PERFORMANCE INVESTIGATION OF LINEARLY POLARIZED HYBRID MODE AND WAVELENGTH DIVISION MULTIPLEXED TRANSMISSION OVER MULTIMODE FIBER TO ENHANCE SYSTEM CAPACITY

[1]RAJAN GUPTA, [2]RAJINDER SINGH KALER

Thapar University, ECE Department, Optical Fiber Communication Research Laboratory (OFCR Lab), Patiala- 147004, Punjab, India
E-mail: gupta.rajan112@gmail.com

Abstract - In this paper, the performance of 10 Tb/s LP-MDM-WDM (Linearly Polarized-Mode Division Multiplexed-Wavelength Division Multiplexing) multimode fiber link has been investigated using Adaptive MIMO LMS equalization algorithm. It is reported that Adaptive MIMO LMS equalization algorithm at receiver provide best results supporting 625 users covering transmission distance of 700 km over MMF with acceptable BER ($<10^{-8}$) and Quality-factor (>9.8 dB) to avoid intermodal crosstalk. Featuring distinctive simplicity with reduced interference and low power consumption, the proposed design is ideal to cope up with the higher data capacity of 10 Tb/s supporting 625 users with minimum use of bandwidth for upcoming optical communication at reduced channel spacing of 0.05 nm.

Index Terms - LP modes, MMF, MDM, MIMO and WDM

I. INTRODUCTION

The hasty increase in internet traffic is raising the demand for higher data capacity in existing communication networks. Therefore, to cope up with the internet capacity a variety of optical networks are being explored gradually [1-2]. In literature, numerous multiplexing techniques utilizing phase, amplitude and wavelength of light; optical networks like WDM ring topology, DWDM (Dense WDM) ring topology etc. has been reported that enhance system capacity and support SMF [3]. But still research field is exploring spatial multiplexing to further enhance the capacity of transmission system. SDM (Spatial Division Multiplexing) fulfill the demand of higher quality and forthcoming capacity as required by end-user applications [4]. MDM utilizing MMFs (multi-mode fibers) has caught curiosity from last 3 to 4 years to large extent to boost capacity of communication networks and compensate for power losses [5]. The present growth in Linearly Polarized MDM systems for reliable transmission requires the advancement of multiple modes domain with wavelength division multiplexing eliminating the necessity of costly conversions in optic domain.

The research in field of MDM was started in 1982 [6] but until 30 years researchers never took interest to this novel technique. The demonstrations done firstly on MDM system with MMF presents coverage of 10 km distance using 3 spatial modes modulated at 14GBaud PDM-QPSK [7]. Bai et al. [8] demonstrated a mode division multiplexing based WDM system covering distance of 50-km over FMF (Few-mode fiber) and utilizing two modes: LP_{01} and LP_{11} (degenerate modes). Recently, Amphawan et al. [2] investigated HG-MDM (Hermite-Gaussian Mode Division Multiplexing) system with MMF and achieved good BER for channel spacing with HG modes x-index (x=2, 3) over 800 m distance of MMF. This testing was restricted by the transmission distance and number of modes.

The single mode fiber does not provide higher data capacity but data transmission over modes in MMF multiplies the data capacity by number of modes. As, demand for higher data capacity is the need of the hour but mode coupling prevails inside MMF during transmission of data over multiple modes. So, it becomes necessary to get higher capacity at the cost of decrease in mode coupling Different numerical analysis and experiments have been made for LP modes transmission in MDM system with MMF to increase internet capacity. Also, these need advancement in fibers supporting various spatial modes, amplifiers with multimode domain, mode MUX and DEMUX compatible with MDM to enhance capacity of system. This paper deals with multi-modal domain to propose 10 Tb/s LP-WDM-MDM system for transmission of 25 independent channels over 25 linearly polarized modes propagating through multimode fiber link. After the introduction, section II explains the system setup. Section III presents results and discussion and finally, section IV summarizes the conclusions.

II. SYSTEM SETUP

The simulation schematic of proposed hybrid 10 Tb/s LP-WDM-MDM system is provided by Fig.1. The

transmitter section of proposed system consists of five multi-mode transmitter arrays (MM Tx Array1to MM Tx Array 5) tuned at wavelengths from 1550 nm to 1550.2 nm (λ_1, λ_2, λ_3, λ_4, λ_5) with channel spacing of 0.05 nm. Each MM Tx Array includes five multimode transmitters (MM Tx1, Tx2, Tx3, Tx4, Tx5). Each MM Tx includes laser source and MZ modulator for each information source (D1 to D25) thus, producing 25 different LP modes. The information source is in NRZ format with 10 Gb/s bit rate for each wavelength per LP mode generating system data rate of 10 Tbps or 1250 Gbps (10Gbps x 5 λ x 25M). The electrical driver creates the suitable data format for transmission, converts the input binary logical signal into electrical one and MZ modulator modulates the laser beam. Signals from 25 channel MM Tx are fed to mode converters for mode conversion and then to 5 mode combiners (indicated as Modal MUX) for grouping of modes each with 5 LP modes.

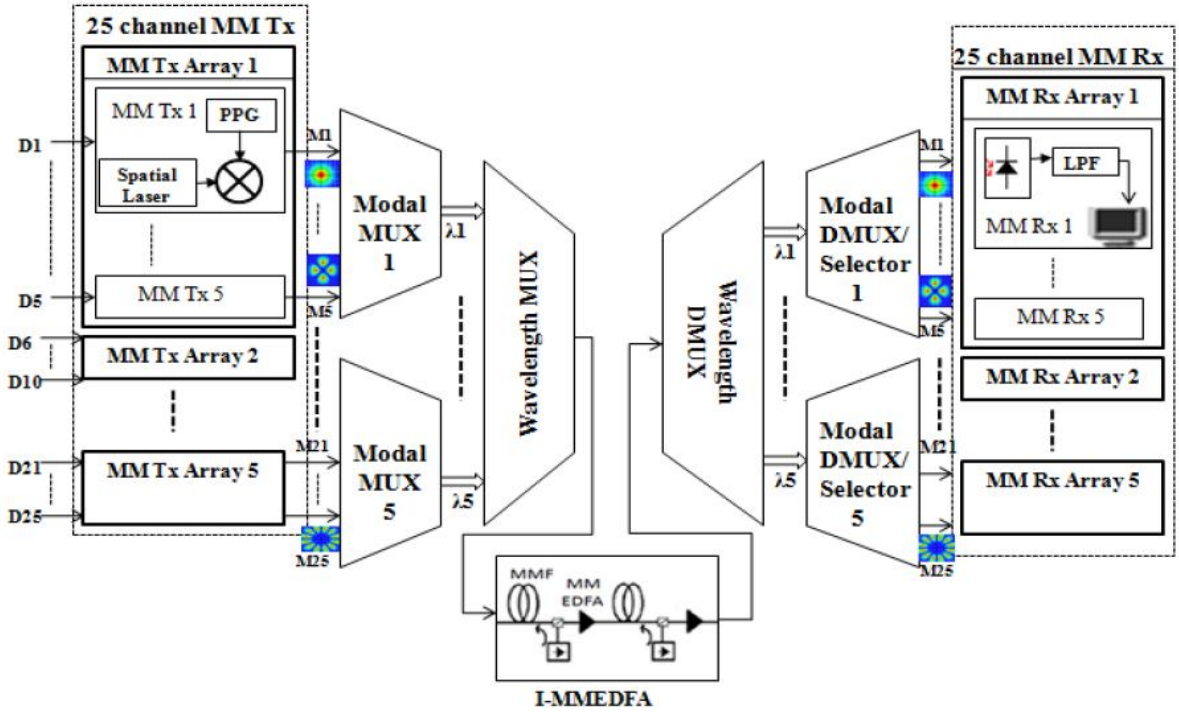


Fig.1. System setup for 25 channel LP-WDM-MDM optical communication system; MM: multimode, Tx: transmitter, Rx: receiver, I-MMEDFA: inline-multimode EDFA amplifier configuration, LPF: low pass filter, M: modes (M1-M25) and D: data (D1-D25).

Here, 5 mode groups at 5 different wavelengths as individual data signals with x-index and y-index separations are multiplexed using WDM multiplexer. Inline-multimode (I-MM) EDFA is designed to amplify multiple modes and support modes (wavelength and mode division multiplexed) through MMF having parabolic index.

Name of parameter	Value
Signal wavelengths	1550 to 1550.2 nm
Channel spacing	0.05 nm
No. of channels	25
Length	15 km
Data rate	10 Tbps
Attenuation/length	0.2×10^{-3} dB/km
EDFA Pump type	Counter-propagate
EDFA pump wavelength	980 nm
EDFA gain	Flat
EDFA noise figure	4 dB
MMF η peak	1.80
Dispersion	-99 ps/nm/km

Table 1: System parameters

Different parameters of source MM transmitter array, MMF fiber and MDM system are described in Table1. In receiver section, signals having different modes at different wavelengths are demultiplexed first by WDM demultiplexer and then by 5 optical mode selectors (indicated as MS). Different independent signals over 25 modes are recovered by 5 MM (multi-mode) receivers. Each MM receiver contain PIN photo detector which is used to convert the optical signal into electrical followed by a LPF and optical analyzer for monitoring the BER, eye diagram and Quality-factor of transmission link.

III. RESULT AND DISCUSSION

The key point of the simulation of LP-WDM-MDM system is to determine the intensity profile of modes while propagating through MMF. The LP modes travelling inside core under weakly guided condition are determined by solving Helmholtz equation 1 with varying index profile.

$$\hat{D}E = \left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E}{\partial r}\right) - \frac{l^2}{r^2}E + \varepsilon(r)k_0^2 E\right] = n_{eff}^2 k_0^2 E \qquad (1)$$

where, D is differential operator, E represents mode field distribution, l corresponds to variation of light intensity in azimuthal plane, n_{eff} is effective propagation index and k_0 denotes wave vector of incident light.

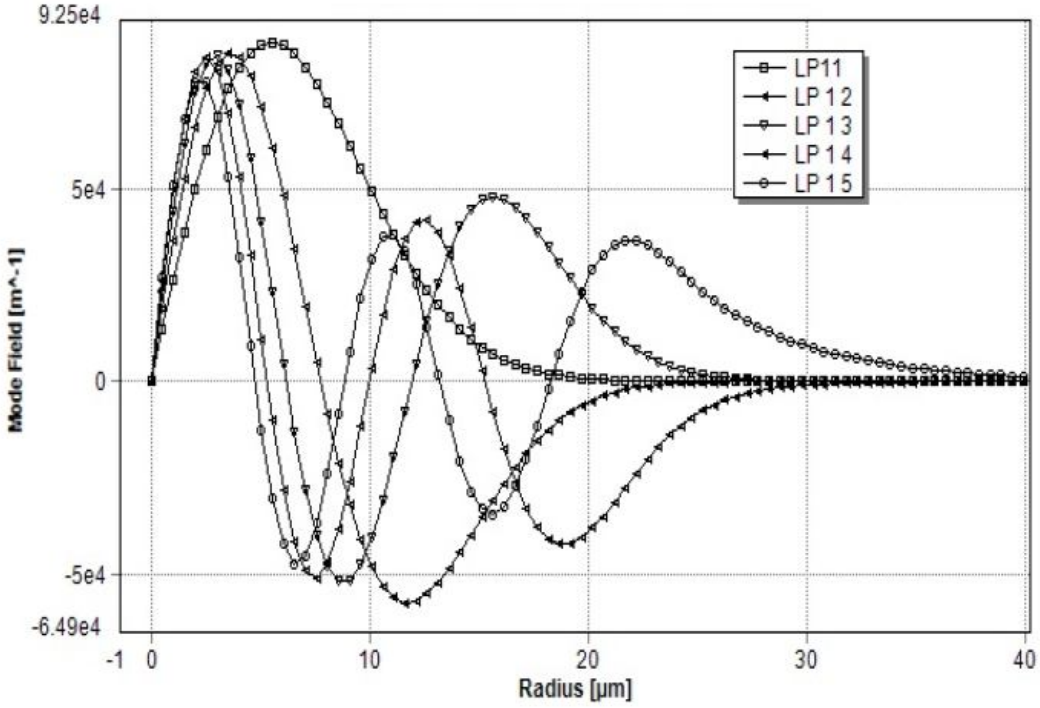


Fig. 2. The mode field intensity distribution of 5 different LP modes as function of the radius in the MMF.

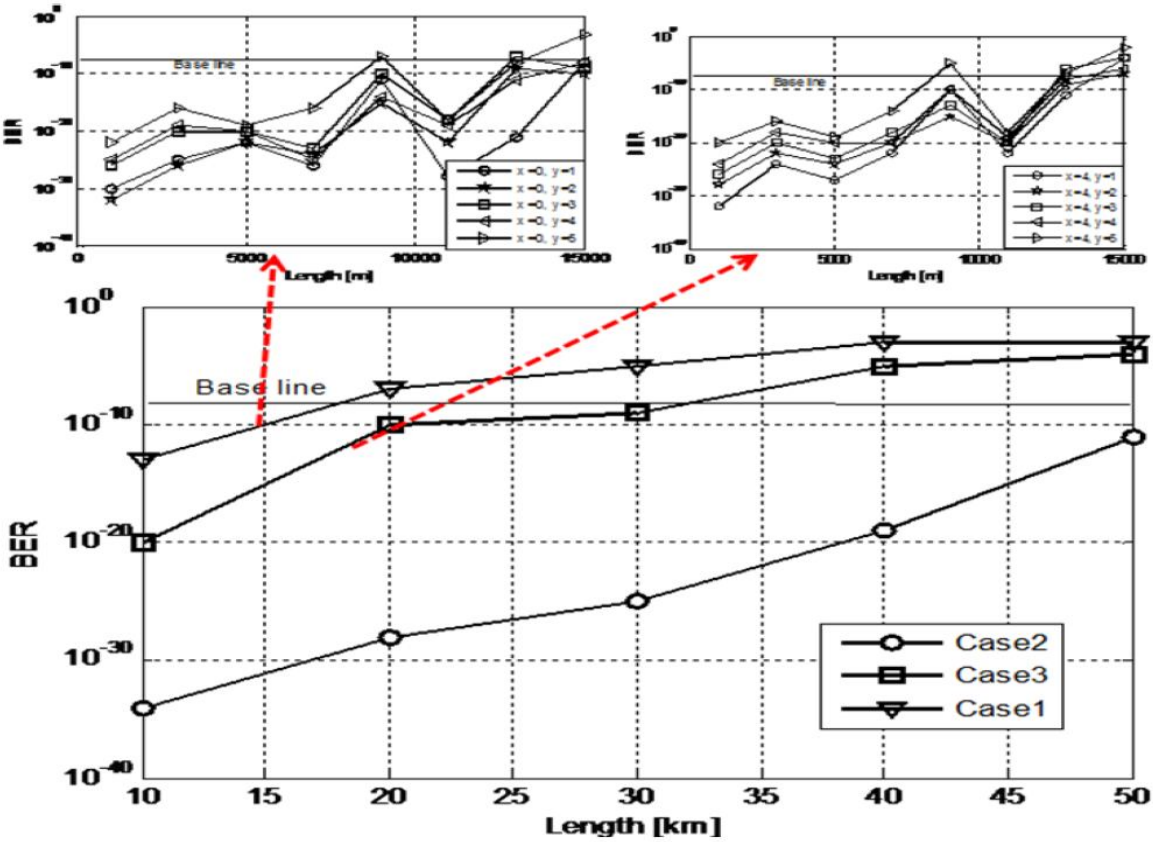


Fig. 3. BER of 25 channel LP- WDM-MDM system as a function of distance for index separations Case1: x=0 and 1, y= 1 to 5; Case2: x=2, y= 1 to 5; Case3: x=4, y= 1 to 5.

Fig.2 represents the calculated normalized mode field of different linearly polarized modes (Mode 1 to Mode 5: LP_{11}, LP_{12}, LP_{13}, LP_{14}, LP_{15}) propagating through MMF at 1550 nm. These 5 modes were generated at MM Tx Array 1 and then normalized by mode combiner (MC1) as shown in Fig. 2. Similarly, 25 modes (Mode 1 to Mode 25) were generated at 5 different MM transmitters (MM Tx Array1 to 5) and then normalized by 5 different mode combiners (MC1 to MC5). The length of MMF has been varied from 1 km to 50 km to investigate the outcome of channel index spacing on performance of hybrid LP-WDM-MDM system. Thus, channel spacing with varied x and y-index of LP modes is observed in terms of bit error rate to evaluate the performance of MDM WDM system. Fig.3 illustrates the variation of bit error rate with MMF length for different channel indices of LP modes for each mode group. Three cases are considered to observe the result of channel index spacing of LP modes on performance of system:- Case1: when x-index spacing is narrow (i.e x=0,1 for y-index= 1 to 5) represented by upper left graph; Case 2: when x-index spacing is moderate (x=2 for y-index= 1 to 5) and Case 3: when x-index spacing is too large (x=3, 4 for y-index= 1 to 5) represented by upper right graph. From upper left graph for case1, it is observed that from length 1000 m to 5000 m, power coupling between LP modes increases and then decreases but modal delay difference is moderate resulting in low interference. From 5000 m to 9000 m, power coupling still prevails but modal delay difference becomes large giving rise to interference but after 13000 m interference goes on increasing.

Same trends are seen in upper right graph (Case3) when x-index separation is too large, modal delay is large and higher interference. When x-index separation of modes is moderate (x=2 in Case2) then good BER is attained for all y-index configurations, therefore low propagation delay and improved interference. It is concluded that maximum transmission distance (i.e. 50 km over MMF) is achieved with low interference and acceptable BER ($<10^{-9}$) for moderate x-index channel spacing (Case 2: x=2, y=1 to 5) between LP modes. These results prove better performance over [2] in which authors achieve good BER for channel spacing (x=2, 3) of HG modes over distance of 800 m MMF. The performance of the system is restricted due to intermodal crosstalk and only a maximum distance of 50 km is achieved with acceptable BER ($<10^{-9}$). The transmission performance is then enhanced by demultiplexing the modes using DSP filter to lower the intermodal crosstalk. During propagation of the signal mode coupling takes place as the modes travels at different velocities in MMF. So, the output signal must be processed using DSP MIMO filter in order to reduce coupling. The time dispersion and mode coupling caused by channels can be compensated by Equalization technique which is performed in the frequency domain. The optimization of taps (filter coefficient) is done by utilizing LMS (least mean square) adaptive MIMO filter algorithm to minimize the mean-squared error at the output signal in order to avoid mode group coupling in MDM based system. The input-output relation of mode division multiplexed system having M (M1 to M25) spatial modes can be represented as:

$$y(t) = H(t) * x(t)$$

where x(t) denotes transmitted signal, H(t) is channel or coupling matrix having M×M matrix (here in proposed: 25×25) of tap delay line filters and y(t) is received signal respectively. To recover signals from different mode channels and to completely compensate the signal distortion at the receiver, an adaptive equalizer implements matrix C(t) that should be the inverse of channel matrix H(t) such that:

$$x(t) = C(t) * y(t)$$

At the coherent receiver signals from different mode channels are demodulated and then digitalized. The digital sequence $x_1(n)$, $x_2(n)$..…….. $x_M(n)$ is fed to equalizer block for adaptive compensation. The equalization of k^{th} sample on i^{th} mode is calculated as given by equation 2:

$$y_i(k) = \sum_{j=1}^{M} \sum_{i=0}^{Ntaps} h_{ij}(i) X_j(k-i) \qquad (2)$$

where, Ntaps is the number of filter taps and i;j are values of mode index ranging from 1 to M. In frequency Equalization LMS, filter coefficient values are taken in frequency domain and computed using following equation 3:

$$\overline{C^{(j)}} = \overline{C^{(j-1)}} + \mu \begin{bmatrix} \overline{E_{1,j}(k)} \otimes \overline{Y^*_{1,j}(k)} & \overline{E_{1,j}(k)} \otimes \overline{Y^*_{2,j}(k)} \\ \overline{E_{2,j}(k)} \otimes \overline{Y^*_{1,j}(k)} & \overline{E_{2,j}(k)} \otimes \overline{Y^*_{2,j}(k)} \end{bmatrix} \qquad (3)$$

where, $\overline{C^{(j)}}$ represents inverse channel equalizer filters, μ is convergence step size, $\overline{E_{i,j}(k)}$ depicts j^{th} error block for i^{th} mode, $\overline{Y^*_{i,j}(k)}$ is conjugate of the received signal block in frequency domain for i^{th} mode and symbol ⊗ denotes element to element multiplication. The error signal (obtained by subtracting received signal from desired signal, $e_i(k) = d_i(k) - y_i(k)$) and the received signal are taken in time-domain. For adaptive Equalization method, to adjust the equalizer coefficients error block is calculated in time domain first and then FFT is taken. After the computation of equalization, comparison of each output sample is done with the desired output and the resultant error is then fed back to Gradient estimation block. The gradient estimation processes the error signal and then updates the value of equalizer filter tap coefficients to minimize the coupling error in

the system.

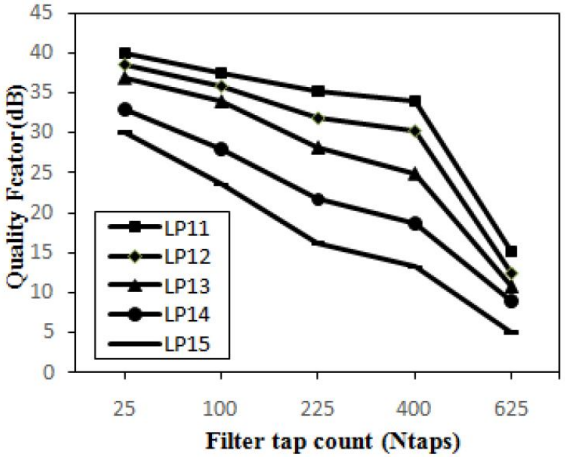


Fig. 4. Optimized performance of LP modes with MxM MIMO filter taps after equalization

The quality performance of different LP modes (LP_{11}, LP_{12}, LP_{13}, LP_{14} and LP_{15}) in LP-WDM-MDM systems has been investigated by varying the MIMO filter tap coefficient as shown in Fig. 4. After equalization, performance of modes in system is optimized by taps thus minimizing the mean square error. It can be seen from Fig. 4 that with the increase in M x M MIMO filter tap size (where Ntaps=M^2) LP modes (LP_{11}, LP_{12}, LP_{13} and LP_{14}) provide good quality above 10dB except higher order mode LP_{15} performs poorely with Ntaps>= 625.

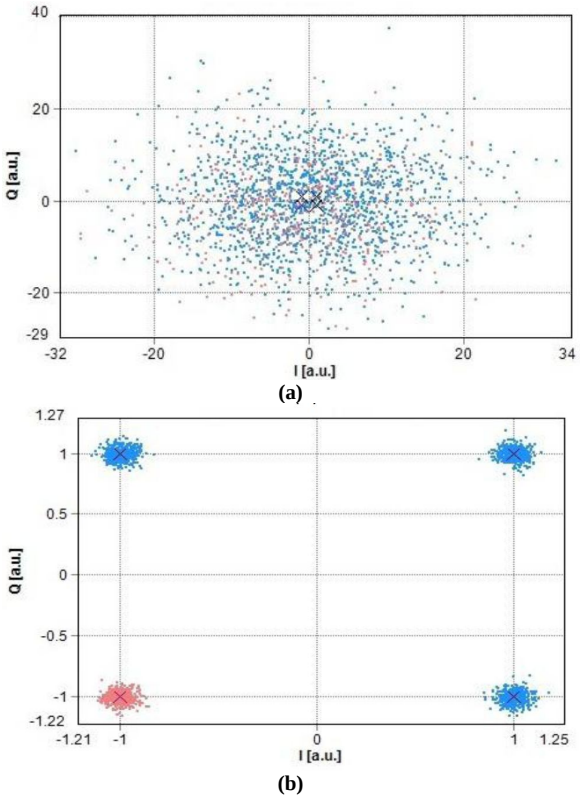


Fig.5. (a) Constellation diagram of received signal over (a) 50 km MDM link without MIMO equalization and (b) 700 km MDM link with Adaptive MIMO LMS equalization.

Fig. 5 represents the received constellations for LP-WDM-MDM link with 25 modes where each mode is QPSK-modulated and transmitted power was set to 0 dBm and maximum differential delay between modes was kept to be 0.2ps/m. It can be observed from Fig. 5(a) that without MIMO equalization there is scattering of received symbols due to intermodal interference whereas Fig. 5(b) shows a notable reduction of the nonlinear interference due to the application of Adaptive MIMO equalization. On comparing without and with MIMO compensation for all the system configurations (5 × 5, 10 × 10, 15 × 15, 20 × 20 and 25 × 25) it is found that the latter is superior to the former.

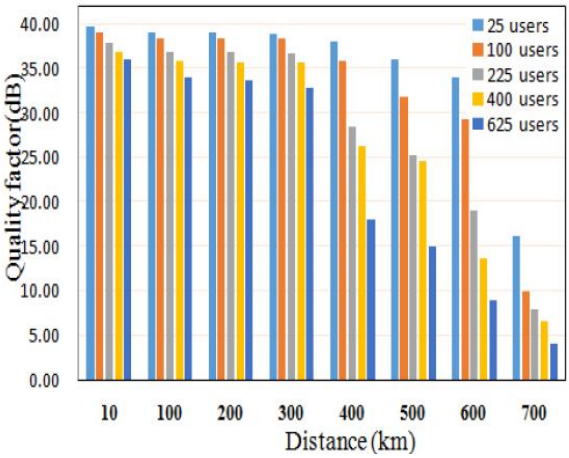


Fig. 6. Enhanced performance of 10 Tb/s LP-WDM-MDM system using MIMO Adaptive LMS equalization.

It is necessary to observe the performance of LP-WDM-MDM system after applying DSP MIMO filter at receiver end with respect to Q-factor to determine the higher possible capacity and transmission. Fig. 6 shows the enhanced performance of LP-WDM-MDM system (with MIMO filter tap optimization) supporting different number of users (25, 100, 225, 400 and 625) for longest possible transmission. It is noticed that for an acceptable quality factor (> 8.01 dB) system supports upto 225 users with maximum transmission distance of 700 km whereas it supports 400 users allowing 685 km and supports 625 users covering maximum transmission of 640 km respectively. It is concluded that using MIMO filter DSP approach, LP-WDM-MDM system achieved Q-factor (> 8.01dB) supporting 625 users with higher data capacity of 10 Tb/s covering 640 km of transmission distance.

CONCLUSION

This paper investigated linearly polarized hybrid wavelength and mode division multiplexing system with adaptive MIMO equalization to improve modal interference and enhance performance capacity. It is concluded that LP-WDM-MDM system covered a

maximum transmission distance of 50 km with intermodal crosstalk whereas by utilizing adaptive MIMO equalization algorithm system performance is optimized by filter taps and thus supports 625 users covering 700 km with acceptable BER ($<10^{-8}$) and Quality-factor (>9.8 dB) over MMF link. The designed hybrid LP-WDM-MDM transmission link can be used in optical network interconnects at data centers to fulfill the higher internet capacity at reduced channel spacing of 0.05 nm.

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