + (\sigma_4)^2}} \tag{7}$$

Table 1 shows the definition and values for the parameters that were used in the above equations during the calculations; most of them are chosen to emulate out experimental setup.

Table 1: Parameters for the oSNR analysis.

Parameter	Value
η_{FO}, Total Att. of fiber	0.67
h, Plank constant	6.62×10^{-34}J.s
N, frequency of the light	461.22 THz
B, Bandwidth of the system	500MHz
η_{PD}, PD conversion efficiency	0.38A/W
I_D, Dark current	10nA
q, electric charge	1.6×10^{-19} C
K, Boltzmann constant	1.38×10^{-23} J/K
η_{Rx}, Preamplifier gain	1000V/A
R, Resistance	1000Ω
T, Temperature	300K

Two power levels at –8 dBm and -12 dBm for P_D were considered (reaching the PD) yielding to oSNR values of 42.5 dB and 38.25 dB, respectively. As expected the oSNR degrades as the power level impinging the PD decreases.

Afterwards for simultaneous transmission, we add the noise contribution from the PoF channel (LD_2) to the overall noise power. RIN of the 405nm channel will affect the oSNR of the data signal thus resulting in an additional penalty. Optical power from LD_2 was later reduced to a certain level in order to calculate the minimum optical power that can be delivered and to see how the power affects the quality of the data channel. Fig.2 illustrates our analysis. As a result it is clearly seen that oSNR is being linearly degraded with the increasing power from the LD_2 and vice versa.

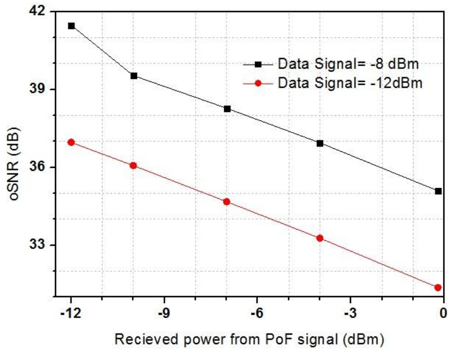

Fig. 2: Data signal oSNR at different power levels vs PoF power delivered at reception stage.

3.- Experiment Setup

An experimental testbed including an optical SI-POF link, power laser, data transmitter and receiver was designed as shown in Fig.3 to emulate the in-home network scenario that was illustrated in Fig.1. The set-up is based on a PC equipped with a 1 Gigabit Ethernet interface in combination with a Media Converter (MC) used to generate and to read the transmitted data bits. The MC transforms the Gigabit Ethernet frames into a 16-level Pulse Amplitude Modulation (PAM) signal (named Tx-signal), and vice versa. At the transmitter side, the Tx-signal is used to modulate the laser diode (LD_1) of the data channel at 650nm; this is represented through the dashed control signal in Fig. 3. The PoF signal is based on a LD_2 emitting at 405nm considered for optically powering some APs in the building through the POF fiber.

In this experiment an external LD is used as the transmitter for the data channel instead of LED provided by the MC in order to enhance the power budget of the link. So the MC is only used to encode the frames into a PAM signal and vice versa. Data and power channels were multiplexed and launched into a 10m-long SI-POF link through a MUX device which is based on reflective diffraction grating technology with low insertion losses ILs ~ 4.5 dB. These channels could also be multiplexed by using fiber bundles as shown in [15].

At the reception stage the received optical signal is converted back to electrical domain by a PIN photodiode (PD) included in the MC. This MC is part of a fully integrated system that is able to establish a 1Gbit/s link over 50 m of 1mm core diameter SI-POF (NA=0.5) [16].

We consider data and power channel values reaching the end of the link as if a demultiplexer (DEMUX) with poor crosstalk (CT) were employed. This is to further analyse the minimum CT required by such device in order to separate power and data channels with an acceptable SNR.

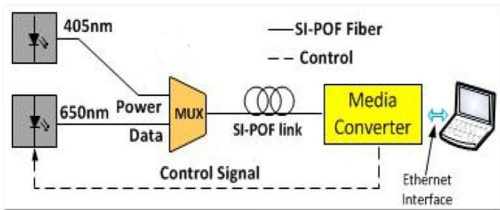

Fig. 3: Experimental setup.

It is worth to say that the measured SNR and our theoretical estimations may not exactly match due to the special signal processing and the different electronics used at the MC device to improve the ratio of the signal. However, the aim of this work is to analyse the SNR behaviour trend and how it is affected by the power channel injected into the POF link. More information about the system and the SNR decoding can be seen in [16]. This is the reason further SNR results shown are normalized with respect to not injecting a PoF signal into the optical link. Experimental characterization and comparison between the estimated SNR and the decoded one (SNR_{decode}), BER performance of the system and the CT required are next presented.

4.- Results and Discussion

The link performance is evaluated using the monitoring features of the MC. The link is tested using different Tx data power levels. For each Tx power level, the effect of varying the PoF optical power simultaneously delivered at 405 nm is characterized. All the measurements are done in a 10m-long SI-POF link. The data signal and power channel input powers are chosen to avoid PD saturation. At first, their values are – 1 dBm and +7.33 dBm respectively. An estimation of the power budget of the link for both channels is shown in Table 2. From those values, the data signal power at the PD is -8 dBm.

Table 2: Power budget of the link

Parameter	Data	Power
LD power (dBm)	- 1	+7.33
Launching ILs (dB)	0.80	0.90
Mux IL (dB)	4.4	4.53
10 m SI-POF (dB)	1.8	2.1
Power at receiver (dBm)	-8	-0.2

4.1. SNR Measurements

The effect of varying the optical power delivery on the SNR_{decode} of the link is next analyzed. Different measurements of SNR_{decode} and BER are carried out using the monitoring features of MC. First, the data signal is transmitted alone through the proposed setup. The results obtained were 32.05dB for the SNR_{decode} with a BER equals to zero. The PD accepts an input optical power up to about 0 dBm. For simultaneous measurements and to avoid the damage of the PD, we configured the greatest power level at 405 nm received at the PD to be – 0.2 dBm while keeping the received data signal at -8 dBm. In this case, the SNR_{decode} is degraded in 4.1 dB. The optical power energy delivered is then decreased in steps of 3 dB resulting in a SNR_{decode} increase. The SNR shows negligible variations to with respect to the case of the data signal transmitted alone up to a power channel level of – 12 dBm. In all the steps, the BER is $< 1\times 10^{-10}$ which represents a free error transmission with the possibility of 1mW delivered power. Fig. 4.a shows a comparison between both normalized calculated SNR and SNR_{decode} which proves that they both have the same tendency against an increasing power from LD_2.

Afterwards, the input data signal is decreased and set to – 12 dBm and the optical power delivered is set to -0.2 dBm, both power levels measured at the PD. The same procedure is repeated. At first, the SNR_{decode} is 28 dB when the data signal is transmitted alone. When both signals are multiplexed, the SNR_{decode} decreases in 3.9 dB with -0.2 dBm at the PD from the PoF power channel at 405 nm. The link is not established as the system requires $SNR_{decode} \geq 25$ dB for 1 Gbit/s transmission. The result in this case is shown in Fig. 4.b and compared with our theoretical estimations.

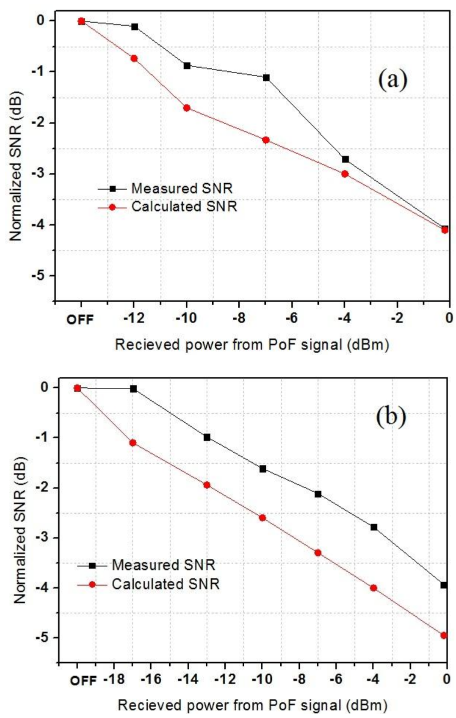

Fig. 4 Normalized calculated SNR and SNR_{decode} vs. PoF power delivered at reception stage with data signal power of: (a) -8 dBm (b) -12dBm.

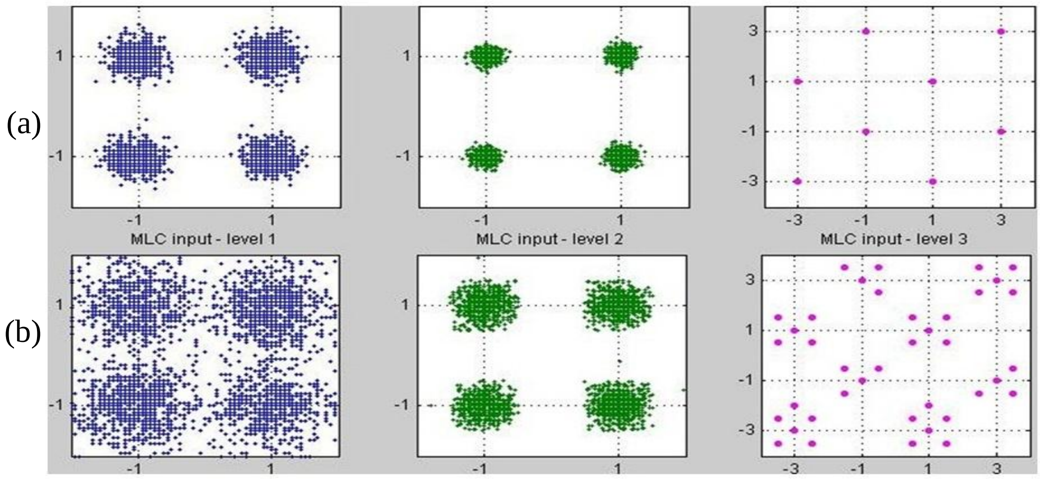

Fig. 5 Constellation diagram of the multilevel decoding inputs: (a) Only data signal, -8 dBm at PD. (b) Both data and power channels at PD; data -12 dBm, power – 0.2 dBm.

However, in this last case it is possible to deliver –4dBm of optical power as SNR_{decode} degrades in 2.8 dB with BER of 7.31×10^{-9}. The constellation diagrams of the three decoding stages at the receiver of the best and worst case are also shown in Fig. 5.

4.2. CT Estimation

From the experimental results is shown that increasing the optical power delivery signal adds additional noise to the system that results in SNR_{decode} and BER penalties. The maximum optical power at 405 nm, P_{HPL}, that can reach the PD depends on the data signal power at 650nm, P_{DATA}. In any case, to keep the same SNR_{decode} obtained when no power channel is considered, the power of both channels at the PD should follow:

$$P_{DATA}\,(\mathrm{dBm}) - P_{HPL}(\mathrm{dBm}) = 5\mathrm{dB} \qquad (8)$$

If a DEMUX is placed at the reception stage, the power channel signal at the PD in the MC, P_{HPL_DEMUX}, is given by:

$$P_{HPL\_DEMUX}(\mathrm{dBm}) = P_{HPL}(\mathrm{dBm}) - \mathrm{CT}\,(\mathrm{dB}) \qquad (9)$$

Then the required CT for the demultiplexer is given by:

$$\mathrm{CT} = P_{HPL}(\mathrm{dBm}) - P_{HPL_{DEMUX}}(\mathrm{dBm}) = P_{HPL}(\mathrm{dBm}) - P_{DATA}\,(\mathrm{dBm}) - 5\mathrm{dB} \qquad (10)$$

So for a 10mW or +10dBm optical power delivery at a photovoltaic cell to be placed in the access point (AP) and a data signal of -8dBm a CT of 23 dB is then required.

Finally, the results show the potential of the system for a real time transmission with BER ~ $1*10^{-10}$ at a speed of 1 Gbit/s and simultaneous optical power delivery of up to ~ 1 mW with acceptable SNR_{decode}. The results also show that theoretical and decoding normalized SNRs are decreased in the same way as the PoF signal is increased in optical power. The insertion losses of the MUX/DEMUX devices needs to be improved as they affect the power budget of the system.

5.- Conclusion

A real-time data link at a data rate of 1 Gbit/s with simultaneous optical power delivery has been proposed and implemented as part of the backbone of broadband wireless communication systems for access point remote feeding in future in-home networks based on SI-POF. We analysed the noise generated with and without PoF power transmission through the link. An analysis to consider the required CT at the reception stage has been also provided. It was possible to deliver powers up to 1 mW while keeping BER values < 1×10^{-10} taking into account the power level of data signal.

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