Performance Evaluation of Multimode Fiber-Based Optical OFDM Communication System

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Abstract:

The most significant limitation of data transmission in Multimode Fibers (MMFs) is intermodal dispersion due to the propagation velocity of each of the guided mode is different. This paper addresses this problem by adopting optical Orthogonal Frequency Division Multiplexing (OFDM) scheme to compensate intermodal dispersion and to enhance the bandwidth-distance product of MMF. The optical OFDM scheme adopted here is based on treating the signal fading due to intermodal dispersion in MMFs in a similar manner to that caused by multipath effect in wireless channels.

A MATLAB simulink model is developed for the optical OFDM system. Simulation results are reported for 1Gbps link operating with different digital subcarrier modulation schemes to assess the impact of various parameters on system performance. The results indicate clearly that a Bit Error Rate (BER) of 10-5 can be achieved for a 1Gbps, 1km (10ns-dispersion) link operating with 1550nm, -23.6dBm laser and 16- Quadrature Amplitude Modulation (QAM) subcarrier modulation scheme.

Keywords: *Optical communication.*

1. Introduction

Recently there is an increasing interest in using Multimode Fiber (MMF) links as the transmission medium for gigabit per second Local Area Networks (LANs) [1]. Such high-speed links are particularly needed for backbone links, because of the increased LAN bandwidths following the 10- Gigabit Ethernet (10GbE) standard [2]. The use of MMFs bring multiple advantages regarding to their ease of installation, handling and maintenance, which in turn implies an important cost reduction. Unfortunately, the bit rate- length product of these fibers is limited by the intermodal dispersion. If the bit rate of the transmitted signal is high, the bit period is small. When a received pulse is spread out in time caused by intermodal dispersion, the neighboring pulses may overlap causing Intersymbol Interference (ISI). This may lead to a wrong decision in the decision circuit in the receiver; thus, a high Bit Error Rate (BER) occurs.

Recently, the concepts of Orthogonal Frequency Division Multiplexing (OFDM) have been applied to reduce the effect of dispersion in high-speed optical communication systems incorporating Single-mode Fibers (SMFs) [3-5]. The motivation behind that is the capability of OFDM technique in efficiently dealing with linear signal distortions encountered when transmitting over wireless dispersive fading channels [6].

OFDM is a form of multicarrier modulation, where a single high-speed information bearing stream is transmitted over a number of harmonically related narrowband subcarriers [7]. This paper investigates the use of optical OFDM technique in reducing the effect of intermodal dispersion in gigabit per second MMF transmission links.

2. MMF channel model

The MMF is modeled here as a two-path fading channel as shown in Fig. 1. The first path represents the shortest path corresponding to mode propagating along the longitudinal axis of the fiber. The second path corresponds to the longest propagating path. The difference between propagation times along these two paths is equal to

$$\tau_{\text{int}} = \frac{L\,n_1}{c}\left(\frac{n_1}{n_2}-1\right) \cong \frac{L\,n_1\Delta}{c} \qquad (1)$$

where L, n_1, n_2 and c are, respectively, fiber length, core refractive index, cladding refractive index and speed of light in vacuum.

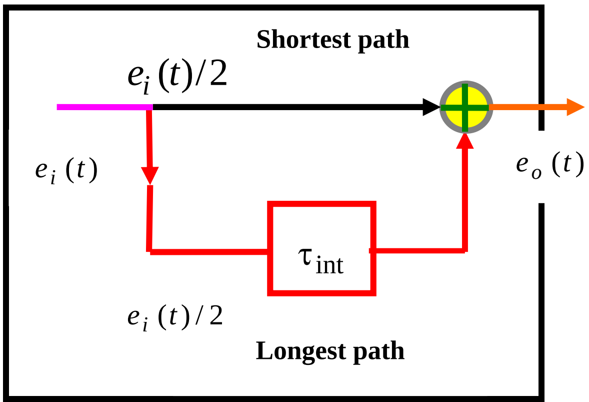


Figure (1) MMF channel model

The transmitted power is assumed to be equally distributed among these two modes. Let $e_i(t)$ is the signal electric field incident on the input of the fiber. The input electric field of each of the fastest and slowest modes is equal to $e_i(t)/2$. If the fiber attenuation is neglected (an assumption which is justified for short link), then field at the fiber end is given by

$$e_o(t)=\frac{1}{2}[e_i(t)+e_i(t-\tau_{int})] \quad (2)$$

Applying fourier transform to eq. (2) yields

$$E_o(f)=\frac{1}{2}\left[E_i(f)+E_i(f)\,e^{-j2\pi\tau_{int}f}\right] \quad (3)$$

where $E_i(f)$ and $E_o(f)$ are, respectively, the fourier transforms of $e_i(t)$ and $e_o(t)$.

The transfer function of the MMF is given by

$$H(f)\equiv\frac{E_o(f)}{E_i(f)}=\frac{1}{2}\left[1+e^{-j2\pi\tau_{int}f}\right]$$

$$=\frac{1}{2}\left[e^{j\pi\tau_{int}f}+e^{-j\pi\tau_{int}f}\right]e^{-j\pi\tau_{int}f}$$

$$H(f)=[\cos(\pi\tau_{int}f)]\,e^{-j\pi\tau_{int}f} \quad (4)$$

Note that the MMF behaves as an optical filter having $|H(f)=1|$ at $f=0$ and a cut-off frequency f_{cut} corresponding to the frequency which makes $\left|H(f)=\frac{1}{\sqrt{2}}\right|$.

Thus

$$\cos\pi\tau_{int}f_{cut}=\frac{1}{\sqrt{2}} \text{ or}$$

$$f_{cut}=\frac{\cos^{-1}(1/\sqrt{2})}{\pi\tau_{int}}=\frac{1}{4\tau_{int}}$$

Thus according to the model adopted here, the bandwidth of the MMF is equal to $1/4\tau_{int}$.

3. Simulation of optical OFDM system

The optical OFDM signal is generated for the simulation model (Fig. 2) as follows:

In the transmitter, an incoming binary data sequence from Bernoulli source is first encoded by (11/15) Reed Solomon (RS) encoder to reduce the probability of error at the receiver due to the optical channel effects. The data binary values are mapped to symbols, using Quaternary Phase Shift Keying (QPSK) or one of the M-ary Quadrature Amplitude Modulation (QAM) constellation formats, on a complex word consisting of a real and an imaginary parts. The so called Gray coding allocates the bits to the respective constellation points. Each subcarrier is assigned one baseband symbol to transmit with duration increasing proportionally to the bit interval. The training frame (pilot subcarriers frame contains 31 samples) is inserted and sent prior to information frame. This pilot frame is used later in the receiver to make channel estimation which is needed to compensate the effects of the channel on the transmitted signal. The complex words frame and pilots frame pass through an 64-bin Inverse Fast Fourier Transform (IFFT) stage to generate an OFDM symbol (i.e., this transform generates time domain waveform that is a superposition of all the modulated subcarriers). Zeros are then inserted in some bins of the IFFT in order to make the transmitted spectrum compacts and to reduce the Intercarrier Interference (ICI). The reason behind that is that the dominant portion of the transmission channel distortion usually located around the edge of a transmission band. The cyclic prefix is taken to be 40% of the IFFT size (26 samples are added), so that the relative delays between the received OFDM subcarriers (due to fiber dispersion) can be accommodated without destroying the orthogonality of the OFDM subcarriers. The OFDM symbol is converted from parallel to serial version by a Parallel-to-Serial (P/S) converter. The OFDM band is used to intensity modulate an optical carrier

(1550nm). In intensity modulation, the laser output power varies linearly with the modulating signal. The laser bias current I_b is chosen above laser threshold current I_{th} to ensure lasing in the absence of Radio Frequency (RF) modulating signal. Further, the minimum value of driving current $I_{driv}(t)$ must be greater than I_{th} to prevent clipping. The laser is assumed to have a linear power-current characteristic in the lasing regime to ensure negligible nonlinear distortion. The optical signal is transmitted over a MMF channel. The intermodal dispersion characteristics are governed by eqns. (1) and (4).

At the receiver, inverse operations to that of the transmitter are employed with additional training tasks, the received signal is converted to parallel version by Serial-to-Parallel (S/P) converter. The interfered cyclic prefix is then discarding. The FFT is used to transfer the signal back to the baseband frequency domain to recover the N_s modulation values of all subcarriers where N_s is the number of OFDM subcarriers. The MMF channel effects are compensated by using the received pilot symbols to estimate the channel frequency response. After channel compensation, the QPSK or M-ary QAM values are demapped into binary values. Finally, an RS decoder is used to decode the information bits.

4. Simulation results

This section presents simulation results to assess the performance of optical OFDM-based link incorporating a Multimode Fiber (MMF). Unless otherwise stated, the important parameters values used in the simulation are listed in Table 1. The values of the fiber parameters used here give a 10ns/km intermodal dispersion according to eq. (1). Such fiber can be used in conventional optical systems to carry a maximum bit rate of $1/4\tau_{\text{int}} = 25\text{Mbps}$

Table (1) Optical OFDM simulation parameters

Parameter	Symbol	Value
Data rate	R_b	1Gbps
RS code rate	k/n	11/15
Number of OFDM subcarriers	N_s	62
OFDM symbol duration	T	64 samples
Guard interval period	T_g	26 samples
Amplitude modulation index	K_m	0.1
Wavelength	λ	1550nm
Relative intensity noise	RIN	-140dB/Hz
Fiber length	L	1km
Core refractive index	n_1	1.48
Cladding refractive index	n_2	1.477
Absolute temperature	T	300K
Amplifier load resistance	R_L	50 Ω
Amplifier noise figure	F_n	3dB
Photodiode quantum efficiency	η	1

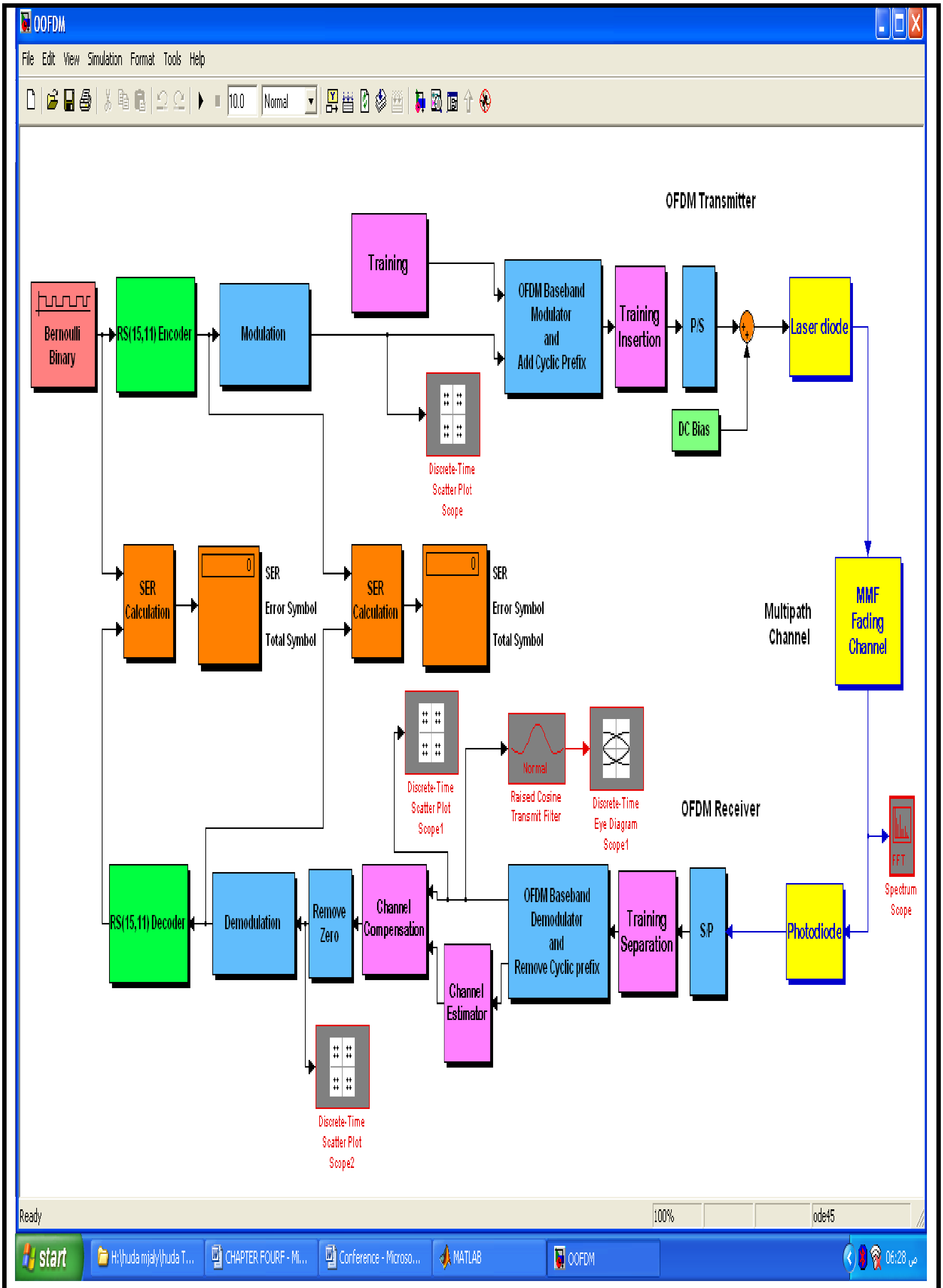


Figure (2) Complete MATLAB simulink model of optical OFDM system

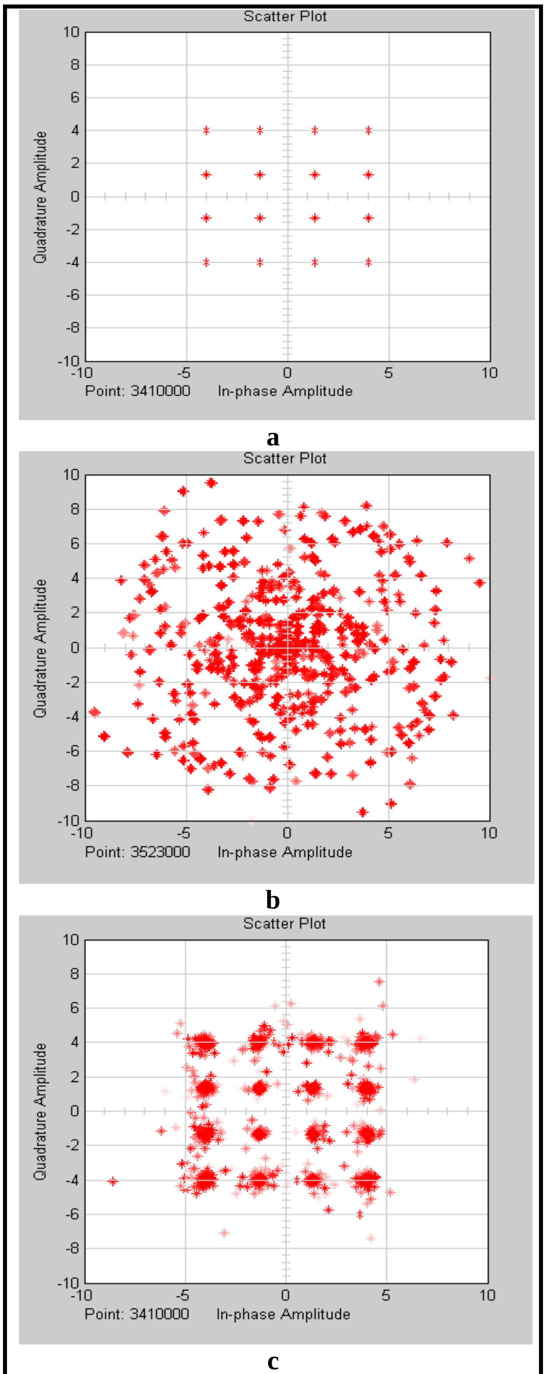


Figure (3) Signal constellation diagrams for a 16-QAM optical OFDM system when $SNR = 20$dB **(a)** In the transmitter **(b)** In the receiver without channel estimation **(c)** In the receiver with channel estimation.

4.1 Performance of 1km, 1Gbps Link

The performance of 1km, 1Gbps link incorporating optical OFDM scheme is simulated and the results are depicted in Figs. (3-5). Figure 3a shows the constellation diagram of the 16-QAM symbols used in the transmitter. Figures 3b and 3c show, respectively, the corresponding constellation diagrams in the receiver computed in the absence and presence of channel estimation. The results are displayed for Signal-to-Noise Ratio $(SNR) = 20$dB. Investigating the results in these figures highlights the following fact

In the absence of channel estimation, the received constellation diagram is completely destroyed. Further, using the channel estimation scheme will enhance the quality of the received constellation diagram. The task of the channel estimation is to learn the reference phases and amplitudes for all subcarriers. A pilot symbol aided channel estimator has been used in the case of fading channels to compensate the ISI occurred due to fading effect.

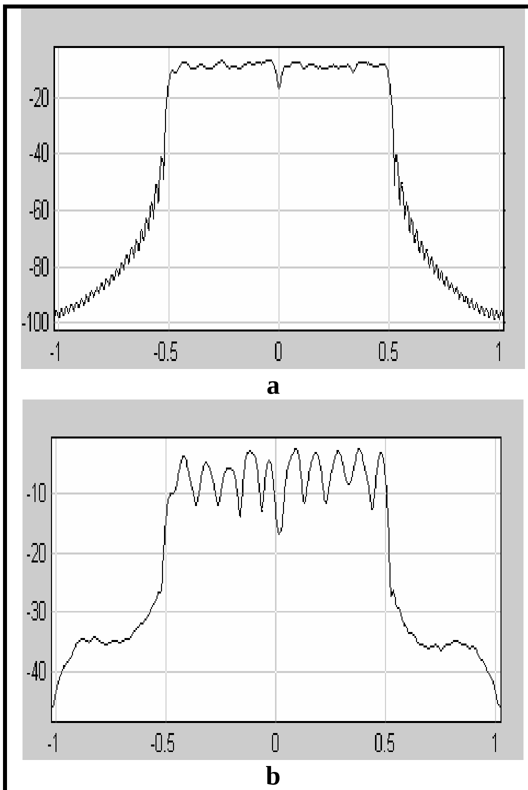
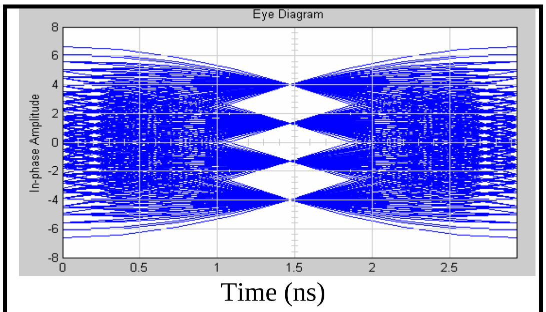


Figure (4) Power spectrum of optical OFDM system for a 16-QAM modulation.**(a)** Transmitted spectrum **(b)** Received spectrum ($SNR = 20$dB)

Figures 4a and 4b show, respectively, the power spectra of the transmitted and received signals (baseband domain). The results are reported when a 16-QAM modulation scheme is adopted for mapping the binary data and assuming a bit SNR (E_b / N_o) equal to 20dB. Note that the spectrum of the transmitted signal is almost uniform and band limited to 0.5GHz which is equal to half the bit rate. However, the uniformity of the spectrum degrades due to the transmission over the

MMF. The reason behind this result is that the intermodal dispersion affects the orthogonality property of the OFDM subcarriers.

Figure 5a shows the eye diagram of the 16-QAM symbols used in the transmitter. Figures 5b and 5c show, respectively, the corresponding eye diagram in the receiver in the absence and presence of channel estimation when $SNR = 20$dB. Note that the eye diagram is almost closed in the absence of channel estimation. Employing the channel estimation opens the eye diagram and gives a lower level of Bit Error Rate (BER).



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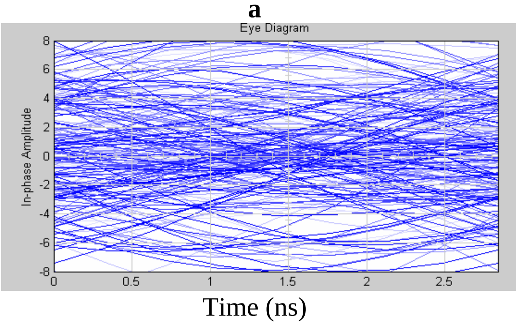

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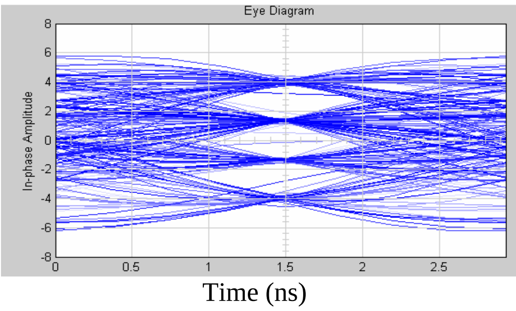
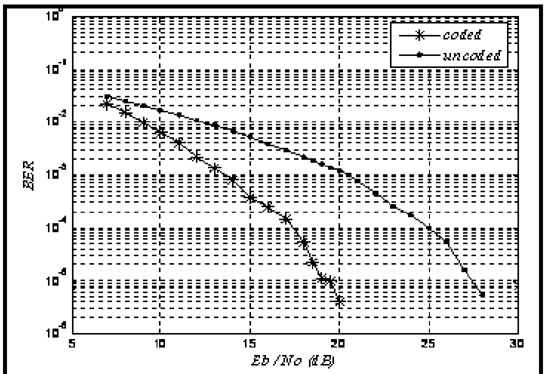


c

Figure (5) Signal eye diagram for a 16-QAM optical OFDM system when $SNR = 20$dB **(a)** In the transmitter **(b)** In the receiver without channel estimation **(c)** In the receiver with channel estimation.



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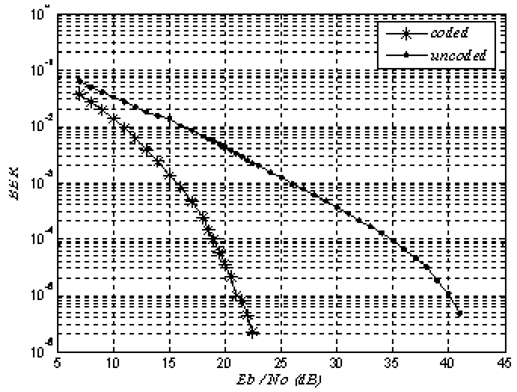

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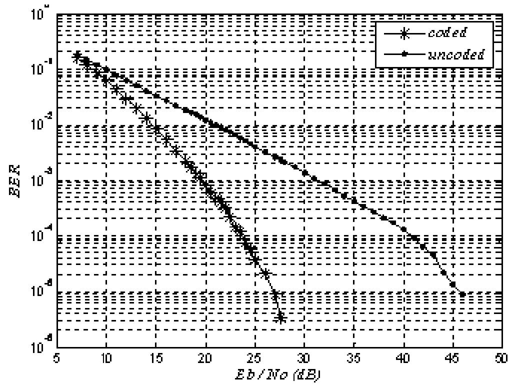

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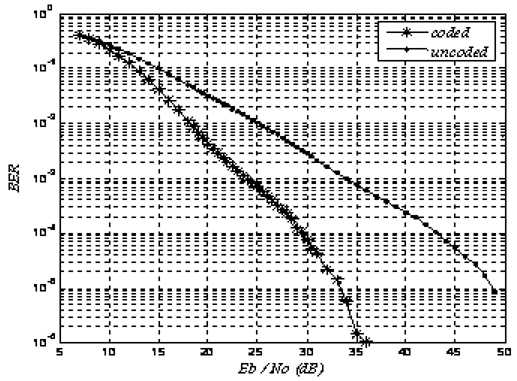


d

Figure (6) Effect of coding on BER characteristics for different modulation schemes **(a)** QPSK **(b)** 16-QAM **(c)** 64-QAM **(d)** 256-QAM.

4.2 Effect of Coding

The performance of the optical OFDM system is investigated in the absence of coding. The results are obtained by running the MATLAB-simulink model described in Fig. 2 without inserting the Reed Solomon (RS) encoder and decoder blocks in the transmitter and receiver, respectively. Figures 6a-6d show, respectively, a comparison among the BER characteristics of the coded and uncoded optical OFDM systems for QPSK, 16-QAM, 64-QAM and 256-QAM schemes. The results in these figures indicate clearly that BER reduces in the presence of coding and this effect is more pronounced as the SNR increases.

Table 2 SNR gain and receiver sensitivity enhancement introduced by coding for different modulation schemes with (RIN = -140 dB/Hz)

BER	SNR Gain (dB)				Receiver Sensitivity Enhancement (dB)			
	QPSK	16-QAM	64-QAM	256-QAM	QPSK	16-QAM	64-QAM	256-QAM
10^{-3}	6.82	10.24	11.66	10.15	7.69	16.21	*	*
10^{-4}	7.60	15.82	17.08	13.16	11.41	*	*	*
10^{-5}	8.03	19.09	18.96	15.52	*	*	*	*

Table 2 summarizes the main conclusions drawn from Figs. 6a-6d and shows the SNR gain and receiver sensitivity enhancement introduced by coding for different modulation schemes when a semiconductor laser with Relative Intensity Noise (RIN) = -140dB/Hz is used.

The calculations in Table 2 are repeated in Table 3 when RIN = -160dB/Hz.

Table 3 SNR gain and receiver sensitivity enhancement introduced by coding for different modulation schemes with (RIN = -160 dB/Hz)

BER	SNR Gain (dB)				Receiver Sensitivity Enhancement (dB)			
	QPSK	16-QAM	64-QAM	256-QAM	QPSK	16-QAM	64-QAM	256-QAM
10^{-3}	6.82	10.24	11.66	10.15	6.83	10.27	11.77	10.35
10^{-4}	7.60	15.82	17.08	13.16	7.62	16.08	18.23	15.87
10^{-5}	8.03	19.09	18.96	15.52	8.07	20.06	13.39	*

Note: (*) denotes that the required BER cannot be achieved even when laser optical power P_b tends to ∞

Investigating the results in Table 2 and Table 3 reveals the following facts

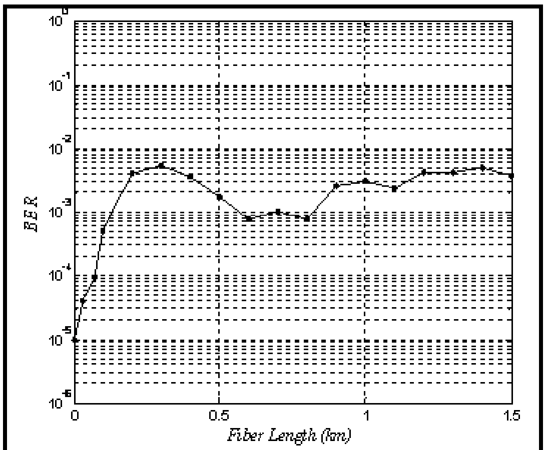
(i) The presence of coding enhances the receiver sensitivity by an amount approximately equal to code SNR gain.

(ii) The sensitivity enhancement increases with decreasing the level of BER.

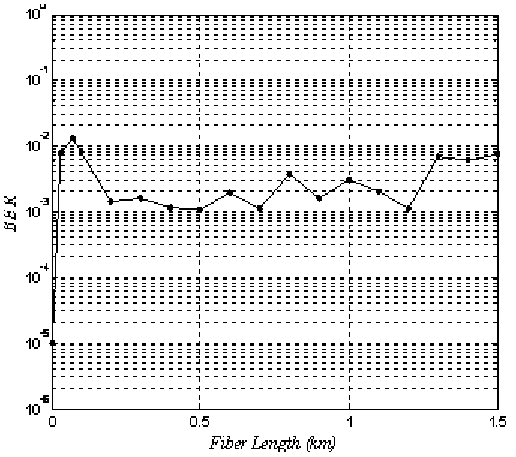
(iii) The code SNR gain is independent on RIN while the receiver sensitivity enhancement increases with RIN .

4.3 Effect of Fiber length

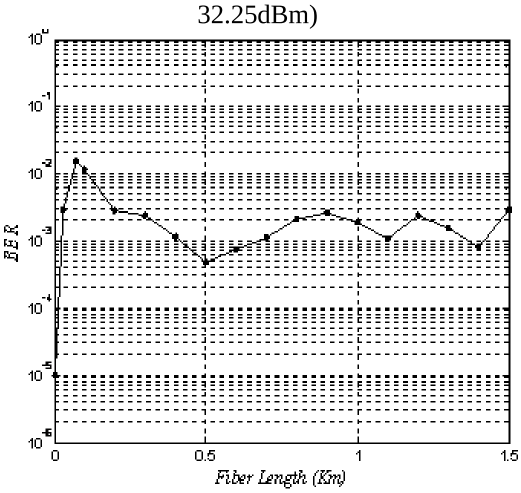
The effect of fiber length on system performance is investigated and the results are presented in Figs. 7a-7d for QPSK, 16-QAM, 64-QAM, and 256-QAM, respectively. In these calculations, the fiber length is varied from 0 to 1500m which corresponds to an intermodal dispersion variation from 0 to 15ns. Then the BER is estimated as a function of fiber length L under the assumption of constant SNR (i.e., constant laser power P_b). In each part of Fig. 7, the SNR (and hence P_b) is chosen to yield a BER=10^{-5} when $L=0$ (i.e., absence of dispersion). Investigating the results in Fig. 7 reveals that the effect of OFDM is more pronounced as the intermodal dispersion increases.



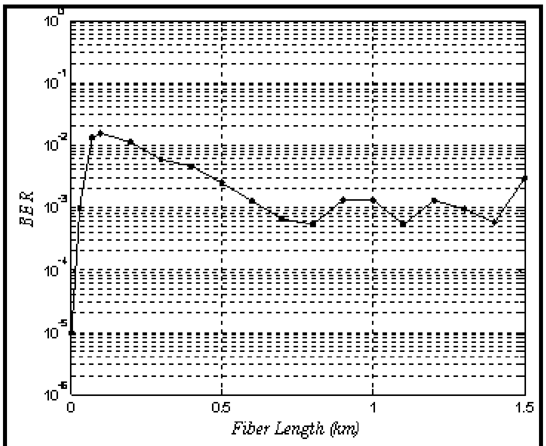
(a) QPSK $SNR = 11.33$dB (P_b = -34.46dBm)



(b) 16-QAM $SNR = 13.47$dB (P_b = -32.25dBm)



(c) 64-QAM $SNR = 18.31$dB (P_b = -26.97dBm)



(d) 256-QAM $SNR = 23.15$dB (P_b = -20.44dBm)

Figure (7) BER as a function of fiber length for optical OFDM system

This result is expected since the fading effect of the fiber increases with distance. Note that the OFDM scheme makes the BER approximately saturates as the fiber length increases. The oscillating behavior observed in the BER-length characteristic is due to the simplified model (two-path model) adopted for the MMF. For the fiber parameter values used here, the 1GHz-frequency component of the signal spectrum (for example) propagates along the fiber via two modes which combine constructively at the end of the fiber when $L = 100$m, 200m, 300m,…. (i.e., $\tau_{int} = 1$ns, 2ns, 3ns,….). For these values, the phase shift between the two propagating modes is equal to $2\pi, 4\pi, 6\pi,$ …….

4.4 Effect of Number of Fiber Propagation Modes

The results reported in the previous sections have been calculated under the assumption that the dispersion characteristics of the step-index MMF is dominated by two main propagating modes. These modes are the fastest (shortest-path) mode and the slowest (longest-path) mode. In practice, the MMF supports many propagating modes whose number M_o is governed by the following expression

$$M_o \cong V^2 / 2 \quad (5)$$

where V is the normalized cutoff frequency, the V parameter determines the number of modes supported by the fiber. To know the exact number of propagating modes along with their individual powers and propagation constants β (and hence their propagation velocities), Maxwell's equations must be solved in the core and cladding regions. The problem should be formulated in the cylindrical coordinates space and taking into account the boundary conditions at the core/cladding interface.

To get a simplified picture about the multimode propagation behavior of the step-index MMF, we propose the model described in Fig. 8. The model assumes that the fiber supports M_o equipower modes. The difference in the propagation time between two successive modes is given by $\tau = \tau_{\text{int}} / (M_o - 1)$.

where $\tau_{\text{int}} = \frac{Ln_1}{c}\left(\frac{n_1}{n_2} - 1\right) = \frac{Ln_1\Delta}{c}$

represents the intermodal dispersion of the fiber.

The transfer function of the MMF is given by

$$H(f) = \frac{1}{M_o}\left[1 + e^{-j2\pi\tau f} + e^{-j4\pi\tau f} + \ldots + e^{-j2\pi(M_o-1)\tau f}\right]$$

$$= \frac{1}{M_o}\sum_{m=0}^{M_o-1} e^{-j2m\pi\tau f}$$

$$= \frac{1}{M_o}\frac{[1 - e^{-j2M_o\pi\tau f}]}{[1 - e^{-j2\pi\tau f}]}$$

The above results can be simplified to

$$H(f) = \frac{1}{M_o}\frac{\sin(M_o\pi\tau f)}{\sin(\pi\tau f)} e^{-j(M_o-1)\pi\tau f} \quad \textbf{6a}$$

Or

$$H(f) = \frac{1}{M_o}\frac{\sin\left(\left(\frac{M_o}{M_o - 1}\right)\pi\tau_{\text{int}} f\right)}{\sin\left(\left(\frac{1}{M_o}\right)\pi\tau_{\text{int}} f\right)} e^{-j\pi\tau_{\text{int}} f} \quad \textbf{6b}$$

The derivation of eq. (6b) is one of the main results reported in this section.

Note that eqn. (6b) reduces to eq. (1) when $M_o = 2$. Further, when f approaches zero, then $\sin(M_o\pi\tau f) \cong M_o\pi\tau f$ and $\sin(\pi\tau f) \cong \pi\tau f$. This yields $H(0) = 1$ independent of the number of modes M_o.

To assess the effect of number of propagation modes on the BER characteristics, the optical OFDM system is simulated using a multipath model for the MMF as described by eqn. (6b). The results are tabulated in Table 4 for different modulation schemes. In each scheme, the ratio E_b / N_o is chosen to yield a BER=10^{-2} when the number of propagating modes $M_o = 2$. The calculations are repeated for a BER=10^{-3} in Table 5. It is clear that increasing M_o beyond 2 may increase or decrease the level of BER. This results leads to the following conclusions "A comprehensive model must be used to calculate the multimode propagation characteristics of a MMF to get an accurate simulation results for an optical OFDM system incorporating this fiber".

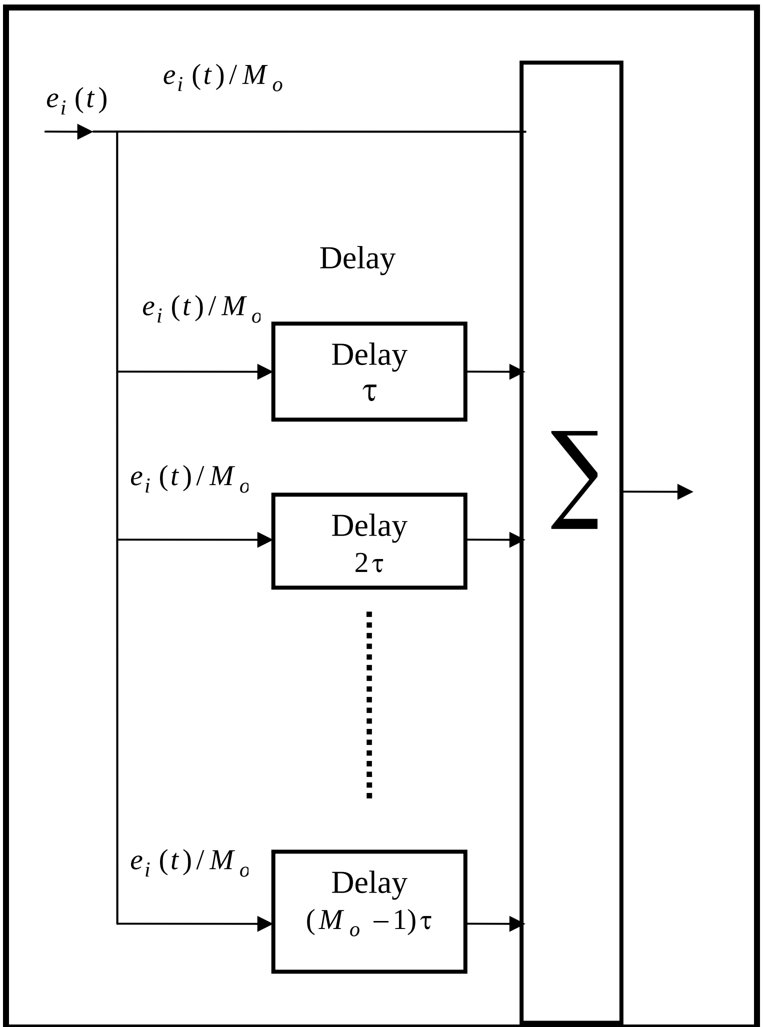


Figure (8) A simplified model for a MMF with M_o equipower propagating modes

Table (4) Effect of number of fiber propagating modes on BER characteristics of an OFDM system assuming a BER=10^{-2} when $M_o = 2$

M_o	BER			
	QPSK $E_b/N_o = 8.80$dB (P_b = -37.05dBm)	16-QAM $E_b/N_o = 10.76$dB (P_b = -35.05dBm)	64-QAM $E_b/N_o = 14.58$dB (P_b = -31.08dBm)	256-QAM $E_b/N_o = 18.19$dB (P_b = -27.11dBm)
6	1.385×10^{-3}	5.325×10^{-2}	1.189×10^{-1}	9.268×10^{-2}
11	9.455×10^{-4}	1.509×10^{-2}	1.469×10^{-2}	3.139×10^{-2}
21	1.068×10^{-2}	6.916×10^{-3}	2.865×10^{-2}	5.039×10^{-2}

Table (5) Effect of number of fiber propagating modes on BER characteristics of an OFDM system assuming a BER=10^{-2} when $M_o = 2$

M_o	BER			
	QPSK $E_b/N_o = 13.59$dB (P_b = -32.12dBm)	16-QAM $E_b/N_o = 15.59$dB (P_b = -29.99dBm)	64-QAM $E_b/N_o = 19.64$dB (P_b = -25.39dBm)	256-QAM $E_b/N_o = 23.88$dB (P_b = -19.12dBm)
6	3.273×10^{-5}	3.384×10^{-3}	3.054×10^{-2}	1.307×10^{-2}
11	1.02×10^{-6}	4.32×10^{-4}	6.938×10^{-4}	2.029×10^{-3}
21	1.018×10^{-4}	9.236×10^{-5}	2.209×10^{-3}	4.505×10^{-3}

4.5 BER Performance in the Absence and Presence of MMF Channel

Figures 9 and 10 show the BER characteristics for four modulation schemes QPSK, 16-QAM, 64-QAM, and 256-QAM. The results in Fig. 9 are reported when the receiver is connected directly to the transmitter without using fiber (i.e., fiber length $L=0$). The calculations are repeated in Fig. 10 when a 1km of fiber is used. For both cases, the QPSK scheme requires the lowest level of signal-to-noise ratio $SNR \equiv E_b / N_o$ to achieve a specific level of a BER compared with other modulation schemes. As the modulation level M increases, the required E_b / N_o increases too.

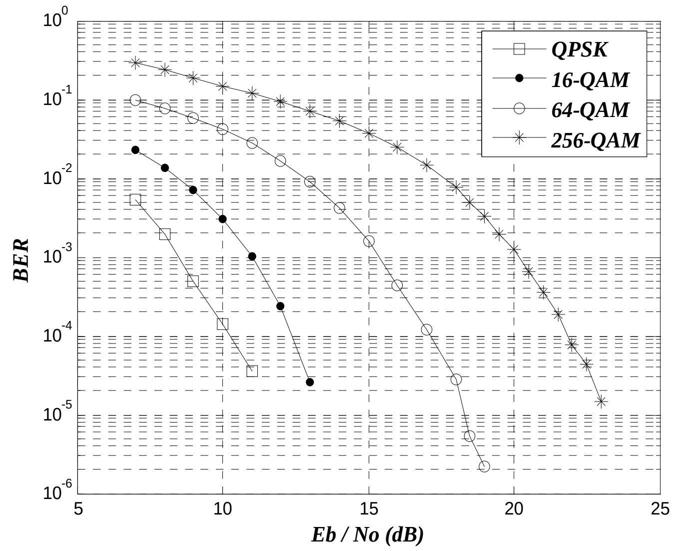


Figure (9) BER performance of OFDM system in the absence of fiber dispersion ($L=0$).

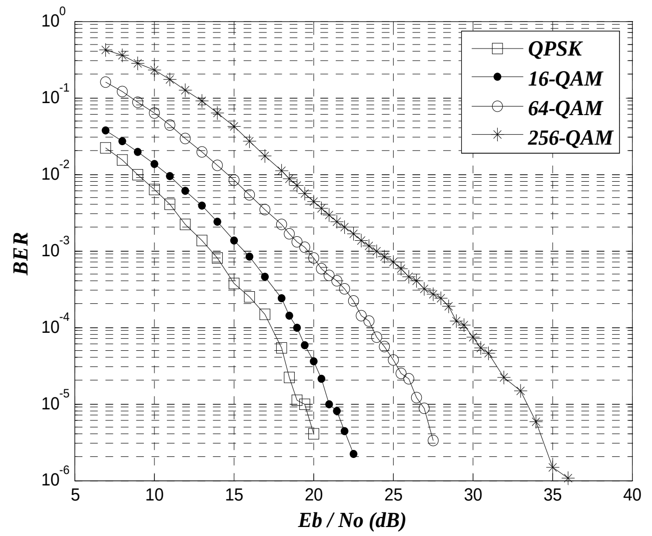


Figure (10) BER Performance of OFDM system over MMF channel with ($L=1$km).

Table (6) Dependence of BER on SNR and received optical power for different modulation schemes in the absence and presence of fiber dispersion

BER	Modulation Scheme	Fiber Length $L=0$		Fiber Length $L=1$km	
		E_b/N_o (dB)	P_b (dBm)	E_b/N_o (dB)	P_b (dBm)
10^{-3}	QPSK	8.49	-37.36	13.59	-32.12
	16-QAM	11.00	-34.80	15.59	-29.99
	64-QAM	15.34	-30.26	19.64	-25.39
	256-QAM	20.16	-24.74	23.88	-19.12
10^{-4}	QPSK	10.26	-35.56	17.38	-28.03
	16-QAM	12.39	-33.37	18.96	-26.21
	64-QAM	17.11	-28.32	23.65	-19.56
	256-QAM	21.85	-22.47	29.58	*
10^{-5}	QPSK	11.33	-34.46	19.40	-25.68
	16-QAM	13.47	-32.25	20.99	-23.67
	64-QAM	18.31	-26.97	26.75	-6.46
	256-QAM	23.15	-20.44	33.25	*

Table 6 summarizes the main results deduced from Figs. 9 and 10. The table lists the required E_b/N_o and the corresponding received optical power P_b to achieve specific levels of BER.

The power penalty due to the intermodal dispersion introduced by the 1km fiber is calculated for different levels of BER. The power penalty in decibels (dBs) is computed as

$$(\Delta P_b)_{dB} = (P_b)_{dB} - (P_{bo})_{dB} \quad (7)$$

where $(P_b)_{dB}$ and $(P_{bo})_{dB}$ are, respectively, the optical power in dBs required to achieve a specific level of BER in the presence and absence of dispersion. The power penalty is calculated using the results of Table 6 and the resultant values are listed in Table 7.

Investigating the results in Tables 6 and 7 reveals the following finding. The power penalty due to intermodal dispersion increases as the level of BER decreases and it depends on the used digital modulation scheme.

Table (7) Power penalty due to intermodal dispersion of 1km MMF (τ_{int} = 10ns)

BER	Modulation Scheme	Power Penalty $(\Delta P_b)_{dB}$ (dB)
10^{-3}	QPSK	5.24
	16-QAM	4.81
	64-QAM	4.87
	256-QAM	5.62
10^{-4}	QPSK	7.53
	16-QAM	7.16
	64-QAM	8.76
	256-QAM	*
10^{-5}	QPSK	8.78
	16-QAM	8.58
	64-QAM	20.51
	256-QAM	*

Note: (*) in Tables 6 and 7 denotes that the required BER cannot be achieved even when P_b tends to infinity.

5. CONCLUSIONS

Comprehensive analysis and modeling have been reported for optical OFDM scheme adopted for communication system incorporating Multimode Fiber (MMF) link. The main conclusions drawn for this study are the power penalty due to intermodal dispersion increases as the level of BER decreases and it depends on the used digital subcarrier modulation scheme. The sensitivity enhancement increases with decreasing the level of BER. The code SNR gain is independent on RIN while the receiver sensitivity enhancement increases with RIN. The effect of OFDM is more pronounced as the intermodal dispersion increases. The QPSK scheme requires the lowest level of signal-to-noise ratio $SNR \equiv E_b / N_o$ to achieve a specific level of a BER compared with other modulation schemes. As the modulation level M increases, the required E_b / N_o increases too. Finally, a comprehensive model must be used to calculate the multimode propagation characteristics of a MMF to get an accurate simulation results for an optical OFDM system incorporating this fiber.

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تقييم أداء منظومة أتصالات الألياف البصريه متعددة النمط المعتمده على طريقة تضمين تقسيم التردد المتعامد

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الخلاصه

أن التقييد الأكثر تأثيراً لأرسال البيانات (المعلومات) في الألياف البصريه متعددة النمط (MMF) هو التشتت النمطي بسبب ان سرعة الأنتشار لكل نمط موجه تكون مختلفه. يتبنى هذا البحث مخطط تضمين تقسيم التردد المتعامد (OFDM) البصري للحد من التشتت النمطي و لتحسين حاصل ضرب الطول و عرض النطاق الترددي للألياف متعددة النمط (MMF).يستند مخطط تضمين تقسيم التردد المتعامد (OFDM) البصري المتبنى في هذا البحث على معاملة تلاشي الأشاره بسبب التشتت النمطي في الألياف متعددة النمط بطريقه مماثله للتشتت للذي تسببه ظاهرة تعدد المسارات في القنوات اللاسلكيه. أن نموذج Simulink لمنظومة تضمين تقسيم التردد المتعامد البصري تطور باستعمال MATLAB. قدمت نتائج التمثيل لوصله 1Gbps ، تعمل مع مختلف مخططات تضمين الناقل الثانوي الرقميه لتقييم تأثير مختلف المعالم على أداء النظام. تشير النتائج التي تم الحصول عليها بشكل واضح بأن $BER=10^{-5}$ يمكن أن تتحقق لوصله (1Gbps,1km) و بتشتت (10ns) تعمل مع -, (1550nm 23.6dBm) ليزر ومخطط تضمين الناقل الثانوي (16-QAM).