Crosstalk Due to Optical Demultiplexing in Subcarrier Multiplexed Systems

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ABSTRACT

We report an in-depth investigation of the inter-modulation crosstalk in subcarrier multiplexed (SCM) systems with optical demultiplexing (ODeMux). Both theoretical derivations and numerical simulations show that the crosstalk in ODeMux systems mainly comes from the nonlinear mixing of the baseband and subcarrier modulations inside the signal channels. Several key parameters are then studied to estimate their effects on the magnitude of the crosstalk. As a result, performance optimization strategies are proposed for ODeMux SCM systems.

Keywords: Subcarrier multiplexed (SCM) systems, crosstalk analysis, optical communications, optical signal processing, optical-label switching (OLS), passive optical networks (PON)

1. INTRODUCTION

Optical subcarrier-multiplexing (SCM) technology has been widely used in cable television (CATV), optical-label switching (OLS) [1], and WDM passive optical network (WDM-PON) systems [2, 3]. Conventional SCM receiver uses electrical-demultiplexing (EDeMux) [2], which is expensive, complicated, and power-hungry due to the need of radio-frequency (RF) components. The RF fading effect caused by fiber dispersion also limits its performance [1]. These drawbacks make EDeMux receiver unsuitable for networks where the cost and power budget is tight or the fiber dispersion is unpredictable, such as in optical access network or optical packet-switching network. Optical-demultiplexing (ODeMux) with an optical filter (e.g. fiber Bragg grating) is then proposed to overcome these drawbacks [1, 4]. An important issue in SCM systems is the inter-modulation crosstalk, which, to the best of our knowledge, still has not been studied for ODeMux systems with a convincing theoretical model. Most of the previous work just simply assumes that the crosstalk is similar to that in EDeMux systems. In this paper, we report an analytical model to investigate the inter-modulation crosstalk in ODeMux systems. Both theoretical derivation and numerical simulation prove that the crosstalk in ODeMux systems is significantly different from that in EDeMux systems. The comparison study involves two types of widely used ODeMux SCM systems: a) electrical-multiplexing (EMux) (as shown in Fig. 1), and b) optical-multiplexing (OMux) (as shown in Fig. 2). Based on the theoretical analysis, we demonstrate system performance optimizations for ODeMux SCM systems.

2. THEORETICAL ANALYSIS

As shown in Fig. 1, after the optical modulation, the optical field of the SCM signal is [5]:

$$E(t) = \cos[\frac{\pi}{V_\pi}(S_0(t) + S_1(t)\cos\omega_c t + V_{bias})] \cdot e(t) \tag{1}$$

where $S_0(t) \geq 0$ and $S_1(t) \geq 0$ are the electrical signals for baseband and subcarrier, ω_c is the subcarrier angular frequency, V_π is the switching voltage of the optical modulator, V_{bias} is the bias voltage, $e(t) = E_0 \exp(j\omega_0 t + \phi(t))$ is the field of the optical carrier.

International Conference on Applications of Optics and Photonics, edited by Manuel F. M. Costa,
Proc. of SPIE Vol. 8001, 80011O · © 2011 SPIE · CCC code: 0277-786X/11/$18 · doi: 10.1117/12.892079

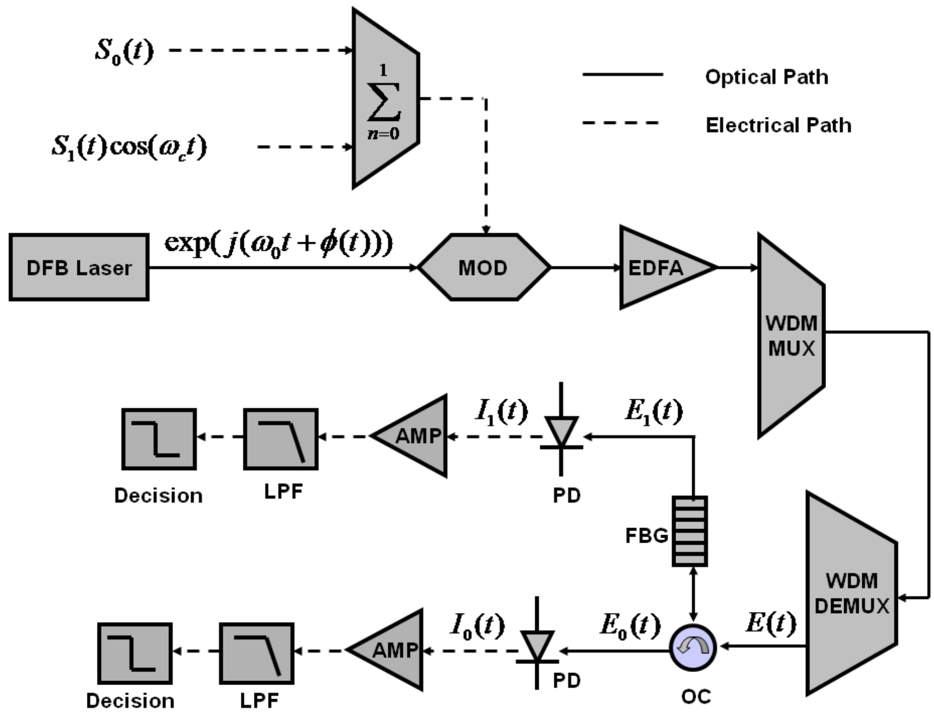

Fig. 1. System architecture of an EMux-ODeMux SCM system, MOD: optical intensity modulator, EDFA: Erbium-doped fiber amplifier, FBG: fiber Bragg grating, OC: optical circulator, PD: photodiode, AMP: electrical amplifier, LPF: low-pass filter

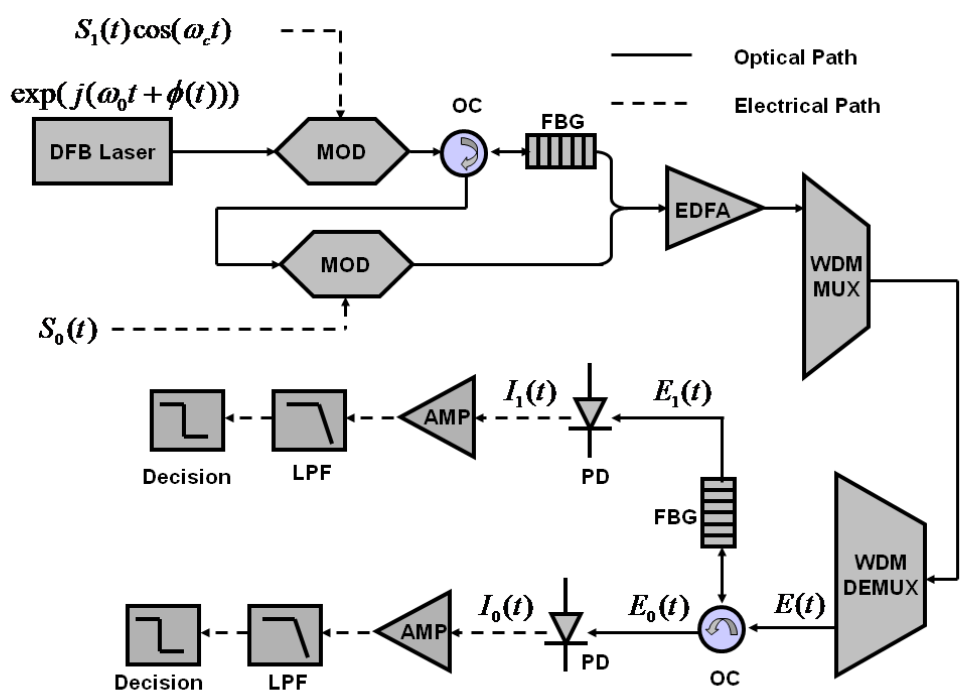

Fig. 2. System architecture of an OMux-ODeMux SCM system

The signal modulations and bias voltage can be normalized with the switching voltage:

$$\alpha(t) = \frac{\pi}{V_\pi} S_0(t), \beta(t) = \frac{\pi}{V_\pi} S_1(t), \theta = \frac{\pi V_{bias}}{V_\pi} \tag{2}$$

If we expand (1) with Bessel functions:

$$\begin{aligned} E(t) = e(t)\{&\cos(\alpha(t)+\theta)[J_0(\beta(t)) + 2\sum_{n=1}^{\infty}(-1)^n J_{2n}(\beta(t))\cos(2n\omega_c t)] - \\ &2\sin(\alpha(t)+\theta)[\sum_{n=0}^{\infty}(-1)^n J_{2n+1}(\beta(t))\cos((2n+1)\omega_c t)]\} \end{aligned} \tag{3}$$

(3) shows that the field of the optical signal is a summation of baseband and subcarrier harmonics. On each harmonic, the baseband and subcarrier modulations, $\alpha(t)$ and $\beta(t)$, coexist as a mixed term. If we ignore the high-order subcarrier harmonics and assume that they can be removed by WDM filters, (3) reduces to:

$$E(t) = e(t)[\cos(\alpha(t)+\theta)\cdot J_0(\beta(t)) - 2\sin(\alpha(t)+\theta)\cdot J_1(\beta(t))\cos\omega_c t] \tag{4}$$

After the optical demultiplexing with a fiber Bragg grating, the field of the optical baseband is:

$$E_0(t) = e(t)J_0(\beta(t))\cos(\alpha(t)+\theta) \tag{5}$$

while that of the optical subcarrier is:

$$E_1(t) = -2e(t)J_1(\beta(t))\sin(\alpha(t)+\theta)\cos\omega_c t \tag{6}$$

(5) and (6) can be used to analyze the inter-modulation crosstalk in ODeMux systems. After ODeMux, the crosstalk is introduced by nonlinear mixing and is different from that in EDeMux systems. Specifically, the original baseband and subcarrier modulations are mixed and spread to the frequency channels of each other.

3. SIMULATIONS AND SYSTEM OPTIMIZATION

Numerical simulation is then performed to investigate the crosstalk's impact on system performance. To quantify the crosstalk, we define the eye-opening penalty (EOP) as:

$$EOP = 10\log_{10}\left(\frac{Best\_Eye\_Opening}{Worst\_Eye\_Opening}\right) \tag{7}$$

The bit-rates of $\alpha(t)$ and $\beta(t)$ are 10 Gb/s and 1.25 Gb/s, respectively, both of them use non-return-to-zero (NRZ) encoding with PRBS $2^{31} - 1$ sequence. Fig. 3-6 shows the simulation results of EOP on recovered baseband and subcarrier signals, with a subcarrier frequency at 14 GHz. There is a performance tradeoff between the baseband and the subcarrier signals. When other conditions are fixed, the EOP on the baseband signal decreases with the amplitude ratio of $\alpha(t)$ to $\beta(t)$, while larger amplitude of $\alpha(t)$ makes the EOP on the subcarrier signal worse. Surprisingly, smaller amplitude of $\beta(t)$ generally brings better system performance. This is due to the fact that smaller amplitude of $\beta(t)$

makes the nonlinear mixing terms smaller in the recovered signals. Higher bias voltage gives better performance for both the baseband and subcarrier signals, because of better linearity on the modulator transfer function.

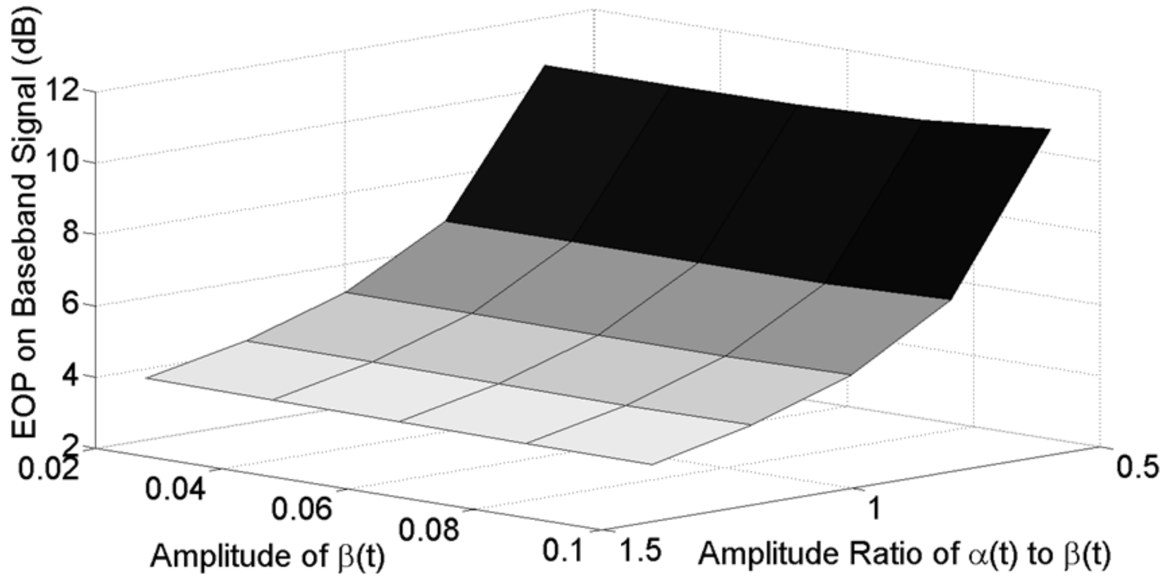

Fig. 3 EOP of baseband signal with V_{bias} as $\frac{\pi}{8}$

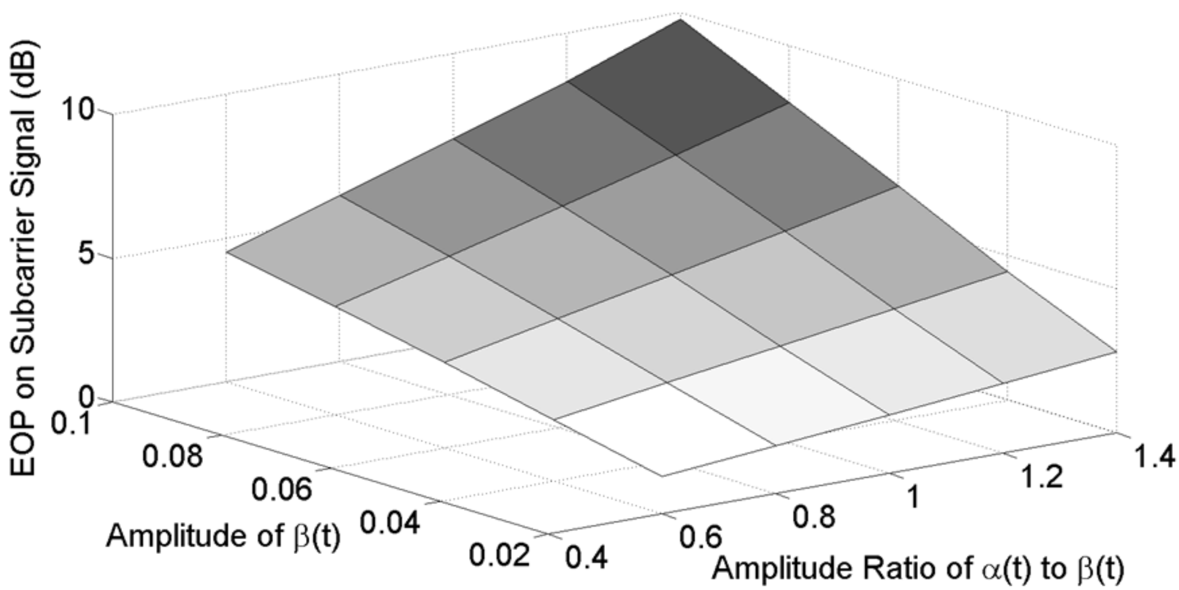

Fig. 4 EOP of subcarrier signal with V_{bias} as $\frac{\pi}{8}$

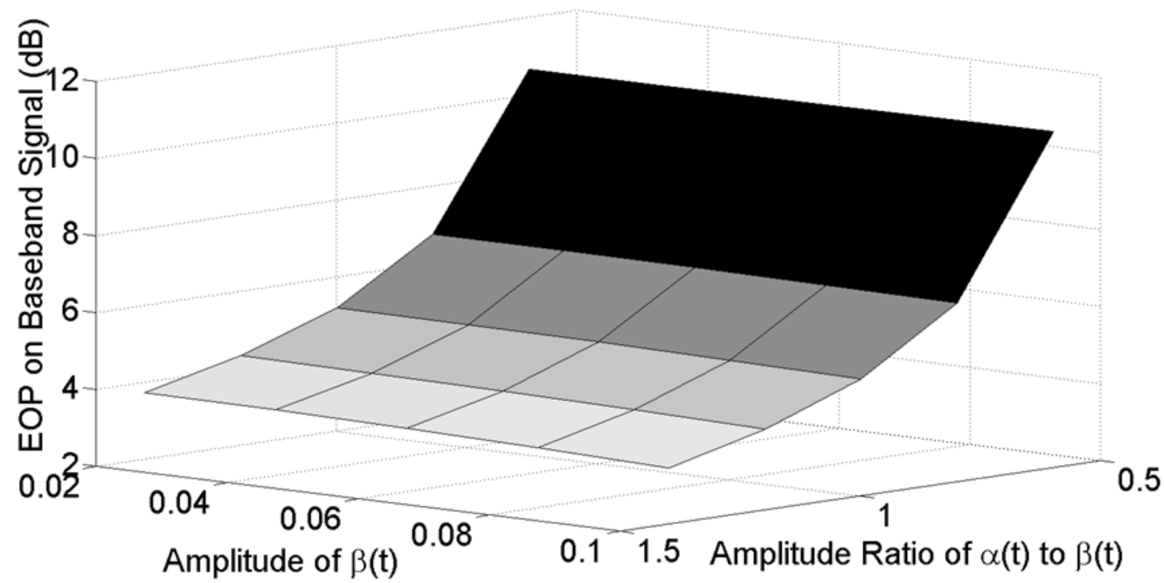

Fig. 5 EOP of baseband signal with V_{bias} as $\frac{\pi}{4}$

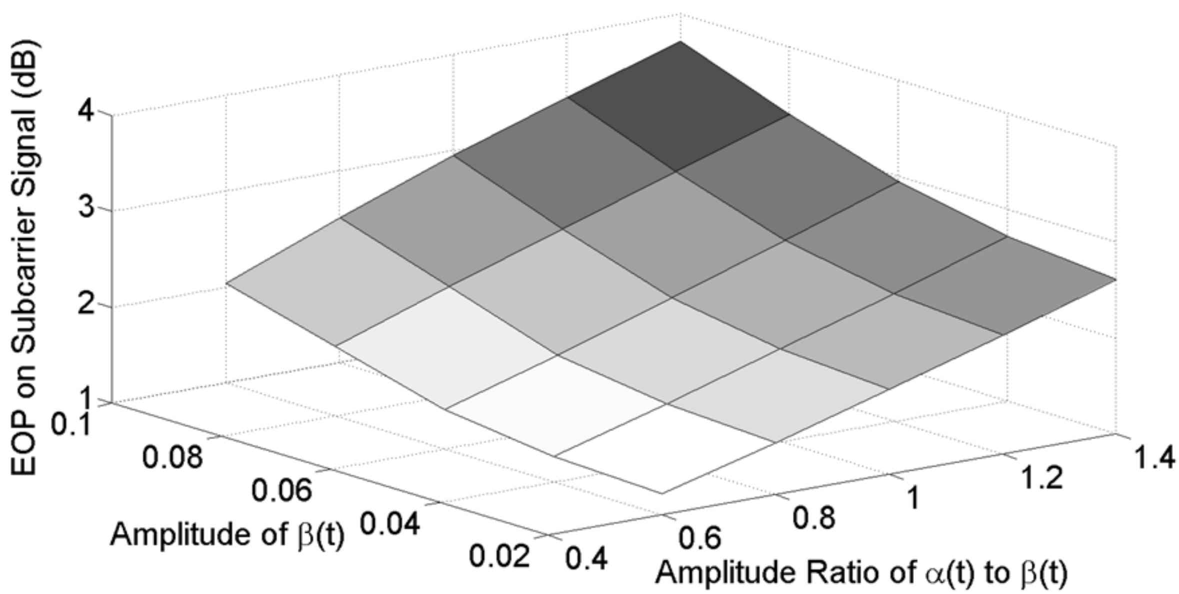

Fig. 6 EOP of subcarrier signal with V_{bias} as $\frac{\pi}{4}$

Fig. 7-8 shows the simulated EOP curves and eye-diagrams when the amplitude of $\beta(t)$ is 0.02, V_{bias} is $V_{\pi}/4$, and the subcarrier frequency changes from 14 to 18 GHz. The results show that larger frequency spacing provides better performance. In all, we can summarize the system optimization strategies of ODeMux SCM systems as: 1) limit the amplitude of the signal $\beta(t)$ on the subcarrier channel, 2) apply a high bias voltage towards $V_{\pi}/2$, and 3) use a large subcarrier frequency when possible.

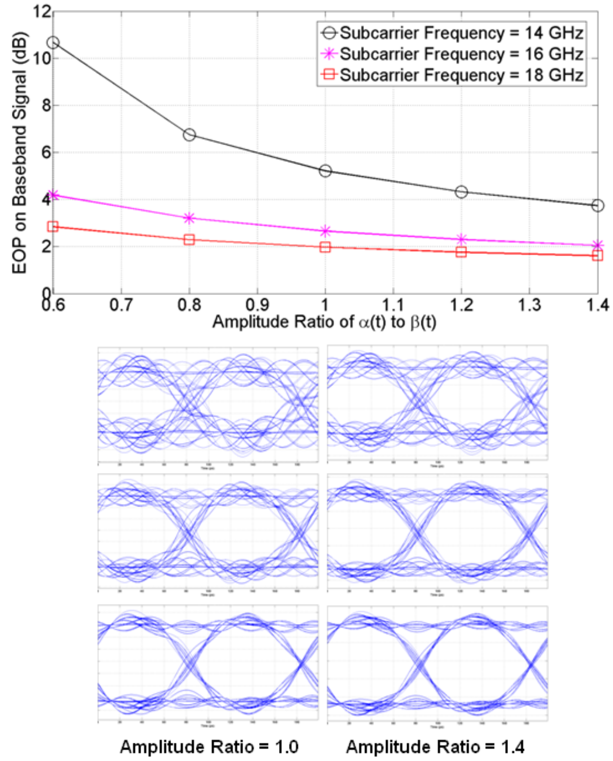

Fig. 7 Simulation results of baseband signals' EOP and eye-diagrams for different subcarrier frequencies

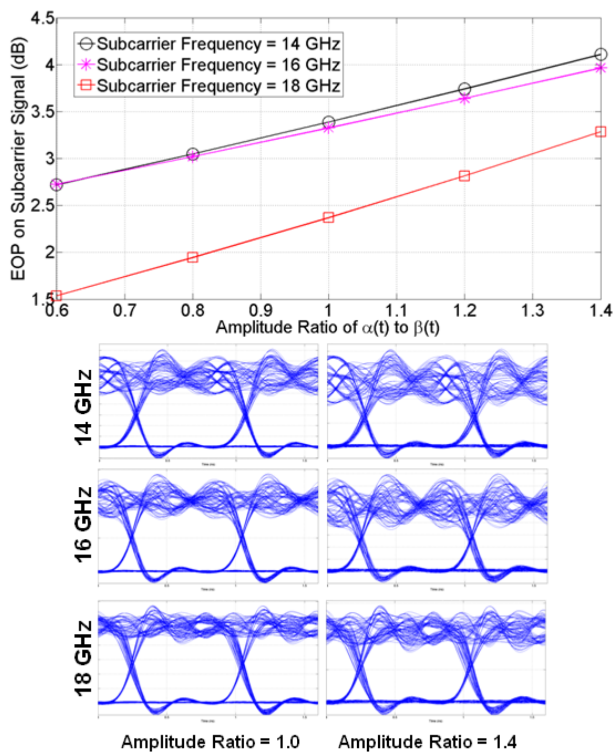

Fig. 8 Simulation results of subcarrier signals' EOP and eye-diagrams for different subcarrier frequencies

4. SUMMARY

We reported an analytical model to investigate the performance of optical SCM systems with an optical-demultiplexing (ODeMux) receiver structure. With both theoretical derivations and numerical simulations, we showed that the crosstalk in ODeMux systems comes from the nonlinear mixing of the baseband and subcarrier modulations. We then proposed strategies for performance optimization of ODeMux SCM systems.

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