

Performance Limitations of a Subcarrier Multiplexed Optical Fiber Link Impaired by Optical Beat Interference and Intensity Noise

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Abstract -Theoretical performance analysis is presented for an optical transmission system with RF subcarriers multiplexing (SCM) for radio on fiber technology considering the effect of PM-IM conversion due to Mach-zehnder modulator (MZM) and optical beat interference (OBI) generated during photodetection process. The computed bit error rate (BER) performance results show that there is a significant deterioration in system BER due to OBI and PM-IM conversion and the system suffers significant power penalty at a given BER. The penalty is found to be approximately 5.8 dB, 11.0 dB, 13.5 dB, 15.0 dB, 17.0 dB for PM-IM conversion factor of -1, -2, -3, -4, -5 and 18.0 dB, 18.5 dB, 20.5 dB, 21.5 dB, 22.0 dB for number of subcarriers of 2, 4, 8, 16, 32 respectively.

Keywords-Optical link, PM-IM conversion, Optical beat Interference (OBI), Subcarrier multiplexing.

I. INTRODUCTION

The demand for ultra-large capacity transmission system for long-haul communication systems and future multi-media services is increasing rapidly [1]. Multiplexing of optical signals promises to meet this demand, several approaches being possible depending on the application [2]. Subcarrier multiplexing techniques (SCM) offers great application potential. Optical subcarrier multiplexing (SCM) is a scheme where multiple signals are multiplexed in the radiofrequencies (RF) domain and are used to modulate directly the laser diode to be transmitted by a single wavelength. A significant advantage of SCM is that microwave devices are more mature than optical devices. The stability of a microwave oscillator and the frequency selectivity of A significant advantage of SCM is that microwave devices are more mature than optical devices. The stability of a microwave oscillator and the

frequency selectivity of Microwave filters are much better than their optical counterparts. In addition, the low phase noise of RF oscillators makes coherent detection in the RF domain easier than optical coherent detection, and advanced modulation formats can be applied easily. A popular application of SCM technology in fiber optic systems is analog cable television (CATV) distribution [1], [2]. Because of the simple and low cost implementation, SCM has also been proposed to transmit multi-channel digital optical signals using direct detection for local area optical networks. The performance of an optical link with RF Subcarrier multiplexing is limited by the Phase modulation to intensity modulation (PM-IM) conversion due to Mach-Zehnder interferometers used in optical modulator [3].

Further, during the photodetection process there is generation of optical beat interference (OBI), which greatly limits the number of subcarrier that can be multiplexed [4]. In this paper, an analytical approach is presented to evaluate the combined interference of PM-IM conversion and the impact of OBI on the bit error rate (BER) performance of a subcarrier multiplexed optical communication system.

II. SYSTEM BLOCK DIAGRAM

The block diagram of the SCM optical transmission system under consideration is shown in Fig. 1. The receiver block diagram is shown in Fig. 2. The square law envelope detection by the nonlinear device photodetector (PD) causes optical bit noise. A total of M optical fields is present at PD input. At the output of the PD, we would expect M terms representing the field intensities, plus M (M-1) cross term, If the spectral content of any one of these cross terms falls within the passband of the bandpass filter (BPF) in the intended user

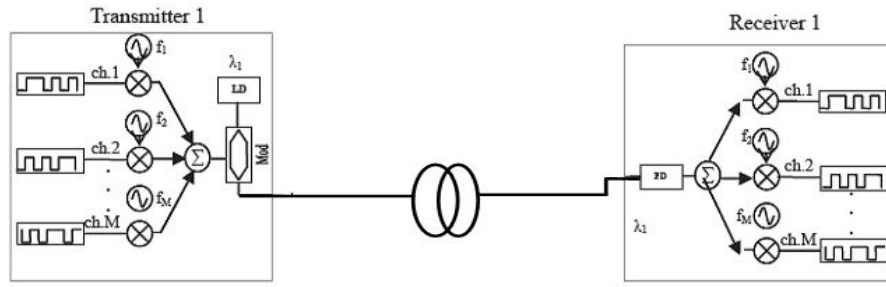


Fig. 1 Block diagram of an optical transmission system using subcarrier multiplexing (SCM).

channel, it will cause interference. OBI causes represent a serious limitation on the transmission capacity [4].

III. THEORETICAL ANALYSIS

3.1 Modulator chirp parameter effect

The chirp parameter v is important in externally modulated systems as it indicates the phase of the output signals from the modulator. While MZ interferometer-type intensity modulators (MZM) can be designed to operate completely chirp-free, in most devices there is a small residual chirp arising from an asymmetry in the overlap of the electric fields at each electrode [2]. A dual electrode MZM, which allows access to both electrodes, can be used to achieve a variable chirp parameter. For such a device, the chirp parameter can be related to the relative amplitude and sign of the RF drive signals to each electrode V_1 and V_2 as [5]

$$V = \frac{V_1 + V_2}{V_1 - V_2} \quad (1)$$

A related parameter for a modulator is the α parameter, which represent the ratio of phase to amplitude modulations and can be defined as [5]:

$$\alpha = \frac{1}{2S} \left(\frac{d\Phi}{dt} \right) / \left(\frac{ds}{dt} \right) \quad (2)$$

where ϕ and S are the instantaneous phase and intensity at the output of the modulator. For the MZM, α is a function of the modulator depth and dc-bias point, and is related to v as [4]:

$$\alpha = v \tan \left(\frac{\pi}{2} \frac{V_{dc} - V_0 - V_\pi}{V_\pi} \right) \quad (3)$$

where V_0 is the offset voltage corresponding to the phase retardation with no applied electric field. Equation (3) indicates that the modulator can be biased to obtain both positive or negative values of α and that if the modulator is biased at quadrature, i.e.

$$V_{dc} = V_0 + V_\pi / 2, V_0 + 3V_\pi / 2 \dots$$

$$\text{Then } |\alpha| = |v|$$

In high-speed baseband digital transmission it has been shown that dispersion-induced power penalties can be reduced using a modulator with a small negative chirp. In fiber-wireless system employing MZM's, the modulator chirp will also influence dispersion effect. Since α affects the phase of the spectral components, it will affect the fiber distance at which the RF beat signals after the photodiode exhibit a π phase difference.

If the MZM has chirp, then fiber length, L , where, [4]

$$L = \frac{c}{2D\lambda_c f_{rfN}} \left(N - \frac{2}{\pi} \arctan(\alpha) \right) \quad (4)$$

$N=1, 3, 5$

Equation (4) indicates that the fiber-link distance in externally modulated analog systems can be increased when α is large and negative. For MZM's, which have nonzero chirp, optimum transmission distance can, therefore, be obtained by biasing on the appropriate slope of the MZM transfer function. A more useful determination of achievable transmission distance is to consider the detected RF power at the modulating frequency P_{rf} , which is given by:

$$P_{sc} = \alpha \cos \left\{ \frac{\pi L D \lambda_c^2 f_{rf}^2}{c \left[1 - \frac{2}{\pi} \arctan(\alpha) \right]} \right\} \quad (5)$$

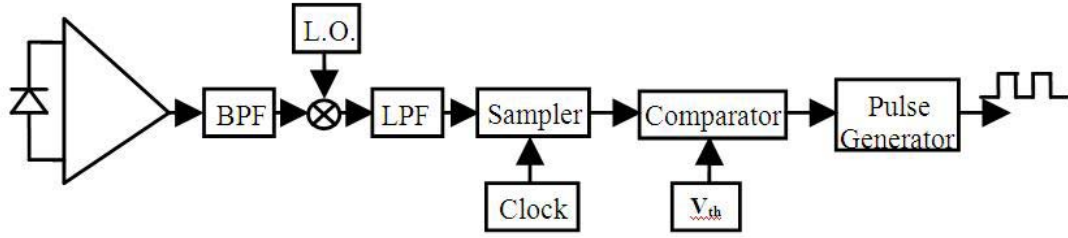


Fig. 2 Receiver block diagram

The signal to noise ratio SNR at the output of the PD can be expressed as:

$$\text{SNR} = \frac{(R_d P_{sc})^2}{\sigma_n^2 + \sigma_{th}^2} \quad (6)$$

where R_d is the PD sensitivity, σ_{th}^2 is the variance of receiver thermal noise and σ_{sh}^2 is the PD shot noise variance.

3.2 Effect of Optical Beat Interference (OBI)

In optical beat interference (OBI), M optical fields in a given optical channel have the same average center frequency. However, the simultaneous optical frequencies are generally different and can be varying with time. Each of these fields

can be represented by: $c_i(t) = [S_i(t)]^{\frac{1}{2}} \cos[\varphi_i(t)]$ (7)

where, the intensity modulated by an RF subcarrier of center frequency f_i is represented by :

$$S_i(t) = S_0 \{1 + m \cos(2\pi f_i t)\} \quad (8)$$

The phase of the electric field in (8) can have a component due to the operating optical frequency F_i , a chirp component $\varphi_{mi}(t)$ in the case of direct laser modulation, a phase noise component $\varphi_{ni}(t)$ modeled by a Wiener- Levy process, and possibly a random component $\varphi_{pi}(t)$ due to polarization fluctuation. Hence, the total phase can be written as :

$$\varphi_i(t) = 2\pi F_i t + \varphi_{mi}(t) + \varphi_{ni}(t) + \varphi_{pi}(t) \quad (9)$$

The front end of the reference receiver (corresponding to user number k) is an optical filter centered on the optical carrier frequency of the intended user channel. As a result, out of a possible filter, only M continue their way to the photodetector. The center frequency of the optical filter in the reference

receiver will be denoted by F_0 . All M users in the same optical channel will have identical optical filters. The total field $e(t)$ at the input of the photodetector is the sum of M fields of which can be written as in (6), hence,

$$e(t) = \sum_{i=1}^M e_i(t) \quad (10)$$

The Photodetector converts this field into an electric signal proportional to the field intensity. The constant of proportionality is equal to the photodetector responsivity. Since the same constant applies to all terms in the PD output current, it will be set to unity without loss of generality. This yields the (normalized) photo-detector output as :

$$I(t) = LP\{e(t)^2\} = LP\left\{\sum_{i=1}^M \sum_{l=1}^M e_i(t)e_l(t)\right\} \quad (11)$$

where the LP operator designates taking the low-pass part of the argument. The right-hand-side of (11) can be broken into a signal component $I_s(t)$ and a cross-term component $I_c(t)$ as follows:

$$I(t) = LP\left\{\sum_{i=1}^M e_i^2(t) + 2 \sum_{i=1}^{M-1} \sum_{l=i+1}^M e_i(t)e_l(t)\right\} \quad (12)$$

Note that, $I_c(t)$ constitute an interference term that is generally nonzero. If any of the spectral components of $I_c(t)$ falls within the bandwidth of one of the M users BPF's, it will cause OBI.

The bit error rate including the effect of OBI can be expressed

$$\text{BER} = 0.5 \operatorname{erfc} \frac{(R_d P_{ff})}{\sqrt{\sigma_{sh}^2 + \sigma_{th}^2 + \sigma_{obi}^2}} \quad (13)$$

where, σ_{obi}^2 is the OBI.

IV. RESULTS AND DISCUSSION

Following the analytical approach presented in sec. 3 , we evaluate the bit error rate (BER) performance of a subcarrier multiplexed optical fiber communication system considering the effect of PM-IM conversion due to MZM and the effect of OBI generated during photodetection process. The plots of BER versus the received subcarrier power P_{sc} are depicted in Fig 3 through Fig 5 considering the effect of PM-IM conversion due to MZM for different values of α and BW=1, 5, 10, 20 GHz. The result show that there are significant degradation in the BER performance due to PM-IM conversion which is higher at higher values of α .

The results further show that the deterioration in BER performance is more at higher bandwidth of the receiver BPF which is assumed to be equal to bit rate. The system suffers significant power penalty due to PM-IM conversion at a given BER. The effect of OBI and the BER performance are shown in Fig. 6 through 8 for bandwidth of 1GHz, 5 GHz, 10 GHz, and 20 GHz and number of subcarrier channels $M=2,4,8,16,32$. It is noticed that there is significant increase in BER due to OBI which is more prominent at higher values of M . At a specific BER, the systems suffers significant amount of power penalty due to OBI. The plots of power penalty as a function of PM-IM conversion factor α are shown is Figure-9 and those as a function of M are shown in Figure-10. It is noticed that the amount of penalty is approximately 5.8 dB, 11.0 dB, 13.5 dB, 15.0 dB, 17.0 dB for $\alpha = -1, -2, -3, -4, -5$ and 18.0 dB, 18.5 dB, 20.5 dB, 21.5 dB, 22.0 dB for $M=2, 4, 8, 16, 32$.

V. CONCLUSION

An analytical approach is presented to evaluate the impact of PM-IM conversion and optical beat interference (OBI) on the bit error rate performance of an optical fiber communication system. The results show that there is significant penalty due to PM-IM conversion and also due to OBI at a sign BER.

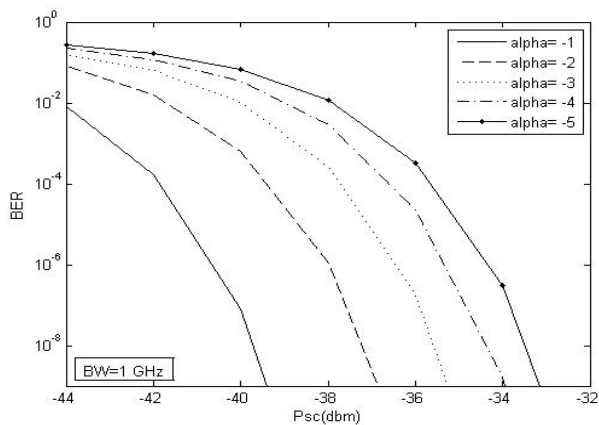


Fig 3: Bit error rate (BER) versus subcarrier power P_{sc} (dBm) for different values of PM-IM conversion factor α .BW=1 GHz

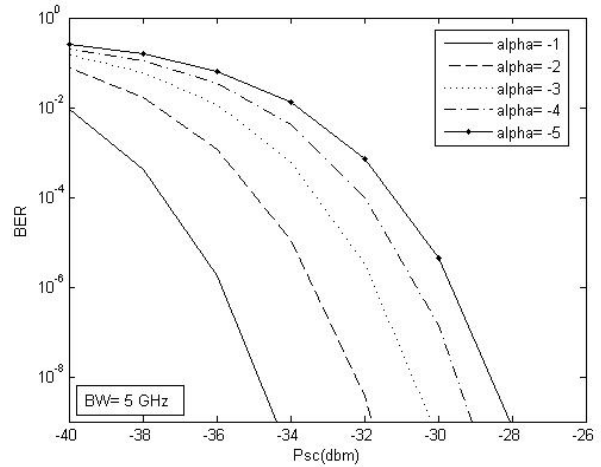


Fig 4: Bit error rate (BER) versus subcarrier power P_{sc} (dBm) for different values of PM-IM conversion factor α .BW=5 GHz

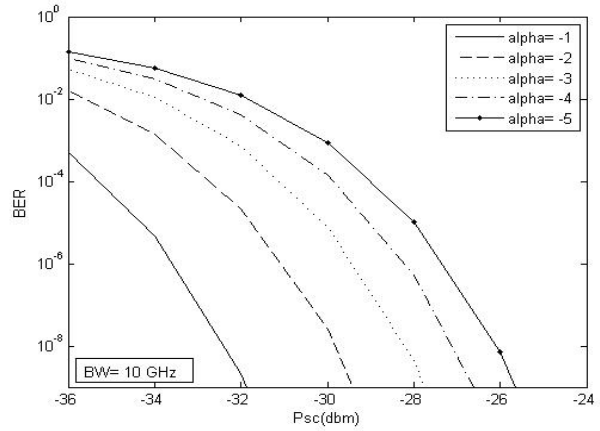


Fig. 5: Bit error rate (BER) versus subcarrier power P_{sc} (dBm) for different values of PM-IM conversion factor α .BW=10 GHz

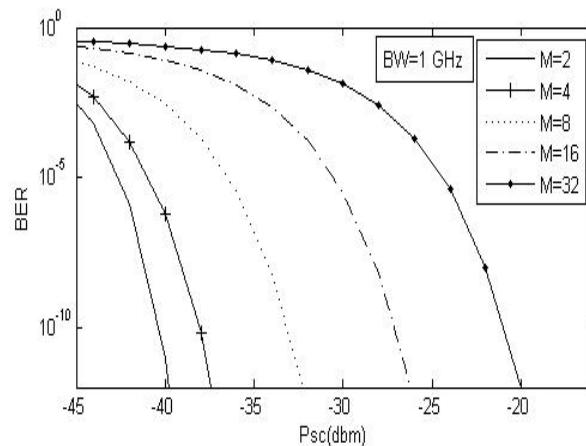


Fig. 6: Bit error rate (BER) versus subcarrier power P_{sc} (dBm) for different Values of number of subcarrier channel, (M), BW=1 GHz

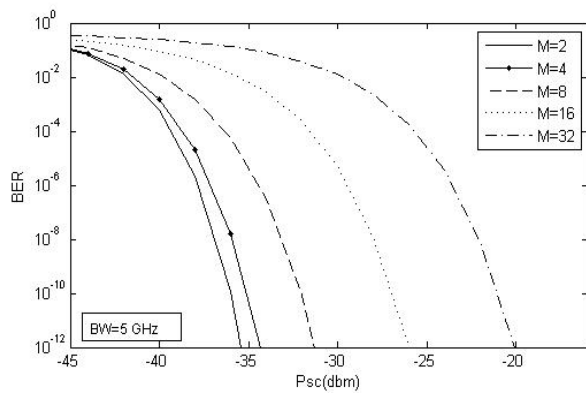


Fig 7: Bit error rate (BER) versus subcarrier power Psc (dBm) for different Values of number of subcarrier channel, (M), BW=5 GHz

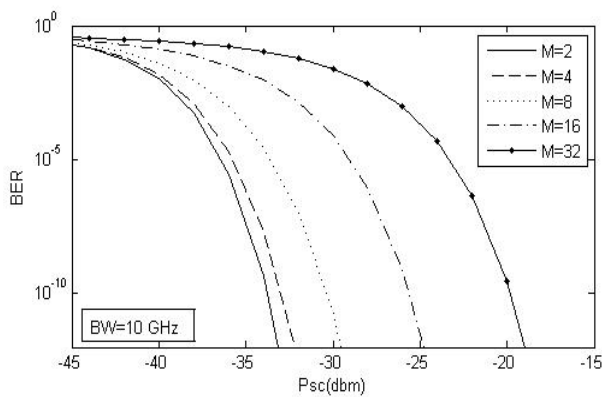


Fig 8: Bit error rate (BER) versus subcarrier power Psc (dBm) for different Values of number of subcarrier channel, (M), BW=10 GHz

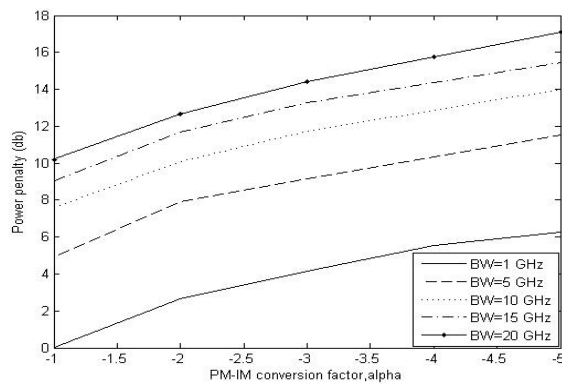


Fig 9: Power penalty (dB) versus PM-IM conversion factor for several receiver bandwidth at BER= 10^{-9}

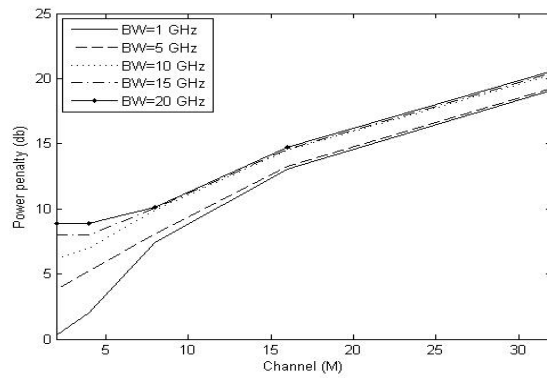


Fig 10: Power penalty (dB) versus number of subcarrier channel (M) for several receiver bandwidth at BER= 10^{-12}

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