10 Gbps transmission over 10 m SI-POF with M-PAM and Multilayer Perceptron Equalizer

Citation for published version:
Osahon, IN, Safari, M & Popoola, WO 2018, '10 Gbps transmission over 10 m SI-POF with M-PAM and Multilayer Perceptron Equalizer', *IEEE Photonics Technology Letters*.
https://doi.org/10.1109/LPT.2018.2825146

Digital Object Identifier (DOI):
10.1109/LPT.2018.2825146

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
IEEE Photonics Technology Letters

10-Gb/s Transmission Over 10-m SI-POF With M-PAM and Multilayer Perceptron Equalizer

Isaac N. Osahon, Majid Safari, and Wasiu O. Popoola

***Abstract*— We demonstrate the gigabit-per-second transmission over a step-index plastic optical fiber (SI-POF) of 10-m length with a pulse-amplitude modulation (PAM). A multilayer perceptron-based equalizer is used to mitigate an intersymbol interference and non-linearity in the system. Using this equalizer with 32-PAM, a data rate of 10 Gb/s is achieved over the 10-m SI-POF at a bit error rate of 10^{-2}, which is below the 20% forward error correction limit.**

***Index Terms*— Polymer optical fiber (POF), multilayer perceptron (MLP), decision feedback equalizer, pulse amplitude modulation (PAM), non-linearity.**

I. Introduction

POLYMER optical fiber (POF) continues to gain prominence as a promising inexpensive medium for indoor networks due to its ease of installation and handling, resistance to electromagnetic interference (EMI) and its lower weight [1]. However, these advantages come at the cost of limited bandwidth-length product (45 MHz $\times$ 100 m) and high attenuation (0.15 dB/m at 650 nm wavelength) particularly for step index POF (SI-POF) [2].

A viable solution for the SI-POF limited bandwidth problem is to use multilevel pulse amplitude modulation (M-PAM) scheme with equalization techniques. With the availability of high power optical sources and sensitive linear receivers, multilevel signalling $\{M \in \; 2, 4, 8, 16, 32\}$ with the conventional decision feedback equalizer (DFE) has been used to achieve data transmission up to 5 Gbps via SI-POF of less than 20 m length [3], [4]. Another set of equalizers used in digital communication systems is the neural network (NN) equalizers and one major NN architecture is the multilayer perceptron (MLP). A comprehensive detail on MLP can be explored in [5]. A 3 layer perceptron based-DFE is illustrated in Fig. 1 with the sigmoid function used for the hidden layer neurons and the linear function used for the output layer neuron. A key advantage of MLP over the conventional equalizer is that it does not only compensate for intersymbol interference (ISI) but also non-linearities in the system [6]. Moreover, it has been shown from a simulation study that under severe ISI, MLP offers better bit-error rate (BER) performance than the conventional equalizer for a Gaussian fitted theoretical SI-POF channel [7].

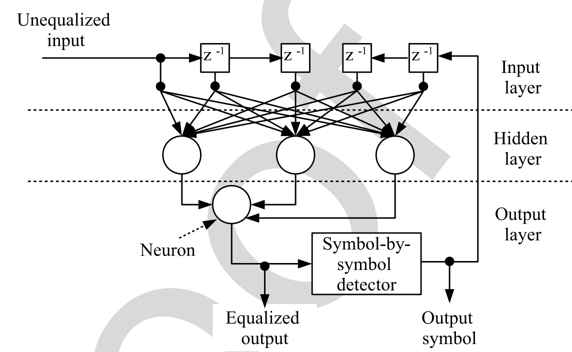

Fig. 1. Decision feedback equalizer structure with three forward taps and two feedback taps for MLP with three hidden layer neurons.

This letter therefore experiments M-PAM transmission over 10 m SI-POF with the MLP based DFE (MLP-DFE). In the experiment, a red laser diode (LD, L650P007, 650 nm wavelength, numerical aperture $\approx$ 0.15, 7 mW optical power) is used as the optical source. The receiver is the New Focus Model 1601 with a responsivity of 0.45 A/W and a noise equivalent power of 35 pW/Hz$^{\frac{1}{2}}$ at 650 nm wavelength. The conventional transversal DFE (TR-DFE) is also considered in this experiment for comparison purpose. The recursive least squares (RLS) algorithm with forgetting factor of one is used to train the TR-DFE while the Levenberg-Marquardart back propagation (LMBP) algorithm is used for the MLP-DFE.

II. The Experimental Set-Up

A block diagram illustrating the experimental set-up is shown in Fig. 2. It should be noted that the technique for coupling both the LD and receiver to the SI-POF is butt coupling [2], [8]. A simplified expression for the link's output signal $I_{rp}(t)$ is provided as:

$$I_{rp}(t) = \mathscr{R}_p \alpha_p (P_{opt}(t) \otimes h_{pch}(t)) + n_p(t), \qquad (1)$$

where $\mathscr{R}_p$ denotes the photodiode (PD) responsivity in A/W; α_p denotes the attenuation of the POF channel; $P_{opt}(t)$ denotes the optical signal from the LD; $h_{pch}(t)$ is the channel's impulse response; and $n_p(t)$ is the noise at the receiver. The end-to-end frequency response of the link is shown in Fig. 3, indicating a 3 dB bandwidth of $\sim$ 180 MHz.

The transmitted binary data is a uniformly distributed random data with a length of 10^6 bits. The binary data is M-PAM

Manuscript received March 5, 2018; revised March 29, 2018; accepted March 30, 2018. *(Corresponding author: Isaac N. Osahon.)*

The authors are with the LiFi Research and Development Centre, School of Engineering, Institute for Digital Communications, The University of Edinburgh, Edinburgh EH9 3JL, U.K. (e-mail: i.osahon@ed.ac.uk; majid.safari@ed.ac.uk; w.popoola@ed.ac.uk).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2018.2825146

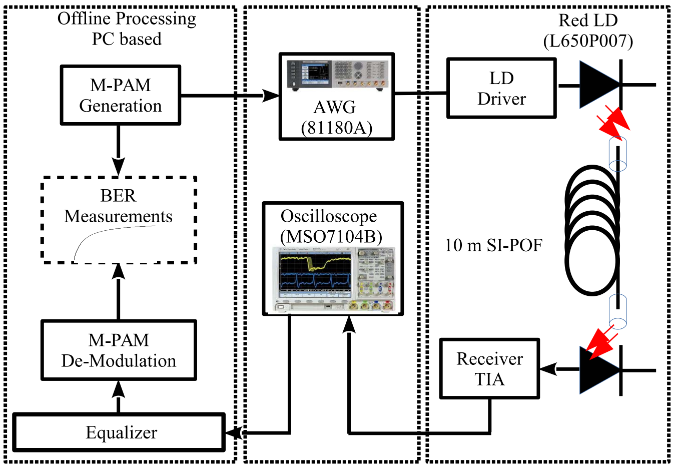

Fig. 2. Block diagram illustration for the Experiment.

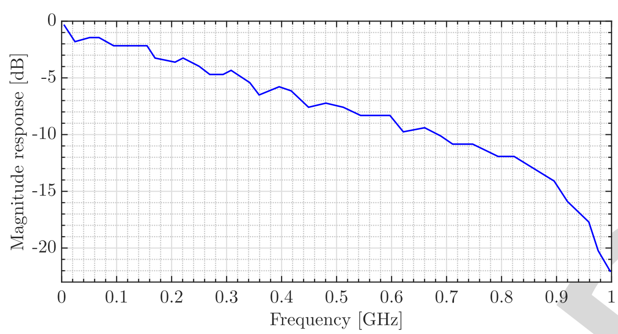

Fig. 3. Measured frequency response of the POF system.

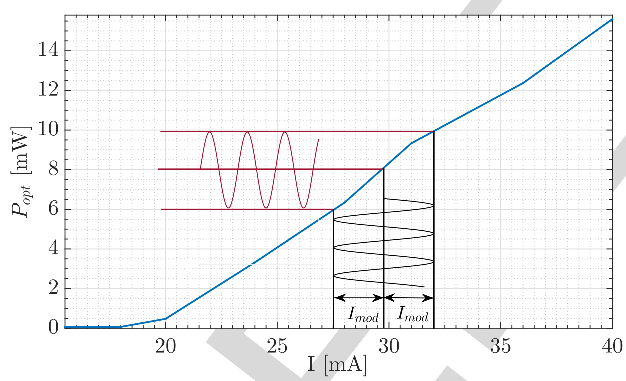

Fig. 4. Measured P-I curve of L650P007.

modulated by mapping $\log_2(M)$ bits to one of M amplitude levels with gray coding. The data symbols are preceded by a preamble of 4000 symbols that is used for synchronization at the receiver and for training the equalizer. The resulting symbol sequence is upsampled and fed through a digital pulse shaping filter, which for this work, is a root-raised-cosine filter with roll-off factor of 0.5. The modulated and pulse shaped signal is then loaded to an arbitrary waveform generator (AWG, Keysight 81180A).

The measured P-I curve of the LD is depicted in Fig. 4 and it shows the threshold current (I_{th}) of the LD to be 20 mA. The non-linearity of the LD is quantified by measuring its total harmonic distortion (THD). Fig. 5 shows the measured THD for the LD at different bias current (I_{bias}) and under peak modulating current (I_{mod}) of 5 mA and 7 mA. The THD in dBc is defined as:

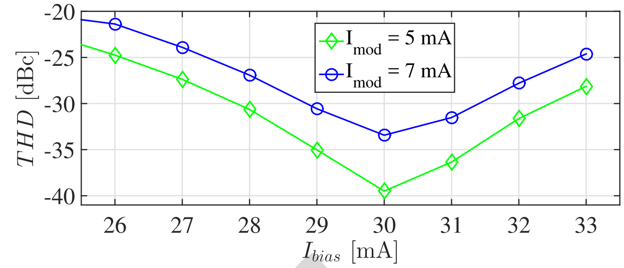

Fig. 5. LD's total harmonic distortion relative to I_{bias}.

$$THD = 10\log_{10}\left(\frac{1}{P_1}\sum_{n=2}^{\infty} P_n\right), \qquad (2)$$

where P_n is the power (in Watts) for the n^{th} harmonic with $n = 1$ being the fundamental frequency. The THD is obtained by measuring the power of the first five harmonics using a fundamental frequency of 40 MHz. The plots in Fig. 5 suggest that a bias current of 30 mA should be used for minimal non-linearity from the LD. Fig. 5 particularly shows that increasing I_{mod} increases the non-linearity of the LD, as the THD is about -33 dBc and -39 dBc when I_{mod} is 7 mA and 5 mA respectively. The LD is therefore biased at about 30 mA with $I_{mod} = 6.5$ mA resulting to an optical modulation index (η_{mod}) of 0.65, where $\eta_{mod} = \frac{I_{mod}}{I_{bias}-I_{th}}$. The LD's output is then transmitted through a 10 m SI-POF (HFBR-RUD500Z, core diameter = 1 mm) with a measured attenuation of ~1.8 dB at DC. The received optical signal from the SI-POF is converted into an electrical signal with the photo-receiver and the resulting signal is captured with an oscilloscope (MSO7104B). The captured signal is then imported into the PC for post-processing, which comprises of filtering, down-sampling and equalization. Finally, the equalized output is demodulated, thus offering the received binary data, that in turn is used to evaluate the bit-error-rate (BER).

III. Equalizer Parameters

The number of input taps and training examples are important parameters required for a DFE. The optimum number of taps for a DFE depends on the data rate and the PAM level. But for fair comparison under similar conditions, both DFEs have 22 forward taps and 18 feedback taps. To determine the optimum number of training examples for the DFEs, the BER is obtained for different training examples as shown in Fig. 6. The plots in Fig. 6 shows that while 2000 symbols are enough for the transversal DFE, the MLP-DFE requires at least 3000. Thus, 4000 training symbols are selected for both DFEs.

The number of hidden layer neurons is another parameter for MLP-DFE. For this study, it is chosen as six because there is no proper definition for optimum value to the best of the authors' knowledge.

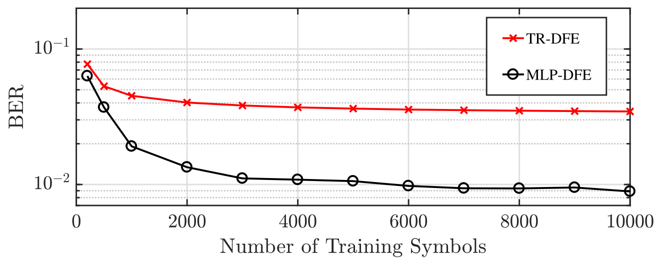

Fig. 6. BER plot comparing the equalizers' performance for different training symbols at a data rate of 10 Gbps with 32-PAM.

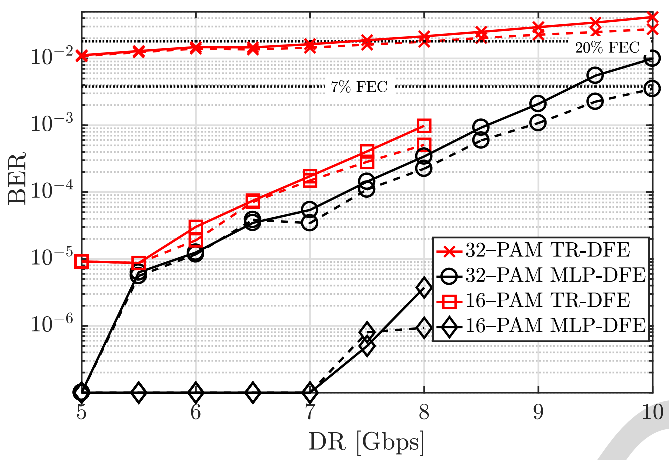

Fig. 7. BER plots comparing the MLP based DFE with the conventional DFE. The solid and dashed lines represents the BER if the feedback inputs for the DFEs are the detected and transmitted symbols respectively.

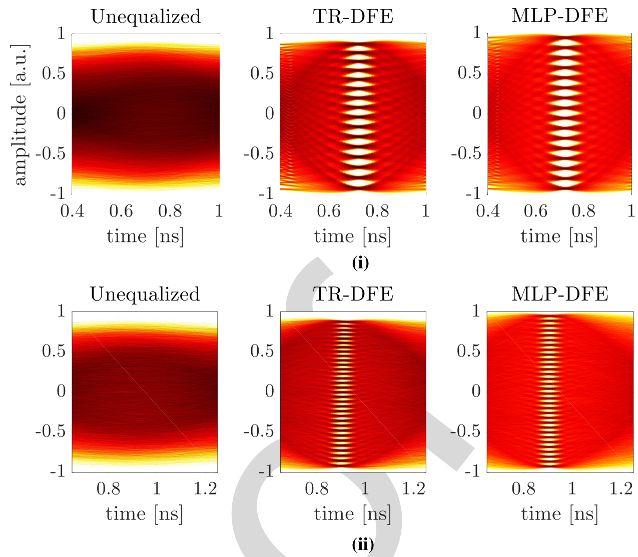

Fig. 8. Eye diagram comparing the equalizers' performance for 5.5 Gbps with: (i) 16–PAM (ii) 32–PAM.

TABLE I
PERFORMANCE OF REED-SOLOMON FEC CODE (RS-FEC) FOR 32-PAM

Parameters	**TR-DFE**	**MLP-DFE**	
Input BER	10^{-2}	10^{-2}	6×10^{-3}
Gross data rate	5 Gbps	10 Gbps	9.5 Gbps
RS-FEC {n,k}	{1023, 791}	{1023, 833}	{1023, 931}
Overhead [%]	22.68	18.57	8.99
Net data rate	3.87 Gbps	8.14 Gbps	8.65 Gbps
Output BER	$\approxeq 8.7 \times 10^{-8}$	$\approxeq 8.2 \times 10^{-8}$	$\approxeq 6.6 \times 10^{-8}$

IV. Results and Discussions

The maximum data rate at a given value of M is limited to $2\log_2(M)$ Gbps, because the maximum sampling rate of the AWG is 4 Gsa/s (from Nyquist theory). So, for $M = 4$ and $M = 8$, the maximum data rate is limited to 4 Gbps and 6 Gbps respectively. Therefore, 16-PAM and 32-PAM are considered owing to their higher spectral efficiency and the sufficient received SNR for the 10 m SI-POF. The BER plot for 16-PAM and 32-PAM is shown in Fig. 7. With 16-PAM, 8 Gbps is achieved at a BER of 10^{-3} with the TR-DFE. With the MLP-DFE however, the BER is $\sim 3.5 \times 10^{-6}$ at 8 Gbps data rate. For 32-PAM, the BER at 5.5 Gbps is about 10^{-2} using the TR-DFE, but this is below 10^{-5} with the MLP equalizer. A gross data rate of 10 Gbps is achieved with 32-PAM and the MLP equalizer at a BER of 10^{-2} which is below the 20% forward error correction (FEC) limit as Table I shows. Furthermore, the eye diagram in Fig. 8 clearly shows a wider eye opening with the MLP-DFE compared to the conventional DFE for 5.5 Gbps using both 16-PAM and 32-PAM.

A drawback of the DFE configuration is their susceptibility to error propagation due to occasional decision error of their input feedback symbols. To assess this error propagation effect on the conventional DFE and MLP-DFE, the BER result is also computed using the transmitted symbols as feedback data. This way, the feedback signal is always error free and therefore no error propagation occurs; the BER results are shown in dashed lines in Fig. 7. As expected, the effect of decision error on both DFEs becomes more significant with increasing data rate due to increasing ISI. The emphasis is therefore on the highest data rate to explore the effect of decision error on the DFEs. For 10 Gbps with 32–PAM, the BER achieved if the transmitted symbols (i.e no error propagation) are fed back to the conventional DFE is 0.03. This is similar to the BER when the detected symbols are fed back to the DFE. For MLP-DFE however, the BER is 3×10^{-3} when the correct symbols are fed back. And this is superior to the BER of 10^{-2} that is obtained when the feedback inputs to the MLP-DFE are the detected symbols. Consequently, the MLP based DFE is more prone to error propagation than the conventional DFE. With the error propagation effect however, FEC codes can still be used to improve the BER performance for both DFEs as Table I shows with the Reed-Solomon FEC code. With interleaving and more robust FEC schemes (e.g. turbo code and low-density parity check code), the BER performance can be further improved with less overhead.

Overall, the MLP-DFE offers superior performance than the TR-DFE for the 10 m SI-POF especially with 16–PAM and 32–PAM. This is attributed to the non-linear distortion from the system (including the LD) that is quantified with a THD of −33 dBc as Fig. 5 shows. The effect of this non-linear distortion is more significant at higher PAM level. However, MLP is more complex than the conventional equalizer as its computational cost is of the order $O(N_t N_{hn})$, while that of the conventional equalizer is $O(N_t)$, where N_t is the total number of taps for the equalizer and N_{hn} is the number of hidden layer neurons for the MLP equalizer. Furthermore, the LMBP algorithm for MLP has the computational order of $O(W^2 + WN_{tr})$, where $W \approx N_t N_{hn}$ is the number of synaptic weights for the MLP equalizer and N_{tr} is the number of training examples [5]. But the RLS algorithm for TR-DFE has the order of $O(N_t^2)$.

V. Conclusion

We have successfully shown that the MLP equalizer offers better performance than the conventional equalizers especially for POF systems with higher order of M-PAM. With 32–PAM and the MLP equalizer, 10 Gbps is achieved over 10 m SI-POF at a BER of 10^{-2}. To the best of the authors' knowledge, this is the highest recorded data rate for a single link SI-POF with PAM scheme.

References

[1] Y. Shi *et al.*, "Plastic-optical-fiber-based in-home optical networks," *IEEE Commun. Mag.*, vol. 52, no. 6, pp. 186–193, Jun. 2014.

[2] M. Atef and H. Zimmermann, *Optical Communication over Plastic Optical Fibers: Integrated Optical Receiver Technology*, vol. 172. Springer, 2012. AQ:1

[3] X. Li *et al.*, "μLED-based single-wavelength bi-directional POF link with 10 Gb/s aggregate data rate," *J. Lightw. Technol.*, vol. 33, no. 17, pp. 3571–3576, Sep. 1, 2015.

[4] R. Kruglov, S. Loquai, C.-A. Bunge, M. Schueppert, J. Vinogradov, and O. Ziemann, "Comparison of PAM and CAP modulation schemes for data transmission over SI-POF," *IEEE Photon. Technol. Lett.*, vol. 25, no. 23, pp. 2293–2296, Dec. 1, 2013.

[5] S. O. Haykin, *Neural Networks and Learning Machines*, vol. 3. Upper Saddle River, NJ, USA: Pearson, 2009.

[6] K. Burse, R. N. Yadav, and S. C. Shrivastava, "Channel equalization using neural networks: A review," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 40, no. 3, pp. 352–357, May 2010.

[7] I. N. Osahon, S. Rajbhandari, and W. O. Popoola, "Multi-layer perceptron as equalisers for multilevel pulse amplitude modulation scheme in SI-POF," in *Proc. IEEE Int. Conf. Students Appl. Eng. (ICSAE)*, Oct. 2016, pp. 318–322.

[8] O. Ziemann, J. Krauser, P. E. Zamzow, and W. [illegible] *POF Handbook: Optical Short Range Transmission Systems*. Springer, 2008. AQ:2

AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

PLEASE NOTE: We cannot accept new source files as corrections for your paper. If possible, please annotate the PDF proof we have sent you with your corrections and upload it via the Author Gateway. Alternatively, you may send us your corrections in list format. You may also upload revised graphics via the Author Gateway.

AQ:1 = Please provide the publisher location for ref. [2].

AQ:2 = Please note that the publisher name "Springer Science & Business Media" was changed to "Springer" for ref. [8]. Also provide the publisher location.

10-Gb/s Transmission Over 10-m SI-POF With M-PAM and Multilayer Perceptron Equalizer

Isaac N. Osahon, Majid Safari, and Wasiu O. Popoola

***Abstract*— We demonstrate the gigabit-per-second transmission over a step-index plastic optical fiber (SI-POF) of 10-m length with a pulse-amplitude modulation (PAM). A multilayer perceptron-based equalizer is used to mitigate an intersymbol interference and non-linearity in the system. Using this equalizer with 32-PAM, a data rate of 10 Gb/s is achieved over the 10-m SI-POF at a bit error rate of 10^{-2}, which is below the 20% forward error correction limit.**

***Index Terms*— Polymer optical fiber (POF), multilayer perceptron (MLP), decision feedback equalizer, pulse amplitude modulation (PAM), non-linearity.**

I. Introduction

POLYMER optical fiber (POF) continues to gain prominence as a promising inexpensive medium for indoor networks due to its ease of installation and handling, resistance to electromagnetic interference (EMI) and its lower weight [1]. However, these advantages come at the cost of limited bandwidth-length product (45 MHz $\times$ 100 m) and high attenuation (0.15 dB/m at 650 nm wavelength) particularly for step index POF (SI-POF) [2].

A viable solution for the SI-POF limited bandwidth problem is to use multilevel pulse amplitude modulation (M-PAM) scheme with equalization techniques. With the availability of high power optical sources and sensitive linear receivers, multilevel signalling $\{M \in 2, 4, 8, 16, 32\}$ with the conventional decision feedback equalizer (DFE) has been used to achieve data transmission up to 5 Gbps via SI-POF of less than 20 m length [3], [4]. Another set of equalizers used in digital communication systems is the neural network (NN) equalizers and one major NN architecture is the multilayer perceptron (MLP). A comprehensive detail on MLP can be explored in [5]. A 3 layer perceptron based-DFE is illustrated in Fig. 1 with the sigmoid function used for the hidden layer neurons and the linear function used for the output layer neuron. A key advantage of MLP over the conventional equalizer is that it does not only compensate for intersymbol interference (ISI) but also non-linearities in the system [6]. Moreover, it has been shown from a simulation study that under severe ISI, MLP offers better bit-error rate (BER) performance than the conventional equalizer for a Gaussian fitted theoretical SI-POF channel [7].

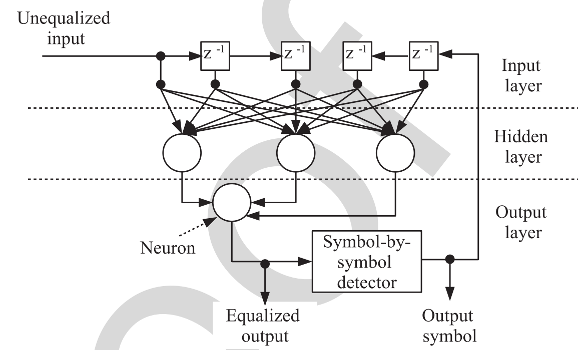

Fig. 1. Decision feedback equalizer structure with three forward taps and two feedback taps for MLP with three hidden layer neurons.

This letter therefore experiments M-PAM transmission over 10 m SI-POF with the MLP based DFE (MLP-DFE). In the experiment, a red laser diode (LD, L650P007, 650 nm wavelength, numerical aperture $\approx$ 0.15, 7 mW optical power) is used as the optical source. The receiver is the New Focus Model 1601 with a responsivity of 0.45 A/W and a noise equivalent power of 35 pW/Hz$^{\frac{1}{2}}$ at 650 nm wavelength. The conventional transversal DFE (TR-DFE) is also considered in this experiment for comparison purpose. The recursive least squares (RLS) algorithm with forgetting factor of one is used to train the TR-DFE while the Levenberg-Marquardart back propagation (LMBP) algorithm is used for the MLP-DFE.

II. The Experimental Set-Up

A block diagram illustrating the experimental set-up is shown in Fig. 2. It should be noted that the technique for coupling both the LD and receiver to the SI-POF is butt coupling [2], [8]. A simplified expression for the link's output signal $I_{rp}(t)$ is provided as:

$$I_{rp}(t) = \mathscr{R}_p \alpha_p (P_{opt}(t) \otimes h_{pch}(t)) + n_p(t), \qquad (1)$$

where $\mathscr{R}_p$ denotes the photodiode (PD) responsivity in A/W; α_p denotes the attenuation of the POF channel; $P_{opt}(t)$ denotes the optical signal from the LD; $h_{pch}(t)$ is the channel's impulse response; and $n_p(t)$ is the noise at the receiver. The end-to-end frequency response of the link is shown in Fig. 3, indicating a 3 dB bandwidth of $\sim$ 180 MHz.

The transmitted binary data is a uniformly distributed random data with a length of 10^6 bits. The binary data is M-PAM

Manuscript received March 5, 2018; revised March 29, 2018; accepted March 30, 2018. *(Corresponding author: Isaac N. Osahon.)*

The authors are with the LiFi Research and Development Centre, School of Engineering, Institute for Digital Communications, The University of Edinburgh, Edinburgh EH9 3JL, U.K. (e-mail: i.osahon@ed.ac.uk; majid.safari@ed.ac.uk; w.popoola@ed.ac.uk).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2018.2825146

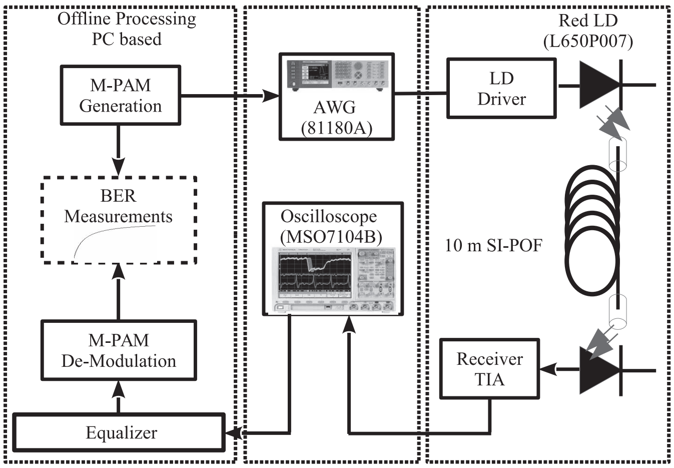

Fig. 2. Block diagram illustration for the Experiment.

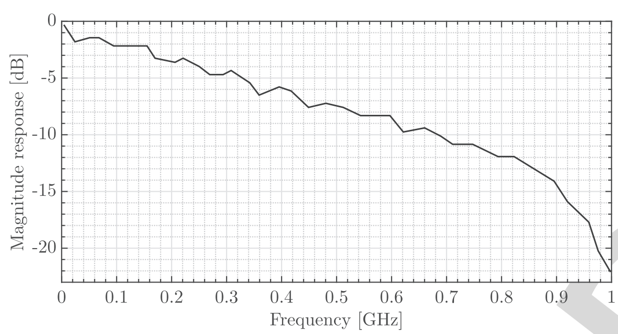

Fig. 3. Measured frequency response of the POF system.

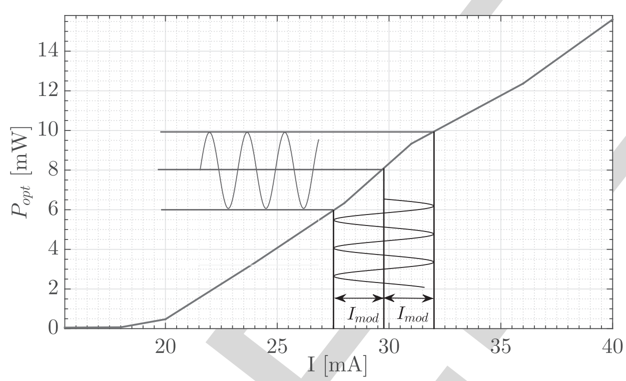

Fig. 4. Measured P-I curve of L650P007.

modulated by mapping $\log_2(M)$ bits to one of M amplitude levels with gray coding. The data symbols are preceded by a preamble of 4000 symbols that is used for synchronization at the receiver and for training the equalizer. The resulting symbol sequence is upsampled and fed through a digital pulse shaping filter, which for this work, is a root-raised-cosine filter with roll-off factor of 0.5. The modulated and pulse shaped signal is then loaded to an arbitrary waveform generator (AWG, Keysight 81180A).

The measured P-I curve of the LD is depicted in Fig. 4 and it shows the threshold current (I_{th}) of the LD to be 20 mA. The non-linearity of the LD is quantified by measuring its

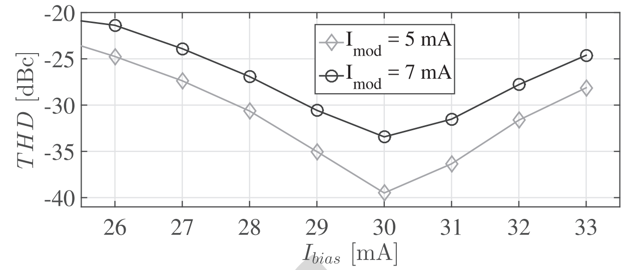

Fig. 5. LD's total harmonic distortion relative to I_{bias}.

total harmonic distortion (THD). Fig. 5 shows the measured THD for the LD at different bias current (I_{bias}) and under peak modulating current (I_{mod}) of 5 mA and 7 mA. The THD in dBc is defined as:

$$THD = 10\log_{10}\left(\frac{1}{P_1}\sum_{n=2}^{\infty} P_n\right), \tag{2}$$

where P_n is the power (in Watts) for the n^{th} harmonic with $n = 1$ being the fundamental frequency. The THD is obtained by measuring the power of the first five harmonics using a fundamental frequency of 40 MHz. The plots in Fig. 5 suggest that a bias current of 30 mA should be used for minimal non-linearity from the LD. Fig. 5 particularly shows that increasing I_{mod} increases the non-linearity of the LD, as the THD is about -33 dBc and -39 dBc when I_{mod} is 7 mA and 5 mA respectively. The LD is therefore biased at about 30 mA with $I_{mod} = 6.5$ mA resulting to an optical modulation index (η_{mod}) of 0.65, where $\eta_{mod} = \frac{I_{mod}}{I_{bias}-I_{th}}$. The LD's output is then transmitted through a 10 m SI-POF (HFBR-RUD500Z, core diameter = 1 mm) with a measured attenuation of ~1.8 dB at DC. The received optical signal from the SI-POF is converted into an electrical signal with the photo-receiver and the resulting signal is captured with an oscilloscope (MSO7104B). The captured signal is then imported into the PC for post-processing, which comprises of filtering, down-sampling and equalization. Finally, the equalized output is demodulated, thus offering the received binary data, that in turn is used to evaluate the bit-error-rate (BER).

III. Equalizer Parameters

The number of input taps and training examples are important parameters required for a DFE. The optimum number of taps for a DFE depends on the data rate and the PAM level. But for fair comparison under similar conditions, both DFEs have 22 forward taps and 18 feedback taps. To determine the optimum number of training examples for the DFEs, the BER is obtained for different training examples as shown in Fig. 6. The plots in Fig. 6 shows that while 2000 symbols are enough for the transversal DFE, the MLP-DFE requires at least 3000. Thus, 4000 training symbols are selected for both DFEs.

The number of hidden layer neurons is another parameter for MLP-DFE. For this study, it is chosen as six because there is no proper definition for optimum value to the best of the authors' knowledge.

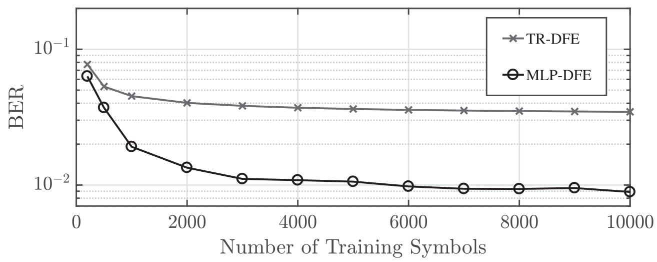

Fig. 6. BER plot comparing the equalizers' performance for different training symbols at a data rate of 10 Gbps with 32-PAM.

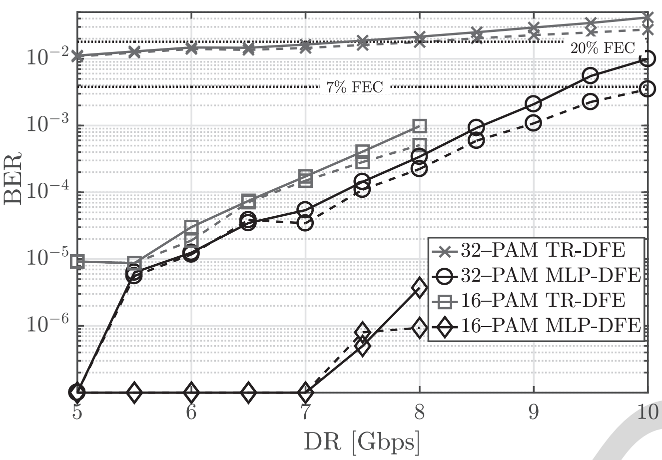

Fig. 7. BER plots comparing the MLP based DFE with the conventional DFE. The solid and dashed lines represents the BER if the feedback inputs for the DFEs are the detected and transmitted symbols respectively.

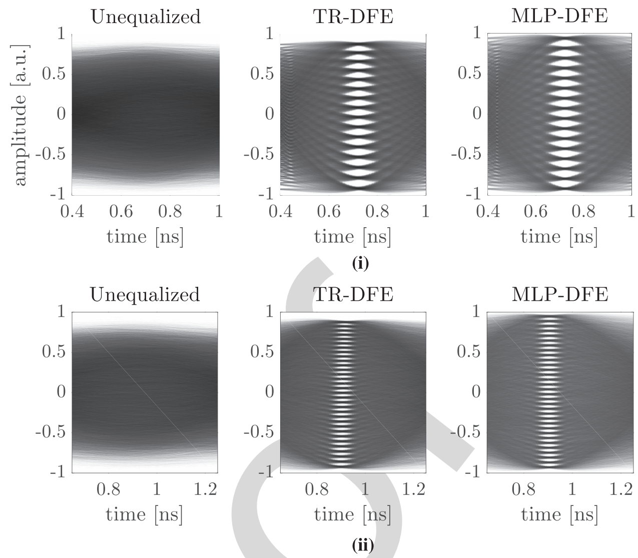

Fig. 8. Eye diagram comparing the equalizers' performance for 5.5 Gbps with: (i) 16–PAM (ii) 32–PAM.

TABLE I

PERFORMANCE OF REED-SOLOMON FEC CODE (RS-FEC) FOR 32-PAM

Parameters	**TR-DFE**	**MLP-DFE**	
Input BER	10^{-2}	10^{-2}	6×10^{-3}
Gross data rate	5 Gbps	10 Gbps	9.5 Gbps
RS-FEC {n,k}	{1023, 791}	{1023, 833}	{1023, 931}
Overhead [%]	22.68	18.57	8.99
Net data rate	3.87 Gbps	8.14 Gbps	8.65 Gbps
Output BER	$\approxeq 8.7 \times 10^{-8}$	$\approxeq 8.2 \times 10^{-8}$	$\approxeq 6.6 \times 10^{-8}$

IV. RESULTS AND DISCUSSIONS

The maximum data rate at a given value of M is limited to $2\log_2(M)$ Gbps, because the maximum sampling rate of the AWG is 4 Gsa/s (from Nyquist theory). So, for $M = 4$ and $M = 8$, the maximum data rate is limited to 4 Gbps and 6 Gbps respectively. Therefore, 16-PAM and 32-PAM are considered owing to their higher spectral efficiency and the sufficient received SNR for the 10 m SI-POF. The BER plot for 16-PAM and 32-PAM is shown in Fig. 7. With 16-PAM, 8 Gbps is achieved at a BER of 10^{-3} with the TR-DFE. With the MLP-DFE however, the BER is $\sim 3.5 \times 10^{-6}$ at 8 Gbps data rate. For 32-PAM, the BER at 5.5 Gbps is about 10^{-2} using the TR-DFE, but this is below 10^{-5} with the MLP equalizer. A gross data rate of 10 Gbps is achieved with 32-PAM and the MLP equalizer at a BER of 10^{-2} which is below the 20% forward error correction (FEC) limit as Table I shows. Furthermore, the eye diagram in Fig. 8 clearly shows a wider eye opening with the MLP-DFE compared to the conventional DFE for 5.5 Gbps using both 16-PAM and 32-PAM.

A drawback of the DFE configuration is their susceptibility to error propagation due to occasional decision error of their input feedback symbols. To assess this error propagation effect on the conventional DFE and MLP-DFE, the BER result is also computed using the transmitted symbols as feedback data. This way, the feedback signal is always error free and therefore no error propagation occurs; the BER results are shown in dashed lines in Fig. 7. As expected, the effect of decision error on both DFEs becomes more significant with increasing data rate due to increasing ISI. The emphasis is therefore on the highest data rate to explore the effect of decision error on the DFEs. For 10 Gbps with 32–PAM, the BER achieved if the transmitted symbols (i.e no error propagation) are fed back to the conventional DFE is 0.03. This is similar to the BER when the detected symbols are fed back to the DFE. For MLP-DFE however, the BER is 3×10^{-3} when the correct symbols are fed back. And this is superior to the BER of 10^{-2} that is obtained when the feedback inputs to the MLP-DFE are the detected symbols. Consequently, the MLP based DFE is more prone to error propagation than the conventional DFE. With the error propagation effect however, FEC codes can still be used to improve the BER performance for both DFEs as Table I shows with the Reed-Solomon FEC code. With interleaving and more robust FEC schemes (e.g. turbo code and low-density parity check code), the BER performance can be further improved with less overhead.

Overall, the MLP-DFE offers superior performance than the TR-DFE for the 10 m SI-POF especially with 16–PAM and 32–PAM. This is attributed to the non-linear distortion from the system (including the LD) that is quantified with a THD of -33 dBc as Fig. 5 shows. The effect of this non-linear distortion is more significant at higher PAM level. However, MLP is more complex than the conventional equalizer as its computational cost is of the order $O(N_t N_{hn})$, while that of the conventional equalizer is $O(N_t)$, where N_t is the total number of taps for the equalizer and N_{hn} is the number of hidden layer neurons for the MLP equalizer. Furthermore, the LMBP algorithm for MLP has the computational order of $O(W^2 + WN_{tr})$, where $W \approx N_t N_{hn}$ is the number of synaptic weights for the MLP equalizer and N_{tr} is the number of training examples [5]. But the RLS algorithm for TR-DFE has the order of $O(N_t^2)$.

V. Conclusion

We have successfully shown that the MLP equalizer offers better performance than the conventional equalizers especially for POF systems with higher order of M-PAM. With 32–PAM and the MLP equalizer, 10 Gbps is achieved over 10 m SI-POF at a BER of 10^{-2}. To the best of the authors' knowledge, this is the highest recorded data rate for a single link SI-POF with PAM scheme.

References

[1] Y. Shi *et al.*, "Plastic-optical-fiber-based in-home optical networks," *IEEE Commun. Mag.*, vol. 52, no. 6, pp. 186–193, Jun. 2014.

[2] M. Atef and H. Zimmermann, *Optical Communication over Plastic Optical Fibers: Integrated Optical Receiver Technology*, vol. 172. Springer, 2012. AQ:1

[3] X. Li *et al.*, "μLED-based single-wavelength bi-directional POF link with 10 Gb/s aggregate data rate," *J. Lightw. Technol.*, vol. 33, no. 17, pp. 3571–3576, Sep. 1, 2015.

[4] R. Kruglov, S. Loquai, C.-A. Bunge, M. Schueppert, J. Vinogradov, and O. Ziemann, "Comparison of PAM and CAP modulation schemes for data transmission over SI-POF," *IEEE Photon. Technol. Lett.*, vol. 25, no. 23, pp. 2293–2296, Dec. 1, 2013.

[5] S. O. Haykin, *Neural Networks and Learning Machines*, vol. 3. Upper Saddle River, NJ, USA: Pearson, 2009.

[6] K. Burse, R. N. Yadav, and S. C. Shrivastava, "Channel equalization using neural networks: A review," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 40, no. 3, pp. 352–357, May 2010.

[7] I. N. Osahon, S. Rajbhandari, and W. O. Popoola, "Multi-layer perceptron as equalisers for multilevel pulse amplitude modulation scheme in SI-POF," in *Proc. IEEE Int. Conf. Students Appl. Eng. (ICSAE)*, Oct. 2016, pp. 318–322.

[8] O. Ziemann, J. Krauser, P. E. Zamzow, and W. [illegible] *POF Handbook: Optical Short Range Transmission Systems*. Springer, 2008. AQ:2

AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

PLEASE NOTE: We cannot accept new source files as corrections for your paper. If possible, please annotate the PDF proof we have sent you with your corrections and upload it via the Author Gateway. Alternatively, you may send us your corrections in list format. You may also upload revised graphics via the Author Gateway.

AQ:1 = Please provide the publisher location for ref. [2].
AQ:2 = Please note that the publisher name "Springer Science & Business Media" was changed to "Springer" for ref. [8]. Also provide the publisher location.