Statistical Investigations of Optical OFDM Adaptive Loading Algorithm over 1000 Worst-Case MMFs

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Abstract: Bit-and-power-loading(BPL) [power-loading (PL)] offers the best (worst) performance. For MMFs of <300m PL is effective for escalating an optical OFDM MMF link performance to its maximum potential; for longer MMFs, BPL has to be adopted.

OCIS codes: (060.2330) Fibre optics communications; (060.2630) Frequency modulation

1. Introduction

It is well known that, for a specific intensity-modulation and direct-detection (IMDD) optical OFDM (OOFDM) system, to maximize its transmission performance and simultaneously improve the flexibility and robustness, full use can be made of various adaptive loading algorithms on each individual subcarrier, according to the SNR experienced by the subcarrier [1]. The widely adopted adaptive loading algorithms include bit-loading (BL), power-loading (PL) and bit-and-power-loading (BPL). In the BL algorithm [2], different signal modulation formats are taken on individual subcarriers which have identical electrical powers. In the PL algorithm [1], electrical subcarrier powers are manipulated with the same signal modulation format being taken on all the subcarriers. In the BPL algorithm [3], both the power and signal modulation format of each individual subcarrier are adjusted independently. Of these three algorithms, the BPL algorithm has the ability of achieving the largest signal bit rate, but it suffers from the highest level of computational complexity and requires sophisticated OOFDM transceiver designs to accommodate variations in both the number of bits per symbol and the selective modulation formats [1]. On the other hand, as a direct result of the least computational complexity and the simplest OOFDM transceiver architecture, the PL algorithm has been successfully implemented experimentally in end-to-end real-time OOFDM transceivers at 11.25Gb/s [1], where comparisons between theoretical results and experimental measurements have also been made, which indicate that there exists small difference between the BPL-enabled highest signal bit rate and the PL-enabled lowest signal bit rate, for SMF links of up to 100 km [1].

As the above-mentioned statement has huge potential for practical cost-effective OOFDM transceiver architecture design, detailed explorations of the validity of the statement in arbitrary transmission links are of great importance. Considering the fact that the IMDD SMF links have very simple system frequency responses, the employment of legacy MMFs with more complicated system frequency responses are therefore essential. As different MMF links reveal large variations in both the 3-dB bandwidths and the system frequency responses [4], any explorations of such a topic over a specific MMF link are not adequate. In this paper, statistical investigations of the performance of these three adaptive loading algorithms are undertaken, for the first time, over 1000 statistically constructed worst-case MMF links. The use of the worst-case MMF links is because their frequency responses have more unpredictable peaks and nulls occurring within the signal spectral region.

2. Statistical worst-case MMF construction

Typical single-channel, optical amplifier-free, IMDD links involving directly modulated DFB lasers (DMLs) are considered [2,4], each of which consists of an OOFDM transmitter and receiver connected by worst-case MMFs, whose system frequency responses are statistically constructed following the procedures presented in [4]. The impulse response of a MMF link can be expressed by:

$$h(t) = \sum_{m=1}^{1000} \beta_m \cdot g(t - \tau_m) \tag{1}$$

where *g(t)* is the optical pulse corresponding to an excited optical mode; M is the total number of optical modes propagating simultaneously through the link, τ_m and β_m are the time delay and the amplitude of the m-th optical mode. To statistically construct worst-case MMF impulse responses, the following assumptions are adopted [4]: 1) Optical modes having Gaussian pulse shapes; 2) Uniform time delay distribution with respect to an average time delay with a maximum time deviation being half of the maximum DMDs of 2 ns/km. Such a DMD value can represent the worst 5% of all fibre links operating at long wavelengths; 3) Identical mode power distribution across all excited optical modes. The adoption of all the aforementioned assumptions gives that the 3-dB optical bandwidths of all the constructed worst-case MMF links are much smaller than the standard bandwidth-length production of 500 MHz•km. The worst-case impulse responses are constructed under a specific transmission distance of say 300m, then these impulse responses are scaled linearly using the transmission distance required.

In simulating the OOFDM transceivers, the DAC/ADC operates at an optimum 7-bit resolution and a 12.5GS/s sampling rate. The clipping level is fixed at 13 dB and the cyclic prefix parameter is fixed at 25%. Since the influence of optical nonlinearities induced by a DML under optimum operating conditions is negligible on the transmission performance of OOFDM signals over MMFs [4], an ideal optical intensity modulator at 1550nm is thus considered, which is assumed to produce a 5dBm optical power coupled into a MMF. In the OOFDM receiver, a square-law photon-detector is employed, which has a quantum efficiency of 0.8 and a sensitivity of -19dBm. The impact of modal noise is not considered [4].

3. Implementation of adaptive loading algorithms

In numerical simulations, the PL and BL algorithms are implemented using the approaches reported in [1] and [4], respectively. The BPL algorithm is implemented following the procedure detailed in [3]. For fair comparisons between these algorithms, it is worth highlighting the following three aspects: a) for a given transmission system, the total electrical signal powers generated by all the algorithms are set to be identical, and comparisons of maximum achievable transmission capacity at a BER of 1.0×10^{-3} are made; b) signal modulation formats vary from DBPSK, DQPSK, 8-QAM to 256-QAM, and c) any subcarrier suffering a very low SNR may be dropped completely if the following condition is met: for the PL algorithm only, the detected errors are too large to achieve the required total channel BER; for the BL and BPL algorithms, the detected errors are too large to achieve the required total channel BER even when the lowest modulation format is employed.

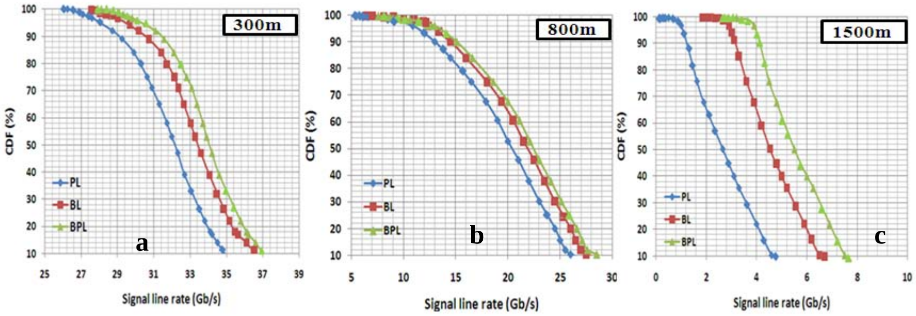

Fig. 1. CDF of signal transmission capacity employing 32 subcarriers for the PL, BL and BPL algorithms over 1000 statistically constructed worst-case MMF links of different transmission distances: (a) 300m, (b) 800m, and (c) 1500m.Experimental system setup

4. Statistical performance

For different adaptive loading algorithms, Fig.1 (a)-(b) show the cumulative density function (CDF) versus signal line rate for 1000 worst-case MMF links of lengths of 300m, 800m and 1500m, respectively. In obtaining Fig.1, the number of subcarriers in the positive frequency bins is fixed at 32. As expected from [1], for all the MMF links, the BPL (PL) algorithm always offers the best (worst) transmission performance. Similar behaviors can also be found in Fig.2 and Fig.3. The worst performance associated with the PL algorithm is due to the fact that the PL algorithm leads to the largest number of subcarriers being dropped. It can also be seen in Fig.1 that the signal transmission capacity differences between the BPL and PL algorithms are independent of signal bit rate, and such differences become slightly larger for longer transmission distances. The aforementioned evolution trends agree very well with the experimental measurements [1]. More importantly, along with the long transmission distance-induced reduction in signal transmission capacity, the relative transmission capacity difference between the BPL and PL algorithms increases from ~7% to ~35% when the MMF lengths are extended from 300m to 1500m, as seen in Fig.1. This implies that, for a fixed OOFDM signal spectral width, a reduction in 3-dB link bandwidth plays an important role in determining the effectiveness of these algorithms. Fig.1 also indicates that, for both worst-case and normal-case MMF links of less than 300m, the simplest PL algorithm can be considered to be an effective means of escalating the OOFDM MMF link performance to its maximum potential; whilst for MMF links of longer than 800m, it is worth considering the sophisticated BPL algorithm.

For the DAC/ADC sampling rates of Rs=12.5GS/s, the CDF as a function of signal line rate is plotted in Fig.2 for different Ns. In computing Fig.2, the transmission distances are taken to be 1500m to reveal large transmission capacity differences between these algorithms. It is shown in Fig. 2 that, with increasing Ns from 32 to 128, a five-fold increase in achievable transmission capacity occurs. The large Ns -induced transmission capacity enhancement is a direct result of an increased CP duration [2]. In addition, with increasing Ns from 32 to 128, the transmission capacity difference between the BPL (best) and PL (worst) algorithms decreases from 35% to 17%. This indicates that, compared to the BPL algorithm, a large number of subcarriers can improve the effectiveness of the PL algorithm.

The impacts of DAC/ADC sampling rate on the performance of these algorithms are presented in Fig.3, in which N_s=128 and worst-case MMF lengths of 1500m are adopted. It can be seen in Fig.3 that, as the sampling rate increases from 12.5 GS/s to 20 GS/s, the transmission capacity difference between the PL (worst) and BPL (best) algorithms grows from 4Gb/s to 11.5Gb/s, giving rise to an 12% enlarged relative transmission capacity difference between the two algorithms. This is because: a high sampling rate-induced wider signal spectral width allows low signal modulation formats to be taken on high frequency subcarriers when the PL algorithm is applied. Clearly, a large sampling rate degrades the performance of the PL algorithm. Moreover, for MMF links capable of supporting the BL-enabled signal bit rates of 40Gb/s at a DAC/ADC sampling rate of 20GS/s, their corresponding averaged 3-dB MMF bandwidths are roughly 0.5GHz [5]. This implies that the use of the BPL algorithm is essential when the 3-dB link bandwidths are less than 5% of the OOFDM signal spectrum.

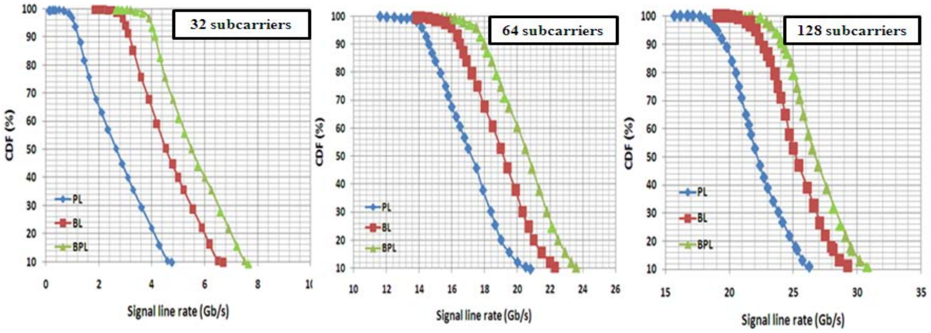

Fig. 2: CDF of signal transmission capacity at 1500m for the PL, BL and BPL algorithms in 1000 statistically constructed worst-case MMF links for different subcarrier numbers:(a) 32, (b) 64, and (c) 128.

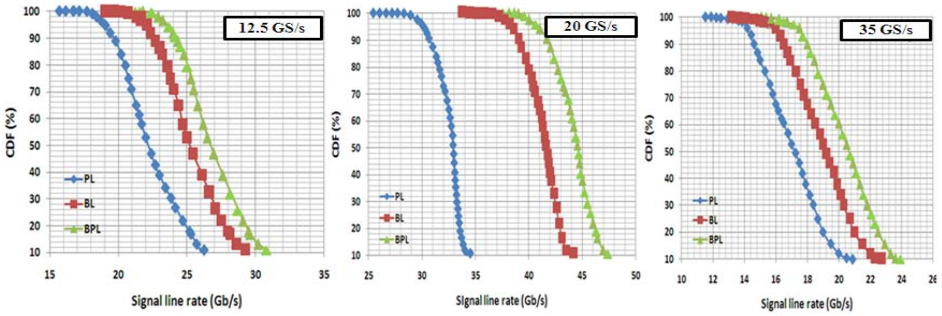

Fig. 3: CDF of signal transmission capacity employing 128 subcarriers at 1500m for the PL, BL and BPL algorithms in 1000 statistically constructed worst-case MMF links for different sampling speeds: (a) 12.5GS/s, (b) 20GS/s, and (c) 35GS/s.

In addition, Fig.3 also shows that, for very high sampling rates of >35GS/s, both the signal transmission capacities for all these three algorithms and the relative transmission capacity differences between them are reduced significantly. The physical mechanisms are: firstly, the rapid decay of the MMF frequency response at high frequencies gives rise to large losses for subcarriers located at the high frequency edge of the broad OOFDM signal spectrum, and hence low signal modulation formats and/or subcarrier dropping have to be applied on these subcarriers. Secondly, a fast sampling rate corresponds to a short CP duration, thus weakens the OOFDM capability of combating the DMD effect.

5. Conclusion

It has been shown that the BPL (PL) algorithm always offers the best (worst) transmission performance. The relative transmission capacity difference between the BPL and PL algorithms significantly decreases for short MMF lengths, large number of subcarriers and low DAC/ADC sampling rates. Numerical results have also indicated that, for MMF links of less than 300m, in comparison with the sophisticated BPL algorithm, the simplest PL algorithm can be considered as an effective means of escalating the OOFDM MMF link performance to its maximum potential, the effectiveness of the PL algorithm can be further improved when a large number of subcarriers are used. Whilst for relatively long MMF links with 3-dB bandwidths much less than the transmitted OOFDM signal spectrum, the BPL algorithm has to be adopted.

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Acknowledgments

This work was partly supported by the EC's Seventh Framework Programme (FP7/2007-2013) within the project ICT ALPHA under grant agreement n° 212 352, and in part by the A4B E2 project.