Advanced modulation schemes and signal processing techniques for transmission in highly multimode fibers

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Abstract. In this dissertation, advanced modulation schemes and digital signal processing techniques are proposed and investigated through both numerical simulations as well as experiments, in order to overcome the limitations of multimode step index plastic optical fibers (SI-POF) to support data rates in the order of Gbps. In particular, novel multi-carrier modulation techniques with the inherent property of symbol spreading (spreading multicarrier modulation schemes) are proposed and applied. These schemes are Discrete Fourier Transform Spread Discrete Multitone (DFT-Spread DMT) and Code Division Multiple Access Discrete Multitone (CDMA-DMT), which, in this thesis, are suitably adapted for short-range IM/DD transmission via SI-POF and compared against conventional Discrete Multitone (DMT) in terms of achieved transmission rate given a target bit error rate. Evaluation is performed for links of 50m and 100m by exploring various cases affecting the overall performance, including rate adaptation and artificial PAPR reduction. In all cases it is found that the DFT-spread DMT perfoms better than all other schemes, followed by CDMA-DMT hence, paving the way for more elaborated research for optimizing its transmission properties.

Keywords: Step Index Optical Fiber, SI-POF, Plastic Optical Fiber, Discrete Multitone, Discrete Fourier Transform, Code Division Multiple Access, Multicarrier Spreading Modulation Schemes, OFDM.

1 Motivation

As the need for very high bit rate transmission become more imperative, conventional transmission media such as copper and air, which are extensively used in wired and wireless transmission respectively, seem to either reaching their available capacity or their usage is not advantageous. The use of optical fiber as a medium for short range networks is now becoming a promising solution to achieve increased transmission rate while at the same time supporting different (broadband) services, such as, for example, the simultaneous transmission of data, video, voice (e.g., VO.IP, IPTV, HDTV). In particular, plastic optical fibers of large core diameter i.e., 1mm SI-POF (Step Index-Plastic Optical Fiber), exhibit a number of advantages regarding not only low manufacturing cost and maintenance but also immunity to mechanical stress, avoidance of electromagnetic interference and enhanced bandwidth. On the other hand, compared to silica fibers, limitations on their usage

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include large optical power loss (e.g. 160-180dB/Km) and limited transmission bandwidth i.e., typically about 100MHz/50m. Therefore, in order to efficiently support transmission rates in the order of Gbps, it is necessary to develop and employ complex modulation schemes together with digital signal processing techniques.

2 Plastic Optical Fiber

High speed short range communications employing large core Plastic Optical Fiber (POFs) have attracted a significant research interest over the past few years and have been assessed for multi gigabit transmission. The plastic optical fibers are multimode waveguides which are made from plastic materials such as polymethyl mathacrylate (PMMA) and fluorinated polymers (PF).

There are two types of PMMA plastic optical fibers: the Step Index Plastic Optical Fibers (SI-POFs) and Graded Index Plastic Optical Fibers (GI-POFs). The fibers of the first type have core with large diameter value (980um) and Numerical Aperture (N.A.) 0.5. Because of the large number of guided modes, these fibers exhibit large modal dispersion values. As a consequence, the available bandwidth of these fibers is reduced to several MHz (50MHz/100m). Another disadvantage of these fibers is the large attenuation value with a typical value 180dB/Km for the case of wavelength of 650nm. The fibers of the second category (GI-POF) have similar geometric features as the SI-POF but they have smaller numerical aperture and reduced modal dispersion.

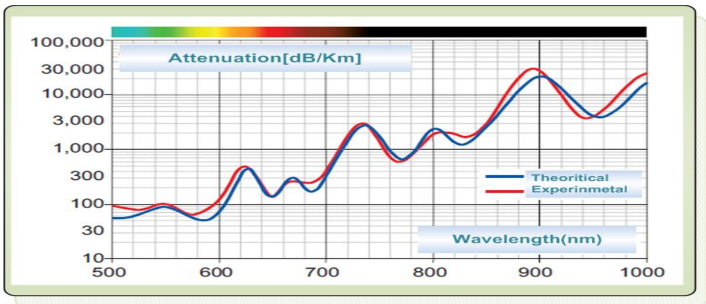

Fig. 1: Attenuation spectra of 1-mm diameter of step index PMMA plastic fiber

In Fig.2, shows the block diagram of a typical communication system based on plastic optical fiber with Intensity Modulation and Direct Detection (IM/DD).

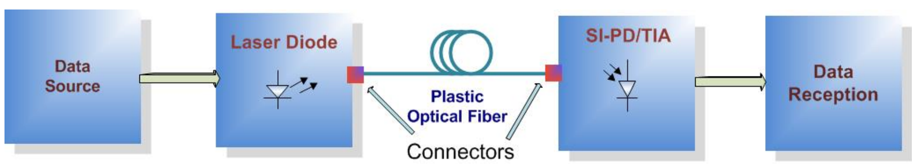

Fig. 2: Block diagram of a typical communication system based on plastic optical fiber

It is obvious that the large values of attenuation constraints the length of an optical link with plastic optical fiber. Also the effect of the large modal dispersion values do not allow the transmission data rates in the order of Gbit/s. As a result, the transmission rate using NRZ-OOK modulation for fiber length in the cases of 25, 50 and 100m is limited in 200, 100 and 50Mbps respectively.

In order, to overcome the constraining factors that plastic optical fibers introduce, it is necessary to develop and employ complex modulation schemes together with digital signal processing techniques. The investigated schemes belong to multicarrier modulation schemes such as DMT with emphasis on inherent spreading properties such as DFT-Spread DMT and CDMA-DMT. In order to maximize the transmission rate of spreading multicarrier modulation schemes over SI-POF, rate adaptive bit loading techniques are also explored.

2 Investigated Modulation Schemes

2.1 Conventional DMT Modulation scheme

The DMT is derived from the well-known Orthogonal Frequency Division Multiplexing (OFDM) and constitute its baseband counterpart. DMT as a multicarrier scheme, provide efficient bandwidth utilization and robustness against dispersive channels. Also, it has tolerance in frequency selective channels in contrast with single carrier schemes, since it divides the available channel bandwidth in smaller narrower sub-channels. In addition, it can be combined with Frequency Domain Equalization (FDE) and can be efficiently implemented using Fast Fourier Transform at the transmitter and receiver.

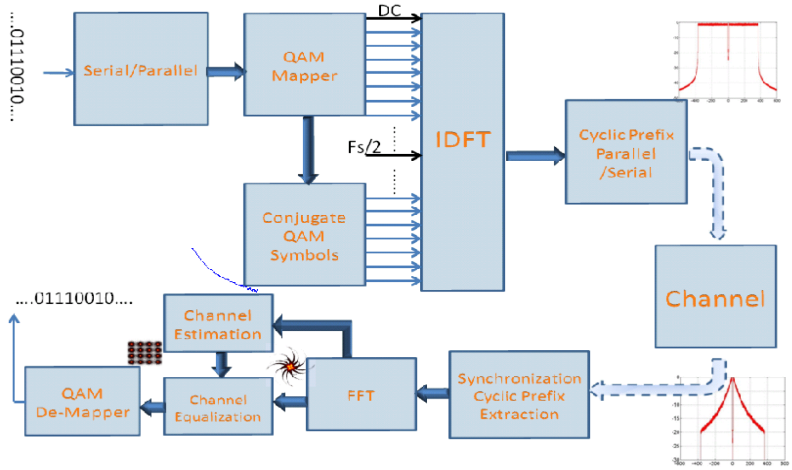

Fig. 3: Block diagram of the DMT transceiver

The principle of DMT is shown in Fig.3. A high speed binary data stream is divided into N parallel data streams. Every M number of bits are given as input to a QAM mapper and produce the QAM complex symbols. These symbols are driven with their complex conjugate symbols to IFFT and the real valued time signal is produced. In order to combat the multipath delay spread and to allow for FDE the last samples of every DMT time signal are copied in the start of DMT signal. These additional samples are the Cyclic Prefix or Guard Interval (CP or GI). The length of CP is chosen to be longer than the channel's maximum delay spread.

2.2 DFT Spread DMT modulation scheme

In this dissertation, the Discrete Fourier Transform Spread Discrete Multitone modulation (DFT-Spread DMT) scheme is proposed for the first time in short range optical IM/DD transmission (over 50 and 100m) with with 1-mm SI-POF link. This scheme combines the advantages of Single Carrier (SC) and Multi Carrier (MC) transmission. The DFT-Spread DMT, likewise DMT, derives from it's wireless counterpart, namely Single Carrier Frequency Division Multiple Access (SC-FDMA). This scheme also has in essence a SC nature hence the inherent advantage of a lower Peak to Average Power Ratio (PAPR) and also allows for FDE. These properties naturally motivate for its exploration in the context of high speed short-range optical transmission over SI-POFs.

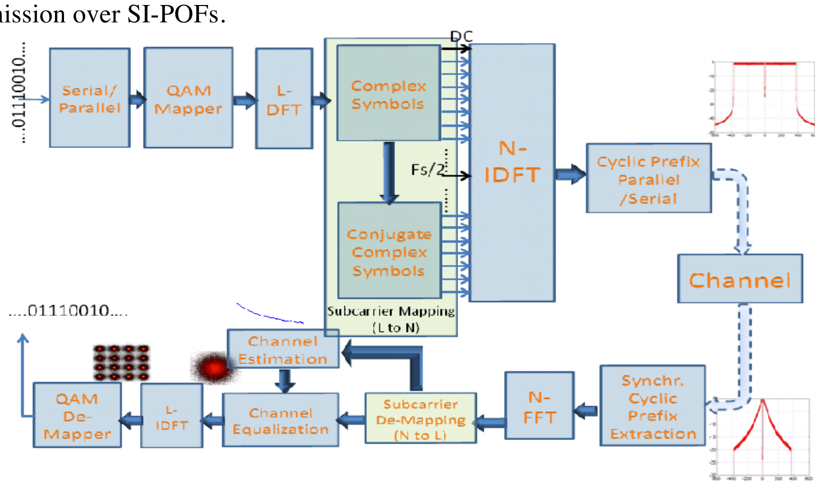

Fig. 4: Block diagram of the DFT Spread DMT transceiver

In Fig.4, the block diagram describing the DFT Spread DMT transceiver structure is shown. Compared to DMT transceiver structure, the DFT Spread DMT has an extra L-point DFT stage at the transmitter combined with a Subcarrier Mapping stage. Also, at the receiver structure there is an extra L-point IDFT stage together with a Subcarrier De-Mapping module [1-2,4].

2.3 CDMA-DMT modulation scheme

In this dissertation, another symbol spreading technique, the Code Division Multiple Access Discrete Multitone (CDMA-DMT) modulation scheme is investigated for transmission over IM/DD link of 50 and 100m of 1mm PMAA SI-POF. CDMA-DMT is a baseband modulation scheme of CDMA-OFDM (also referred as MC-CDMA) which combines the advantages of OFDM (i.e., MC transmission) and CDMA (i.e., spreading of data symbols via orthogonal codes). It is not only a multiple access scheme but a spread spectrum technique aiming to boost and offer enhanced immunity in the presence of high transmission loss and increased noise. This fact motivates for its exploration in short range high speed large core SI-POF transmission.

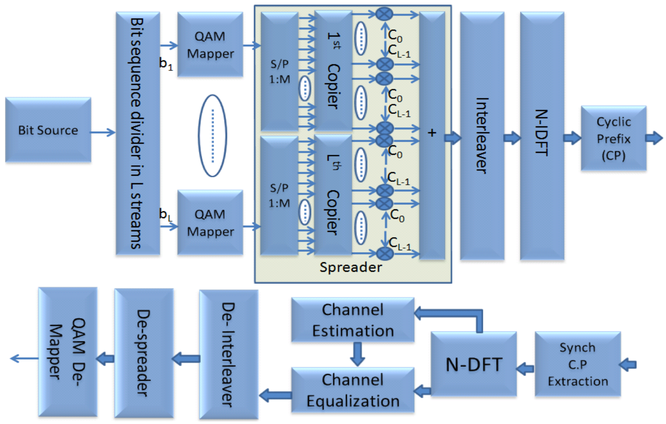

Fig. 5: Block diagram of CDMA-DMT transmitter and receiver

The block diagram describing the CDMA-DMT transceiver structure is shown in Fig. 5. The transmitter consists of the followings parts: parallel divider of initial bit stream in L bit streams, QAM mapper, spreader, interleaver and DMT modulator [3].

2.4 Comparison of DFT Spread and DMT - Experimental results

In order to evaluate the performance of DFT-Spread DMT as well as to compare it against DMT, an offline experiment using conventional components was performed, as is shown in Fig.6.

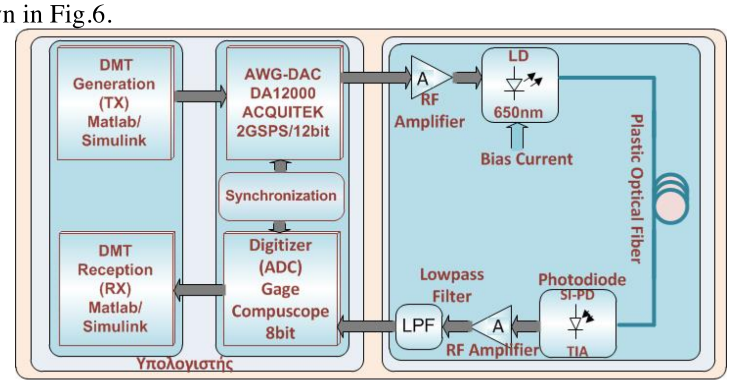

Fig. 6: Block diagram of experimental setup

We have measured the achieved Bit Error Rate (BER) against a range of transmission rates by varying the number of the L data subcarriers as well as using different modulation formats 32, and 64-QAM and SI-POF lengths 50 and 100m. The results are shown in Figs 7 and 8.

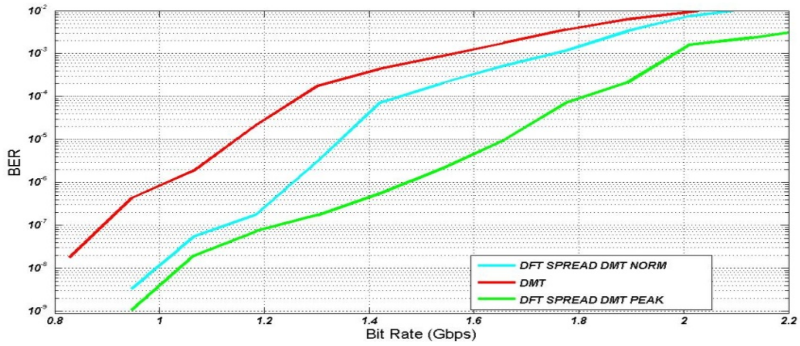

Fig. 7: Comparative results of BER versus net transmission rate for DFT-spread DMT and DMT for the case of 32-QAM and 50m SI-POF

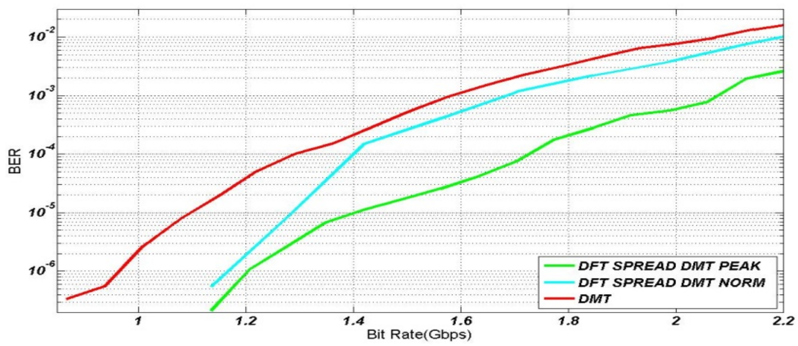

Fig. 8: Comparative results of BER versus net transmission rate for DFT-spread DMT and DMT for the case of 64-QAM and 50m SI-POF

A general observation can be made for all cases evaluated in this study related to the performance enhancement of the proposed technique relative to the pure DMT approach. Spreading of the symbols in the frequency domain via the DFT Spread procedure seems to offer a performance enhancement relative to conventional DMT. For the DFT Spread DMT, the case where it is generated at the transmitter with an average electrical power greater than that of conventional DMT (PEAK case) outperforms DMT in terms of achieved transmission rate for a given threshold BER. A reason for this performance enhancement can be attributed to the fact that DFT-spread DMT has a lower PAPR compared to DMT, as depicted in Fig.7 and Fig.8. Enhanced performance is observed for DFT Spread DMT in the standard case, where both schemes have equal peak power (NORM case). Table 1 summarizes the achievable data bit rates for all investigated schemes. The same performance is observed for the case of transmission over 100m SI-POF (Figs 9 and 10).

Length of SI-POF	50m		100m	
Modulation Scheme	32-QAM Rate (Gbps)	64-QAM Rate (Gbps)	32-QAM Rate (Gbps)	64-QAM Rate (Gbps)
DMT	1.56	1.58	0.81	0.89
DFT SPREAD (PEAK)	1.97	2.05	1.01	1.05
DFT SPREAD (NORM)	1.75	1.68	0.85	0.91

Table 1: Transmission rates for a target ber of 1E-3

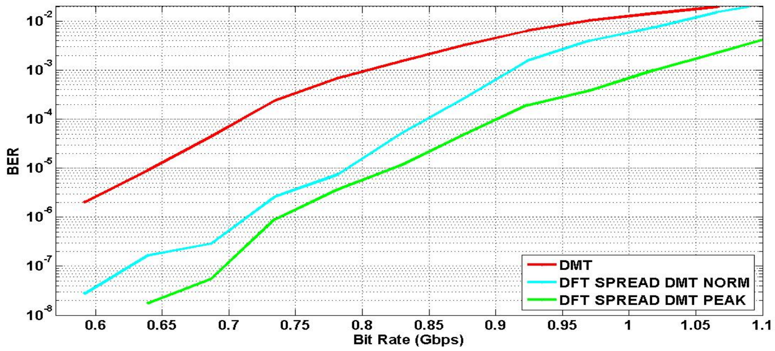

Fig. 9: Comparative results of BER versus net transmission rate for DFT-spread DMT and DMT for the case of 32-QAM and 100m SI-POF

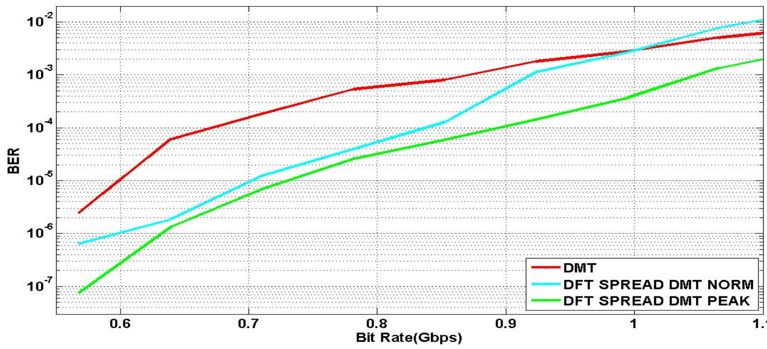

Fig. 10: Comparative results of BER versus net transmission rate for DFT-spread DMT and DMT for the case of 64-QAM and 100m SI-POF

2.5 Comparison of CDMA-DMT and DMT - Experimental results

In order to evaluate the performance of CDMA-DMT as well as to compare it against DMT, we have used the same experimental setup, as is shown in Fig.6. The comparative results are depicted in Figs 11 and 12 for 32- and 64-QAM modulation per subcarrier.

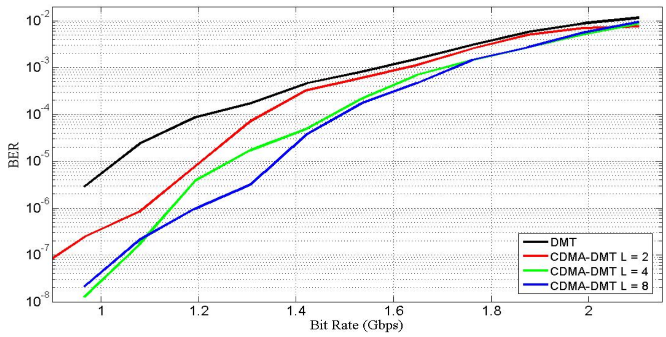

Fig. 11: Comparative results of BER versus net transmission rate for CDMA-DMT and DMT for the case of 32-QAM and 50m SI-POF

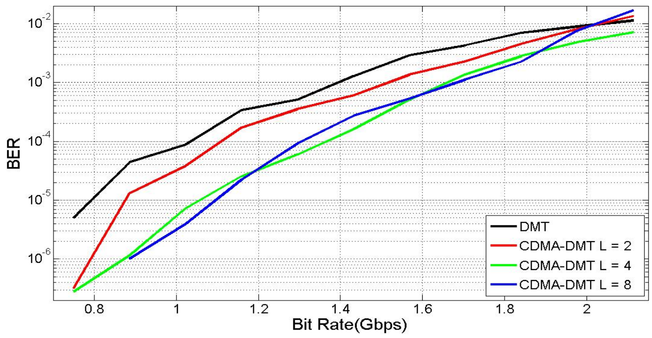

Fig. 12: Comparative results of BER versus net transmission rate for CDMA-DMT and DMT for the case of 64-QAM and 50m SI-POF

A general observation can be made for all cases evaluated in this study related to the performance enhancement of the proposed technique relative to the pure DMT approach. Spreading of the symbols in the frequency domain via the CDMA procedure seems to offer a performance enhancement relative to conventional DMT. This can be attributed to the inherent spreading property of CDMA-DMT where parts of the same QAM symbol are transmitted in different subcarriers due to the chipping process, combined with the fact that the receiver employs the energy of all the received symbols which are scattered in the frequency domain. Finally, as the spreading factor L increases, the *CDMA-DMT* performs better than DMT, especially for the cases of L = 2 and L = 4, as well as for the cases of L = 8. Table 2 summarizes the achievable data bit rates for all investigated schemes for the case of CDMA-DMT and for the cases of spreading factors L = 2, 4 and 8 when evaluated for links of 50m and 100m.

SI-POF (m)	50				100			
	Modulation Schemes							
	DMT	**CDMA-DMT**			**DMT**	**CDMA-DMT**		
Spreading Factor	**L=1**	**L=2**	**L=4**	**L=8**	**L=1**	**L=2**	**L=4**	**L=8**
32-QAM	**1.57**	**1.63**	**1.69**	**1.70**	**0.84**	**0.95**	**0.99**	**1.01**
64-QAM	**1.97**	**1.52**	**1.66**	**1.68**	**1.97**	**1.00**	**1.03**	**1.05**

3 Rate Adaptive Bit Loading

Rate adaptation refers to the process of maximizing the transmission rate subject to a power constraint and given a target BER. This is accomplished via bit-loading that is, by allocating the number of bits transmitted per subcarrier according to its corresponding channel SNR hence, by varying the modulation's constellation (e.g., M-QAM) as the channel indicates. In practice, the Chow's algorithm is usually implemented to allow for finite granularity over allocated bits per sub-channel [4]. Since DMT divides the available channel into sub-channels, bit-loading is directly applicable for each sub-channel (i.e., subcarrier). For the DFT-spread DMT and CDMA-DMT case, some modifications are essential prior to applying bit-loading [4].

3.1 Rate Adaptive Bit Loading

The rate-adaptive bit-loading maximization problem for DMT is formulated as,

$$\max(b)_{E_n} = \sum_{n=1}^{N} log_2\left(1 + \frac{SNR_n}{\Gamma}\right)$$

where, b is the achievable bit rate expressed as the sum of the individual bit rates of the N available subcarriers, is the SNR gap between the SNR needed for maximum capacity and the SNR to achieve this capacity at a given BER, SNRn = E_n□g_n is the signal to noise ratio of each subcarrier with gn being the sub-channel SNR when unit energy is applied and En is the allocated energy per subcarrier subject to the constraint of the total energy for transmission i.e $E_{tot} = \sum_{n=1}^{N} E_n$. subcarrier with gn being the sub-channel SNR when unit energy is applied and En is the allocated energy per subcarrier subject to the constraint of the total energy for transmission.

3.2 Rate Adaptive DFT-Spread DMT

Relative to the DMT case, the DFT-Spread DMT transceiver employs a precoding (spreading) stage. Hence, it has an extra L-point DFT stage at the transmitter combined with a Subcarrier Mapping module, as well as an extra L-point IDFT stage at the receiver combined with a Subcarrier De-Mapping module, with L < N/2 and N being the DFT/IDFT size of conventional DMT [4]. Generalizing for the case when bit-loading is to be utilized, after bit allocation is derived as obtained for DMT and which determines the constellation order M (i.e., M-QAM) for a group of subcarriers with size Li, an extra Li-point DFT is performed for each group of these subcarriers. That is, an extra DFT stage is added for each group of subcarriers having the same QAM order M. Then, power loading as estimated by Chow's algorithm is applied to each spread subcarrier prior to applying the N-point IDFT which produces the final time domain DFT-spread DMT signal.

3.3 Rate Adaptive CDMA-DMT

CDMA-DMT, which is the baseband version of multicarrier (MC) CDMA involves a different approach for spreading the QAM symbols. It divides the initial bit stream into L parallel streams and after QAM mapping it copies and then spreads these symbols via point wise multiplication (i.e., chipping) with orthogonal spreading sequences (e.g., Walsh-Hadamard sequences). Then the parallel symbol streams are added prior to a DMT modulation. For the case of CDMA-DMT, bit-loading is achieved by considering the concept of equivalent sub-channel (i.e., subcarrier) which is introduced as in the case of MC-CDMA. This is based on the notion that a group of L spread data (where L is also the spreading factor and length of the spreading sequence) represent a single equivalent sub-channel having an effective channel function expressed as,

$$|h_{eff}|^2 = \frac{L}{\sum_{i=1}^{L} \frac{1}{|H_i|^2}}$$

where H_i is the i_{th} subcarrier's frequency response. Following [ ], Chow's algorithm uses the effective SNR, to produce the power and bit loading distribution [4].

3.4 Experimental results

In Fig. 13 the estimated SNR per sub-channel that is used to compute the rate-adaptive bit-loading Chow's algorithm for each modulation scheme is shown. This gives rise to the bit and power allocation shown in Fig. 14-16 for DMT, DFT-spread DMT and CDMA-DMT respectively.

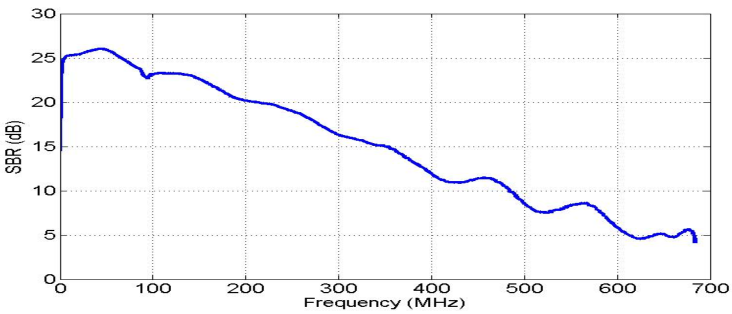

Fig. 13: Measured SNR per subchannel

When bit-loading is utilized, a transmission rate of ~2.55 Gbps is achieved for DFT-spread DMT whereas DMT and CDMA-DMT realizes a rate of ~2.37 Gbps and ~2.45 Gbps respectively. It is observed that DFT-spread DMT exhibits enhanced performance compared to the other two schemes. A reason for this performance enhancement can be attributed to the fact that DFT-spread DMT has a lower PAPR compared to DMT hence, the average transmitted power is greater than that of DMT resulting in a SNR gain of approximately ~1.5 dB for bit-loading.

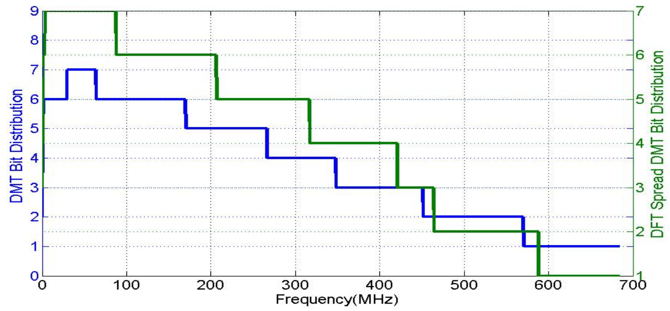

Fig. 14: Bit distribution per subchannel for the cases of DMT and DFT Spread DMT

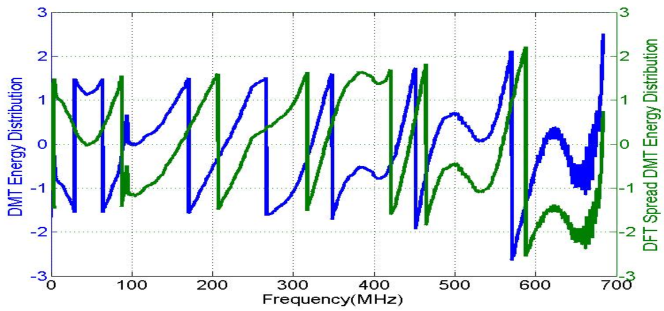

Fig. 15: Energy distribution per subchannel for the cases of DMT and DFT Spread DMT

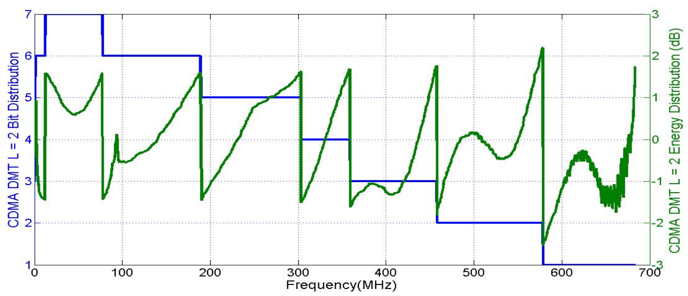

Fig. 16: Bit and Energy distribution per subchannel for the case of CDMA-DMT (L= 2)

4 Conclusions

In this dissertation, spreading multicarrier schemes have been proposed, providing performance improvement in transmission rates over SI-POF IM/DD high speed short range links.

The first modulation scheme, the DFT Spread DMT, spreads the symbols across subcarriers in the frequency domain. It exhibits improvement performance in comparison with conventional DMT because of its lower PAPR as well as due to its inherent single carrier nature. In this thesis, it is experimentally confirmed that DFT-spread DMT offers a performance improvement of 29.7% and 18% in achieved data rates given a target BER, for transmission over links of 50m and 100m respectively. In addition, when rate adaptation is utilized, the DFT-spread DMT offers a performance improvement of 12.6% compared to conventional DMT.

The second modulation scheme namely, CDMA-DMT also spreads the QAM symbols across subcarriers in the frequency domain, using specific spreading sequence. It is experimentally shown that as the spreading factor L increases, the CDMA-DMT performs better than DMT, especially for the cases of L = 2 and L = 4. Also, this technique outperforms DMT when combined with rate adaptive bit loading.

In conclusion, it is experimentally verified that both of the proposed modulation schemes outperform conventional DMT in all examined cases for IM/DD SI-POF transmission. Among them, the DFT-spread DMT exhibits the best performance. Taking into account that this scheme effectively combines the relative merits of multicarrier and single carrier transmission techniques, more elaborated research is motivated for optimizing its modulation properties and that could lead to a converged MC and SC modulation scheme for low cost short range high speed optical links based on plastic optical fibers.

Publications

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