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## Characterization of Equalized 10-Gb/s Multimode Fibre LAN Links Using Transverse 7-Tap Analog FIR Filter in 0.13 $\mu$m CMOS

**Aleksandar Risteski**
Faculty of Electrical Engineering
Karpos 2 bb
1000 Skopje
Macedonia

**Scott Reynolds, Jose Tierno, Laurent Schares, Sudhir Gowda,**
**Jeffrey A. Kash, Petar Pepeljugoski**
IBM Research Division
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, NY 10598

# Characterization of Equalized 10-Gb/s Multimode Fibre LAN Links Using Transverse 7-Tap Analog FIR filter in 0.13 μm CMOS

Aleksandar Risteski (1), Scott Reynolds (2), Jose Tierno (2), Laurent Schares (2), Sudhir Gowda (2), Jeffrey A Kash (2) and Petar Pepeljugoski (2)
1 : Faculty of Electrical Engineering, Karpos 2 bb, 1000 Skopje, Macedonia, acerist@etf.ukim.edu.mk
2 : IBM TJ Watson Research Center, Yorktown Heights, NY 10598, USA. petarp@us.ibm.com

**Abstract** *BER and ISI measurements of over 600 equalized 300-m long 10-Gb/s MMF links using a 7-tap analogue-FIR filter show offset launch is preferred for OM1 fibres, while centre launch is preferred for OM3 fibres*.

## Introduction

The inter-modal dispersion of legacy (FDDI grade) multimode fibres (MMF) is the main limitation in achieving longer distances in links operating at 10 Gb/s. Achieving distances up to 300m in 10 Gb/s Ethernet (10 GbE) LAN links, reusing installed FDDI MMF, is possible through use of electronic dispersion compensation (EDC) at the receiver [1-3]. Other approaches like multilevel modulation and mode filtering have been proposed, but are not seen as robust and cost effective.

We built a modified conventional receiver in which an EDC chip [3] follows a PIN photodiode and a linear trans-impedance amplifier (TIA), but precedes the clock and data recovery circuit. We tested the performance of this modified receiver on a large number of legacy MMF, which originated from round robins conducted by the Telecommunications Industry Association [4]. We showed that the centre launch is preferred for OM3 fibres, while the offset launch is preferred for OM1 fibres.

## EDC experiment

Figure 1 depicts the equalization measurement setup. A 1310-nm FP laser is directly modulated by a 10-Gb/s PRBS signal ($2^7$-1) from a pattern generator. The launch conditions into the MMF under test are controlled by using two micromechanical precision stages that adjust the lateral offset between the single-mode fibre (SMF) at the laser output and the MMF. The optical receiver is composed of a commercially available 7-GHz-bandwidth front-end comprised of a PIN-photodiode and a trans-impedance amplifier (TIA) with differential outputs, followed by analogue-FIR (AFIR) filter mounted on a test board, and by a commercial clock and data recovery (CDR) unit. A bit-error-rate tester (BERT) and an oscilloscope are used to measure the output signal quality.

Our EDC chip architecture is a 7-tap transverse AFIR filter with differential inputs and outputs. Although it is currently implemented as a separate 0.13μm CMOS chip with a 1.5 mm by 4.8 mm die area, it is intended for future integration with the CDR. The delay of each tap is 75ps and the bandwidth is typically 7GHz. Power consumption was about 300 mW from a 2.5V supply. The linear range of the input signal to the filter is 50-300mV. A digital interface for controlling tap weights is added to facilitate an adaptive algorithm.

The equalized link performance was tested on a large number of 300-m optical links. The measurements were performed on a subset of fibres described in [4] that was comprised of 25 OM1 (62.5 μm, FDDI grade), 20 OM2 (50 μm, FDDI grade) and 12 OM3 fibres. The lengths of the OM1 and OM2 fibres were 300m or 1km. We also explored the influence of lateral offsets in two types of SM-launch in the MMF: the centre launch (-4 to 4 μm) and offset launch (10-18 μm for OM2 and OM3, and 16-24 μm for OM1 fibres). The EDC chip performance was measured in more than 600 MMF links.

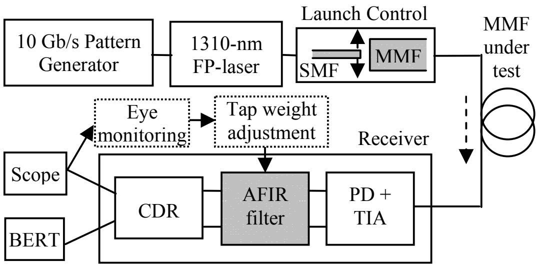

*Figure 1:Experimental equalized MMF link setup*

Simulations of the equalized link using information from the measured fibre DMD were performed to assess the performance of several adaptation algorithms. We also generated a small set of tap weights that would at least partially open the eye in most unknown MMF links. These preset values are used as a starting point for the adaptive equalization algorithm. The algorithm works in a closed loop: each time the tap weights are changed, the quality of the eye is measured and new tap weights are calculated. We used several criteria for measuring the eye quality, including the vertical and/or horizontal eye closure, and the total eye area.

## Results

As a result of the fibre differential mode delay and limited transmitter and receiver bandwidth, the signal at the output of the link suffered from severe ISI and timing jitter. Figure 2a shows the completely closed eye diagram before equalization.

After the equalization process, the eye is well improved (figure 2b), enabling 10-Gb/s data transfer over 300-m long MMF with a BER below $10^{-12}$.

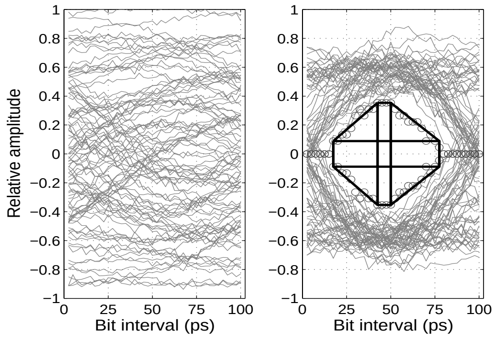

*Figure 2: Typical 10-Gb/s eye diagrams (a) before (b) after equalization. This example illustrates the centre launch in a 300-m OM2 fibre (4-orange from RR 12/96 cable [3]).*

Deterministic jitter at the equalizer output is less than 20ps. Similar experimental results using the same filter to equalize a 600m-long optical link that uses OM3 fibre are shown in [3]. We achieved 10-Gb/s error-free data transfer over selected 1000m long OM1 and OM2 fibres (from cable 1km RR [4]).

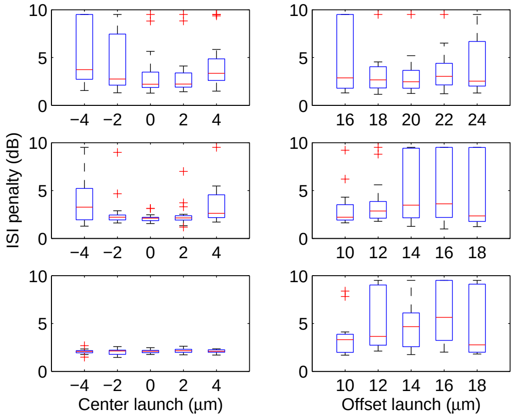

*Figure 3: Statistical box-plots of measured ISI penalty after equalization for OM1 (top), OM2 (middle) and OM3 (bottom) fibres versus lateral offset. Boxes show the 25-75 percentile of the data, while the line in the middle is the media.*

Figure 3 shows statistical box-plots of the ISI penalty at the link output after equalization of the 300m-long links. Boxes represent the 25-75 percentile range of the data, while the line in the middle is data median., The results are grouped by fibre type (OM1, OM2 and OM3) and by launch type (centre launch and offset launch). It is apparent that OM1 fibres have the highest ISI penalty, which is minimized by using an offset launch centered around 20 µm. In our fibre set, OM2 fibres have much better performance with centre launch. Some offset launch channels (10-12 µm) also produce small ISI. OM3 fibres with centre launch show significantly lower ISI in a very wide region around the optical centre of the fibre than for the offset launch channels. These results might be adversely affected by mode mixing introduced by offsets in additional connectors in the link.

The link performance is limited by the noise enhancement and the maximum residual ISI penalty (since the filter is not ideal) at the equalizer output that the CDR can handle. Figure 4 presents the ISI failure rate (ISI FR), defined as the fraction of the equalized fibres that cannot provide an ISI penalty less than the allocated value (5.5 dB here), versus the lateral offset. ISI FR for 50-µm fibres (both OM2 and OM3) is much lower for centre launch. All OM3 fibres are successfully equalized in the whole region of centre launch offsets. OM1 fibres have the lowest ISI FR of 10-15% in restricted ranges of the offset with both centre and offset launch. We expect that the failure rate can be further reduced by using a larger number of taps in the analogue FIR filtering scheme studied in this work, or by using a decision-feedback equalizer (DFE) architecture.

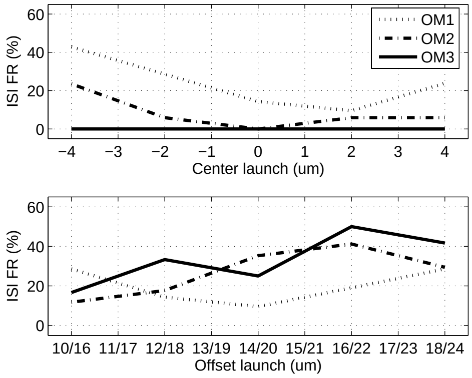

*Figure 4: ISI Failure Rate of equalized fibres for (a) centre and (b) offset launch*

## Conclusions

Failure rates in OM3 MMF links with centre launch are much lower than in the other fibre types (OM1, OM2). OM1 and OM2 may benefit from an offset launch or a union of centre and offset launch. DFE architecture is required to improve the failure rates in OM1 and OM2 fibres.

## References

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