Optical OFDM for the Data Center

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ABSTRACT

We investigated the use of orthogonal frequency division multiplexing (OFDM) to increase the capacity of multimode fiber (MMF)-based optical interconnects for data center applications. This approach provides a solution to modulation bandwidth limitations of the lasers, and to the intermodal dispersion of the MMF which leads to frequency-dependent attenuation. Recent studies on adaptively modulated OFDM are reviewed, and new simulation results assessing the capacity of such links for lengths of up to 300 m are presented, assuming the use of 50/125 μm graded-index MMF at a wavelength of 850 nm. The use of coded OFDM as an approach to deal with intermodal dispersion is also discussed.

Keywords: optical OFDM, multimode fiber, optical interconnects.

1. INTRODUCTION

New applications, particularly video, continue to increase bandwidth requirements in data centers and computer clusters. Recent top performing supercomputers are increasingly relying on optical interconnects [1, 2]. Data center architects, in a traditionally lower cost environment, are also looking to optical interconnects to relieve bandwidth bottlenecks. Standard interconnects in data centers and high performance computing are based on directly modulated 850 nm vertical cavity surface emitting lasers (VCSELs) transmitting over multimode fibers (MMF) with direct-detection [3]. These links are short compared to typical telecommunication distances. The longest links are expected to reach up to 300 m in large data center warehouses with most being considerably shorter. In current supercomputers, the rack-to-rack links are typically less than 30m, the longest being 100 m [4]. As bandwidth demand increases and the transceivers become more tightly coupled to the compute boards for cost and power consumption, various methods have been proposed and investigated to increase the data rate using low cost optical hardware; i) increasing the modulation rate of the laser, ii) using multiple transceivers (and fibers) in parallel [1-4], and iii) using advanced signal formats with more than one bit/symbol. We have considered the latter approach, specifically optical orthogonal frequency division multiplexing (OFDM) with high-order modulation formats [5], as a technique to enable transmission at higher data rates over the longer distances without increasing the number of optical components required. Recently, several studies confirming the practical viability of real-time DSP for multi-gigabit per second optical OFDM signal generation and detection have been published [6-9]. Alongside this work, there is a need to obtain a better understanding of the properties of multimode fiber and its effect on OFDM signal transmission to exploit the capabilities of this technology to achieve upcoming performance requirements.

The challenge with MMF is that multiple optical modes exist, which propagate with different group velocities. Even over short distances, the resulting differential modal delay (DMD) gives rise to severe intersymbol interference with conventional single carrier signal formats, while in OFDM the orthogonal channels experience frequency selective attenuation. In this way, equalization consists only of (complex) scalar multiplication in OFDM, but since some channels can be in deep fades, their high error rate will dominate the total bit error rate. In wireless OFDM-based systems, such as digital audio/video broadcast, strong forward error correction (FEC) is used to correct these errors, but this might be too expensive or energy consuming for data center applications. Instead, the relative stability of DMD in comparison to wireless channels makes adaptive modulation attractive, in which power and/or modulation format of each sub-carrier can be adaptively selected at the transmitter to achieve a uniform bit error rate at the receiver. In this paper, we review recent studies on the application of optical OFDM in MMF interconnects, present results of calculations of the capacity of adaptively modulated OFDM interconnects, and discuss the suitability of this technology for data center applications.

2. ADAPTIVELY MODULATED OFDM

A number of numerical and experimental studies of optical OFDM transmission over MMF have recently been reported in the literature, e.g. [5, 10-14]. In one of the most comprehensive studies, Jin *et al.* carried out a statistical investigation of the transmission performance of optical OFDM in MMF-based links by numerical simulation [12]. 1000 worst-case MMF links with 3 dB bandwidths varying between 220 and 490 MHz.km were considered. OFDM signals with 31 sub-channels were generated with a directly modulated laser. In this study, adaptive modulation was used, where, for each sub-carrier, the modulation format was chosen according to its SNR, from DBPSK, DQPSK, 16 to 256-QAM or no data. All sub-carriers carrying data had the same (average) power. Numerical simulations were performed in a statistical study with a large number of worst-case MMF transfer functions, showing that with optical OFDM, a capacity of more than 30 Gbit/s over 300 meters could be achieved for over 99.5% of MMF, based on links installed today. 100 Gbit/s capacity could be supported in 99.5% of links of 150 meters length

Lee *et al.* experimentally demonstrated OFDM transmission over 500 m and 1 km of MMF [13]. The system used a directly modulated VCSEL operating at 850 nm. Using higher order modulation formats, the link capacity was 30 Gbit/s over 500 m, with 256 sub-carriers and 20 GS/s signal converter sampling rate. As described above, the QAM order was selected based on the SNR on each sub-carrier, varying from 2 to 7 bits per symbol. The BER averaged across all channels was 2.5×10^{-4}, which, through the use of a standard Reed-Solomon FEC code, would be reduced to below 10^{-10}.

We carried out numerical simulations assessing interconnect capacity using adaptively modulated OFDM, based on the model of signal propagation through MMF described in [14] and [15]. The considered system consisted of a 50/125 μm graded-index fiber with a refractive index profile approximated by a single α-factor varying between 2.02 and 2.06. A VCSEL-like light source was assumed with a spectral line-width of 10 MHz and an 850 nm wavelength with overfilled launching condition. The chromatic dispersion at this wavelength was -94 ps/nm.km and the fiber attenuation was 2.3 dB/km. Transmission of a single-band adaptively modulated OFDM signal over this MMF was simulated, assuming 28 GS/s DSP, 128 point (I)FFT cores which, with 1.28 oversampling, provided up to 50 discrete multitone (DMT) subcarriers. The power at the receiver was assumed to be +1 dBm. Figure 2 (left) shows the fiber frequency response after 300 m (α = 2.06) where modal coupling and differential mode attenuation were neglected. The graph also shows the modulation format used on each band or group of subcarriers to guarantee a BER of less than 10^{-3}. The overall bit-rate achieved over 300 m was 41.7 Gbit/s. This bitrate may be increased by improving the refractive index profile (α-factor). Figure 2 (right) shows the maximum achievable bit-rate as a function of fiber length for α = 2.02 and 2.06. The frequency response of the fiber is flat over a longer distance when α = 2.02, and the bit-rate increases to 48.5 Gbit/s at 300 m.

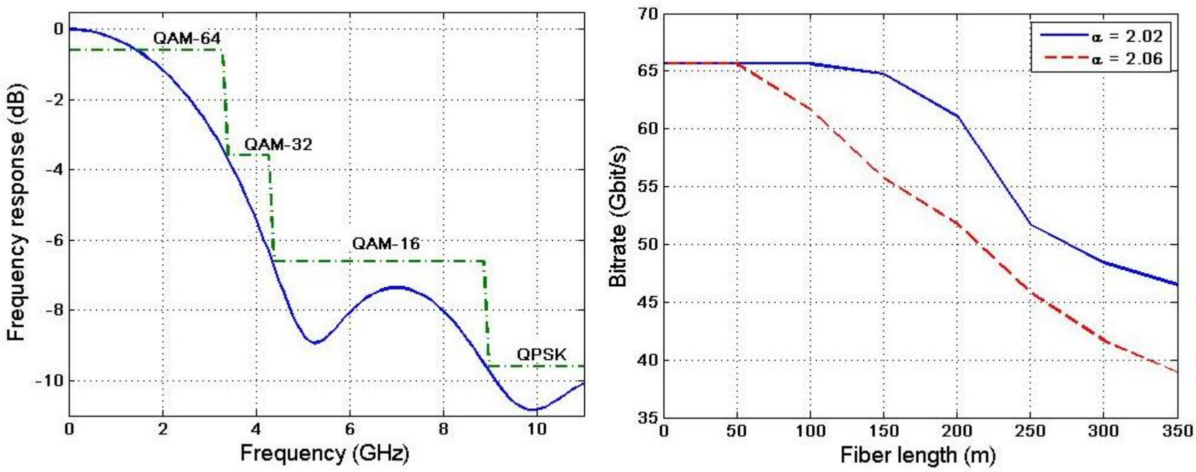
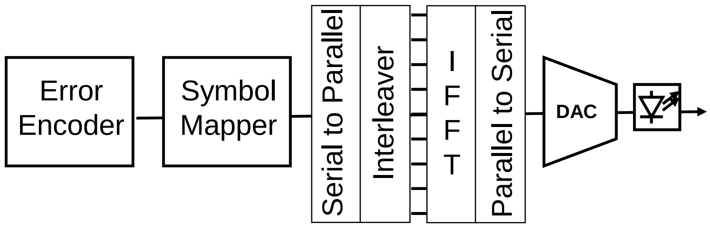


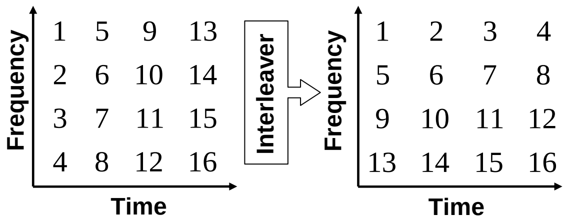
Figure 1. Left: Calculated transfer function of 300 m of 50/125 μm graded index MMF at λ = 850 nm, with refractive index profile parameter α = 2.06. The sub-channel modulation formats used in the OFDM signal used in the transmission simulations are also shown in this plot. Right: Calculated interconnect capacity versus length for two values of refractive index profile parameter α.

3. CODED OFDM

Instead of adaptively selecting the modulation scheme on each sub-carrier to achieve a uniform bit error rate, it is more common in wireless systems to address the problem of frequency selective attenuation by using FEC. In a technique similar to one commonly used in wireless applications, the effect of DMD-induced frequency-dependent attenuation can be combated by using error coding across the subcarriers so that the information conveyed by the strong carriers can be utilised to correct the erroneous symbols received in the weaker ones. This type of OFDM is termed coded OFDM (COFDM) and is widely deployed in wireless and digital audio/video broadcasting. By applying coding across the sub-channels, error correction on the faded carriers is improved by the lower error rate on the other carriers which otherwise may not be possible if per carrier coding was deployed. Various OFDM coding schemes have been proposed in the literature with turbo codes and low-density parity check (LDPC) techniques being the most popular for high-speed transmissions [16-19]. The performance of LDPC-coded OFDM has been investigated in systems deploying graded-index plastic optical fibre (GI-POF) and it was shown that significant SNR gains can be achieved when compared to conventional optical OFDM [17, 18]. This may be improved even further by using soft-decision FEC albeit at the expense of more hardware complexity [16].



(a)



(b)

Figure 2. (a) Coded OFDM transmitter design. (b) A simple interleaving scheme.

Some FEC codes, especially convolutional codes, are sensitive to large numbers of consecutive bit errors. Since neighboring sub-carriers will usually have a similar frequency response, see Fig. 1 (left), a bit interleaver can improve decoding performance for such FEC codes in conjunction with COFDM [19]. This can be part of the error-coder or performed after the modulation encoder as shown in Fig. 2 (a). A simple interleaving example is also shown in Fig. 2 (b) where a buffer receiving parallel data column wise, feeds it to the IFFT in row order. The data is reordered at the receiver before passing through the decoder. This technique increases the robustness of COFDM and helps combat long error bursts as de-interleaving at the receiver spreads the errors over different OFDM frames which can be corrected.

Finding a good trade-off between coding and choice of modulation format leads to the insight that close collaboration between coding and modulation is beneficial. Work is ongoing to assess the performance achievable by combining coded optical OFDM with adaptive modulation. This study includes calculations of the OFDM transceiver energy per bit (taking into account power consumption of coding circuits, discrete Fourier transform cores, synchronization circuits and DAC/ADC), which will be a critical factor in deciding the viability of this signal format for data centers. Our initial work on this is described in [20].

4. CONCLUSIONS

Data center architects are increasingly relying on optical interconnects to relieve bandwidth bottlenecks. Standard interconnects in the data center and high performance computing are based on directly modulated 850 nm vertical cavity surface emitting lasers (VCSEL) transmitting over multimode fibers (MMF) with direct-detection. The capacity of such links is limited both by the modulation bandwidth of the lasers, and by the intermodal dispersion of the MMF which leads to frequency-dependent attenuation. We investigated the use of orthogonal frequency division multiplexing with high-order signalling formats as an approach to increase capacity, due to the increased spectral efficiency and robustness to frequency-dependent fading such an approach makes possible. Recent work on adaptive OFDM was reviewed, and results assessing the capacity limit of such links for distances up to 300 m were presented. Back-to-back capacity of 65 Gbit/s was reduced by approximately one third for transmission over 300 m, due to intermodal dispersion (the exact capacity limit is dependent on the refractive index profile of the fiber). The use of coded OFDM as a method to deal with intermodal dispersion was also discussed, and future studies are planned to quantify performance improvements that can be achieved by combining adaptive modulation with advanced coding in MMF links.

ACKNOWLEDGEMENTS

This work was funded by Intel Corporation and EU FP7 NoE BONE.

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