EFFECT OF OPTICAL BEAT INTERFERENCE IN SCM/WDM OPTICAL NETWORKS IN PRESENCE OF FWM

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ABSTRACT

Subcarrier multiplexing (SCM) with Wavelength Division multiplexing (WDM) can be used to increase the capacity of any optical network. For simultaneously accessible subcarrier channels the capacity should ideally increase linearly with the number of subcarrier channels. However, when two lasers carrying subcarrier channel multiplexed data operate with very closed spaced wavelength, beating between the lasers and between the lasers and Four-Wave mixing terms can occur. This will increase the noise at the photodetector. This paper presents a general model of optical beat interference in presence of Four-Wave Mixing (FWM). Computer simulations for externally modulated single-mode laser transmitted through a Dispersion Shifted Fiber (DSF) are presented. For degenerate case, the results show degradation in Carrier to Interference Ratio (CIR) when the laser frequency separation is equal to and half of the subcarrier channel frequency.

KEYWORDS: Subcarrier multiplexing, optical beat interference, and four-wave mixing.

1. INTRODUCTION

The world of communications has been revolutionized by the appearance of lightwave technology. The key to the great success of optical communications lies with the enormous potential bandwidth (in the range of tens of Terahertz) and low transmission loss of optical fibers. In order to maximize the information transfer over any communication link, it is usual to multiplex several signals onto the transmission medium. Multiplexing schemes are related to multiple-access schemes, as they provide a way for several users to access a system.

Subcarrier multiplexing (SCM) is a simple and cost-effective alternative to high capacity Time-Division Multiplexing (TDM) lightwave systems [1-2]. SCM take advantage of matured electronic and microwave technologies and the full bandwidth capacity of single mode fiber and electro-optic components. SCM can be used in an all-optical access network where P users are interconnected via a passive star coupler. In a multiple-optical-carrier SCM Passive Optical Network (PON), each subscriber transmits in the upstream direction with its own optical source (nominally the same wavelength) by modulating a different subcarrier frequency. The photodetector at the receiver then detects the sum of all the optical signals.

The biggest challenge in MOC-SCM systems is to reduce the noise due to the optical beat interference (OBI). For upstream transmission, the dominant noise is generated from OBI, which occurs at the optical receiver when different sub-frequencies are received from different light sources but at the same (nominal) optical frequency. This dominant noise limits

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the maximum number of SCM channels that can be transmitted in a wavelength. Many efforts to study OBI have been made. Desem [3] studied how OBI affected microwave subcarriers. Shankaranarayanan *et al*. [4] investigated the statistics of the microwave subcarrier outage due to the OBI in MOC-SCM networks. Wood and Shankaranarayanan showed significant bit error rate degradation due to the OBI [5]. Nevertheless, all the previous research considered the fields at the input of the photodetector as clean modulated fields. Practically, the fields at the input of the photo detector will be affected by the non-linearity in the fiber. One of the most significant nonlinear effects is Four-Wave mixing (FWM), which is considered in this paper. FWM should be considered since a PON only consists of passive components and higher transmitted power is required. Furthermore, DSF is widely used in current optical networks

In this paper, OBI in the presence of FWM is analytically analyzed for MOC-SCM optical networks in Section 2. In Section 3, OBI due to both the laser sources and FWM is simulated and analyzed with respect to wavelength spacing and laser output power. With this analysis, we are able to quantify the effects of OBI in MOC-SCM optical networks in the presence of FWM.

2. OBI IN THE PRESENCE OF FWM

In a multi-channel system with N channels, FWM results in $(N(N-1)^{2})$ interfering signals, each denoted by the combination of subscripts i, j, and k, where they vary from 1 to N. If the total number of the fields plus the FWM terms is equal to M, we would expect at the photodetector output $M\text{-}N(N-1)^{2}$ terms representing the field intensities, plus $M(M-1)$ cross-terms. If the spectral content of any one of these cross-terms falls within the passband of the bandpass filter (BPF) in the intended user channel, it will cause interference. The power spectral density of the cross-terms is comparable to that of the desired signal, hence, OBI can represent a serious limitation on the transmission capacity.

In a SCMWDM system using the angular optical frequencies $w_1,\ldots,w_N$, the intensity dependence of the refractive index induces phase shifts within a channel and gives rise to signals at new frequencies such as $2w_i\text{-}w_j$ and $w_i+w_j\text{-}w_k$. This phenomenon is called Four Wave Mixing (FWM). In contrast to Self Phase Modulation (SPM) and Cross Phase Modulation (CPM), which are significant for high-bit-rate systems, the FWM effect is independent of the bit rate but is critically dependent on the channel spacing and fiber chromatic dispersion. Decreasing the channel spacing increases the FWM effect, and so does decreasing the chromatic dispersion. Thus, the effects of FWM must be considered even for moderate-bit-rate systems when the channels are closely spaced and/or when dispersion-shifted fibers are used, that is why we are only considering FWM in the current paper.

Consider a SCM/WDM signal that is the sum of N fields. The electric field of this signal can be written as

$$E(r,t)=\sum_{i=1}^{N}\left[S_i\right]^{1/2}\cos(w_i t+\phi_i(t)-\beta_i Z) \tag{1}$$

where the intensity modulation by an RF subcarrier is represented by:

$$S_i(t)=S_0\left\{1+m\,.\,x_i(t)\right\} \tag{2}$$

where $x_i(t)$ can have any form of digital or analog modulation, and m represents the intensity modulation index. β_i is the propagation constant for the WDM channels, with the corresponding angular frequencies w_i.

The additional phase $\varphi_i(t)$ of the electric field in equation (1) can have 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 [6]. Hence, the total phase can be written as:

$$\varphi_i(t)= \varphi_{pi}(t) +\varphi_{ni}(t)+ \varphi_{mi}(t) \quad (3)$$

Because of its minor effect [6], phase noise $\varphi_{ni}(t)$ will be neglected. $\varphi_{mi}(t)$ is also neglected because we assume external modulation of the lasers. As a worst case assumption, the two fields will be assumed to have the same polarization phase, hence $\varphi_{pi}(t)$ will be set to zero. These assumptions help to demonstrate how serious the OBI problem can be.

It has been shown in [7] that the power of the signal generated at the frequency w_{ijk} after traversing a fiber length of L_{eff} is

$$P_{ijk} = \eta_{ijk}\left(\frac{w_{ijk}d_{ijk}\bar{n}}{3A_e c}\right)^2 P_i P_j P_k L_{eff}{}^2 \quad (4)$$

where P_i, P_j and P_k are the input powers at w_i ,w_j and w_k, $\bar{n}$ is the nonlinear refractive index and cross-sectional area is A_e. The presence of chromatic dispersion reduces the efficiency of the mixing, so a parameter η_{ijk} which represents the efficiency of mixing of the three waves frequencies w_i, w_j and w_k has been modeled. The efficiency η_{ijk} goes down as the phase mismatch $\Delta\beta$ between the interfering signal increases. The dependence of FWM efficiency on the phase mismatching around the zero-dispersion wavelength was calculated for the partially degenerate case [8]. The results show that FWM efficiency is highest when the pump wavelength is at the zero-dispersion wavelength and that it rapidly decreases as the pump wavelength is detuned from the zero-dispersion wavelength. Frequency bandwidth within which FWM light is efficiently generated is dependent on wavelength difference between pump and probe sources. The phase-matched frequency bandwidth is narrower for the larger wavelength difference. As a result, when the difference between any two wavelengths is 50 GHz (laser frequency fluctuation) or less, the efficiency is highest.

A MOC-SCM system [3, 6] with a nominal wavelength of w_i with a wavelength fluctuation that follows a uniformly distributed random range of 50GHz, can be seen as a closely spaced WDM system. Referring to Figure 2, the efficiency is highest when the difference between any two wavelengths is 50 GHz or less [8]. Therefore, a MOC-SCM system using a DSF will be prone to FWM effect. The presence of FWM terms and the fluctuation of the wavelengths will cause severe OBI at the photodetector.

If we assume a two-subcarrier per optical channel, in either of the two optical channels, the total field amplitude $E(t)$ at the input of the photodetector is the sum of the two field amplitudes plus the FWM terms. $E(t)$ can be written as:

$$E(t) = E_1(t) + E_2(t) + E_{112}(t) + E_{221}(t) \quad (5)$$

The photodetector normalized output current can be given as:

$$I(t) = LP\left\{\left|E(t)\right|^2\right\} \quad = LP\left\{\left|\begin{array}{l} E_1{}^2(t) + E_2{}^2(t) + E_{112}{}^2(t) + E_{221}{}^2(t) \\ + 2E_1E_2(t) + 2E_1E_{112}(t) + 2E_1E_{221}(t) \\ + 2E_2E_{112}(t) + 2E_2E_{221}(t) + \\ 2E_{112}E_{221}(t) \end{array}\right|\right\} \quad (6)$$

The signal and cross-terms currents are:

$$I_s(t) = LP\left\{\left|E_1(t)\right|^2 + \left|E_2(t)\right|^2\right\} \tag{7}$$

and

$$I_c(t) = LP\left\{\begin{aligned}&2E_1E_2(t)+\\&2E_1E_{112}(t)+2E_2E_{221}(t)\\&+2E_2E_{112}(t)+2E_1E_{221}(t)+\\&2E_{112}E_{221}(t)\end{aligned}\right\} \tag{8}$$

The first term in (8) is the main OBI, which has been considered in previous research [3-6]. The second and the third term will strengthen the beating of the first term, since they have the same optical frequency. Due to its small power, the last term will be neglected. The fourth and the fifth term will cause a considerable degradation on the subcarriers signals if they fall within its BPF. These two terms will be denoted as FWM-OBI. In the case where $w_i = w_j$, both the FWM-OBI terms have the same optical frequency, which is twice the separation between the two main wavelengths. Since we are concentrating on beating terms in this paper, FWM components will be neglected.

3. SIMULATION SETUP AND RESULTS

The simulation software used in this section is OptSim. In the setup shown in Figure 1, a configuration using two-subcarriers externally modulated at two wavelengths has been modelled. The two signals are modulated with two different subcarrier frequencies by using a PSK modulator at a modulation index value of $\sqrt{0.5}$. Subcarrier center frequencies are assumed to have the values f_1 = 16 GHz and f_2 = 32 GHz. The electrical BPF bandwidth B is equal to twice the PSK signal bit rate. The bit rate used in this simulation is 622 Mbps.

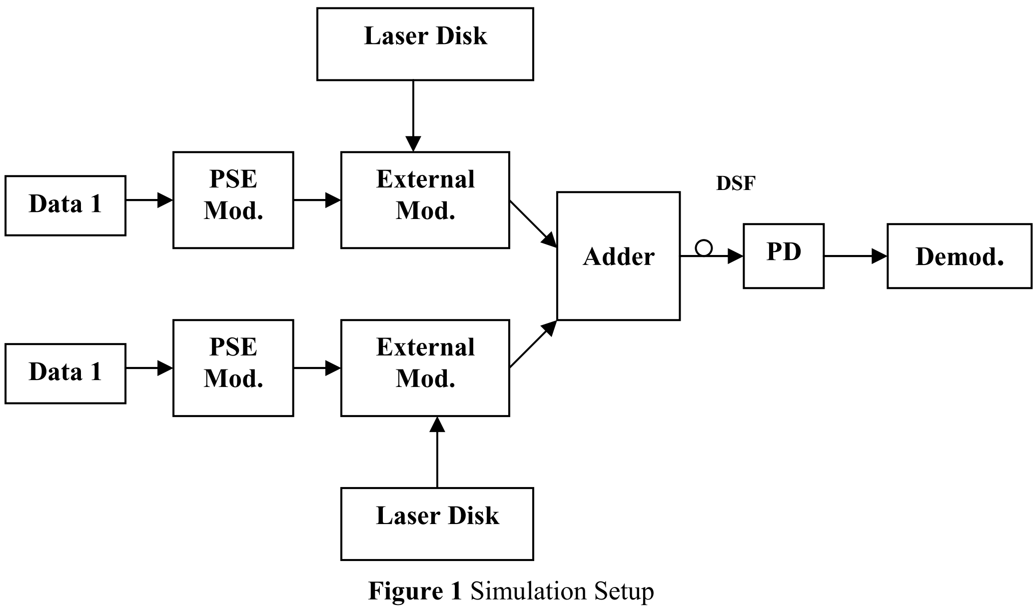

Figure 1 Simulation Setup

The two lasers are then amplitude modulated by the subcarriers. In the first channel, the wavelength was fixed to 1550 nm. However, in the second channel, the wavelength was varied from 1550.008 nm to 1551 nm. Both of the optical signals will be combined by an adder and sent through a DSF to a photodetector. The photodetector converts the optical signal back to electrical signal. The converted signal will then be demodulated. The subcarriers were recovered using a Costas Loop. The other parameters used in the simulation are: $dD,/d\lambda$ = 0.07 ps/km-nm-nm, fiber length = 20 km, and fiber loss = 0.21 dB/km.

The result of the simulation that we are concerned about is the CIR. All the measurements in this section have been done for the 32 GHz subcarrier frequency. The result is shown in Figure 2 in form of CIR as a function of optical frequency separation. There is a high drop in CIR when the carrier separation satisfies:

$$\left| optical \quad Frequency \quad separation(F_o) - f_1 \right| < \frac{B}{2}$$

Also there is a considerable drop in CIR when separation between the two lasers equals half the subcarrier frequency, which can be written as:

$$\left| \frac{optical \quad Frequency \quad separation(F_o)}{2} - f_1 \right| < \frac{B}{2}$$

The FWM beating term will fall within the BPF of the signal at this optical Frequency separation. This causes a considerable drop in CIR at 16 GHz in Figure 2. Figures 3 and 4 show clearly the eye diagram at high optical frequency separation and at 16GHz where the FWM-OBI happens.

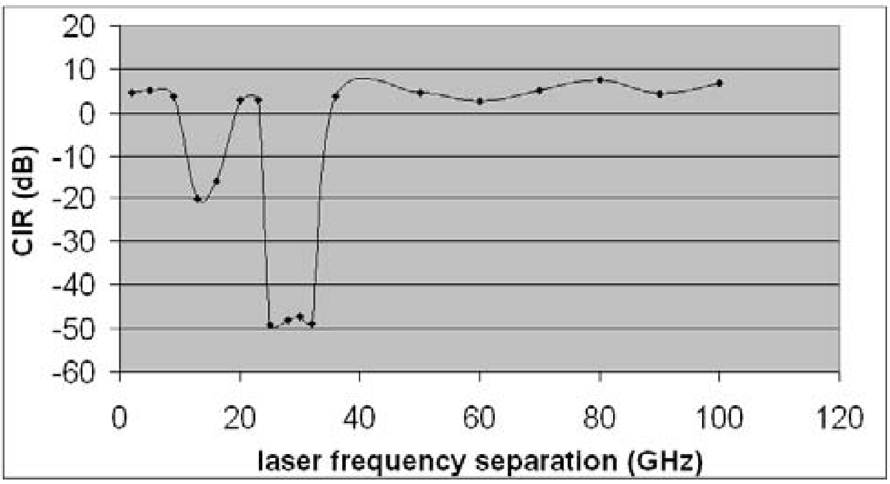

Figure 2 CIR vs. optical frequency separation

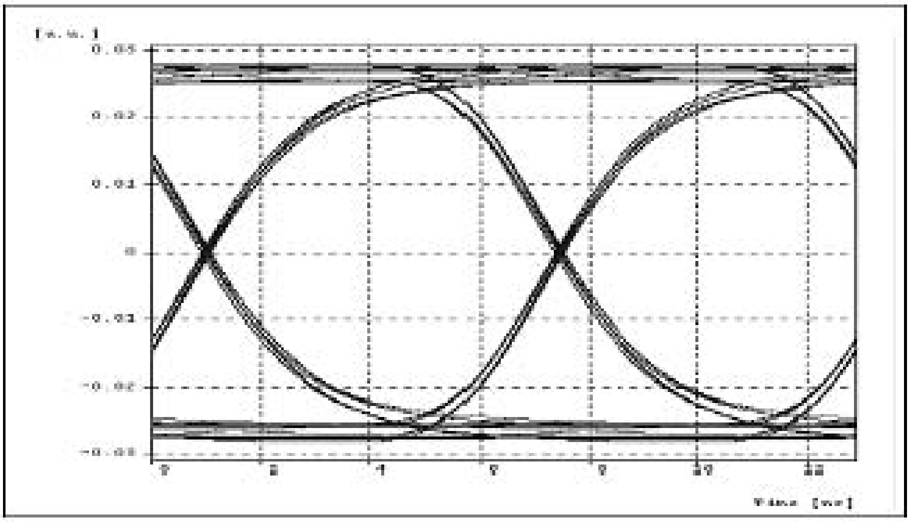

Figure 3 The Eye-diagram at 100 GHz optical frequency separation

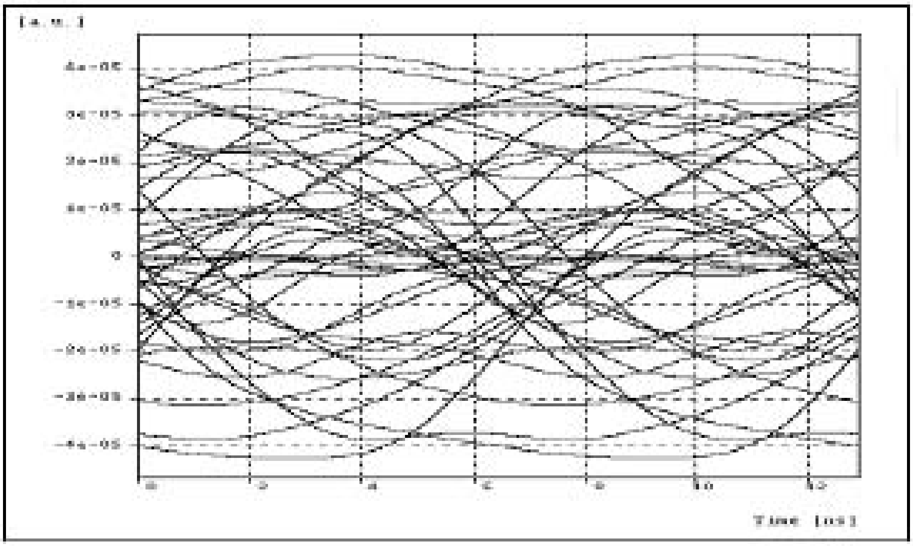

Figure 4 The eye-diagram at 16 GHz optical frequency separation

From all the graphs above, we can see how serious is the effect of main and FWM-OBI to a MOC-SCM system. Since the separation between the two wavelengths and the separation between any wavelength and the FWM terms are the same, it has been found that the CIR at the subcarrier frequency equal to the optical frequency separation is higher by 30dB compared to CIR at half the optical frequency separation (at 10dBm laser transmitted power).

4. CONCLUSION

It has been shown that the maximum number of channels or the bandwidth of the MOC-SCM system will be limited by main OBI and FWM-OBI when FWM is present. In this paper, it is shown that the beating not only occurs between the optical carriers, but also occurs between optical carriers and the FWM terms. For a degenerate case, OBI causes a considerable degradation in CIR at the frequency equal to and half the optical frequency separation. FWM-OBI will be very important at high laser transmitted power and it will limit the number and the performance of MOC-SCM optical networks.

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