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Performance Analysis of Crosstalk Subcarrier Multiplexing and Wave Division Multiplexing in Optical Communication System

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Abstract

In traditional optical communication, duplexity is achieved by using two fibers, each having a transmitter and a receiver. Economically, bidirectional wavelength division multiplexing (WDM) transmission systems utilizing a single fiber will be more attractive not only reducing the use of the fiber by a factor of two, but also the number of components. Duplex transmissions over a single fiber can double the capacity of an installed unidirectional link. The idea of this paper is to study another approach using the subcarrier multiplexing (SCM)-based optical network and evaluate the physical transmission quality of analog and digital signal using SCM approach and the characteristic of fiber nonlinear crosstalk such as stimulated Raman scattering, Cross phase modulation and four-wave mixing in the SCM externally modulation optical link. A suitable bandwidth of 890 – 950 MHz is selected for subcarriers and channel bandwidth of 200 KHz and carrier. By measuring the optical bit interference (OBI) performance limitations of the subcarrier multiplexing WDM optical transmission system is investigated. The OBI for 10 channels for input power 1 dB is -40 dB whereas for 110 channels the OBI is -20 dB separation of 250 KHz are considered.

Keywords: WDM, BER, OBI, SCM, SNR, SMF.

1) INTRODUCTION

An optical communications system is similar to other communication systems in that it consists of the three main parts: Transmitter, Receiver and the Communication channel [1-3]. In order for a fiber to guide the light signal, it must consist of a core of material whose refractive index is greater than that of the surrounding medium, which is called the cladding. Depending on the design of the fiber, light is constrained to the core by either total internal reflection or refraction [4].

2) The Basic Blocks of Fiber Optical Transmission Link

The basic block of an optical fiber transmission system is illustrated in Figure 1 consists of three main parts: The transmitter block “Laser Driver and temperature control” [5-8]: the electrical signals will be transferred into optics. For long haul, laser diode is used for this purpose because of the narrow spectral

width and high optical power that is used to carry data over long distance. The light is then coupled into the transmission channel, the optical fiber cable, where most of the dispersion and attenuation takes place [5]. The receiver block which is the last part of the system converts the optical signal back into the replica of the electrical signal using the Avalanche photodiode (APD) or PIN-type photodiode then to the amplification stage before reaching the end user [9-12].

Figure 1: Basic block diagram of fiber optic communication.

3) Wavelength Division Multiplexing (WDM) System

WDM as shown in Figure 2, [1, 13-16] combines multiple optical TDM data streams onto one fiber through the use of multiple wavelengths of light. Each individual TDM data stream is sent over an individual laser transmitting a unique wavelength of light. Wavelength division multiplexing was used with only two wavelengths 1310 nm and 1550 nm. However, this was suitable only for limited applications for example; applications in which analog optical cable television signals co-existed with digital optical telecommunication signals. WDM takes advantage of the fact that different wavelengths of light can be transmitted over a single fiber simultaneously [17, 18].

Figure 2: Schematic representation of the wavelength division multiplexing system.

Figure 3: SCM/WDM architecture.

4) Types of Crosstalk

- Crosstalk due to Filtering [15-19]
 - ✚ Crosstalk element superimposed on the signal as a random power adding process. However, there is no significant beating element. A narrow band optical filter would largely reduce the electrical impairment [18-20].
- Linear Crosstalk
 - ✚ Space switches crosstalk.
 - ✚ Homo wavelength crosstalk.
 - ✚ Hetero wavelength crosstalk.
- Non-linear Crosstalk
 - ✚ Four wave mixing (FWM) : Wave mixing to give rise of new frequency
 - ✚ Cross phase modulation: Intensity dependent refractive index.
 - ✚ Scattering: Transfer of power between propagation modes.

5) Fiber Nonlinear Crosstalk

In addition to transmitter and receiver noises in optical systems, fiber nonlinear crosstalk can significantly degrade the transmission system performance. There are two basic fiber nonlinear mechanisms [1, 4, and 15]. The first mechanism that causes fiber nonlinearities is the scattering phenomena, which produces Stimulated Raman Scattering. The second mechanism arises from the refractive index of glass being dependent on the optical power going through the material. This results in producing Cross Phase Modulation (XPM) and FWM crosstalk [13-16].

- Stimulated Raman Scattering (SRS) Crosstalk Frequency Response.
Stimulated Raman Scattering (SRS) is a nonlinear phenomenon found in wavelength-division multiplexed (WDM) transmission system. As shown in figure 3, where the shorter wavelength channels are robbed of power and that power feeds the longer wavelength channel [9, 20-26].

- Figure 4: Stimulated Raman scattering (SRS) crosstalk frequency response.

As for the crosstalk interaction between pump channel and signal channel in the SCM/WDM system, assuming pump channel has a shorter wavelength than probe channel, the most significant crosstalk term is due to the SRS interaction between pump channel optical carrier and probe channel subcarriers [18-20, 26-30].

A formal approach to determining SRS crosstalk levels is to solve the coupled propagation equations for the optical intensity I at wavelengths λ_1 and λ_2 [10, 15].

$$\frac{\partial I_1}{\partial z} + \frac{I}{v_1} \frac{\partial I_1}{\partial t} = (gI_2 - \alpha)I_1 \quad \text{Eq. 1}$$

$$\frac{\partial I_2}{\partial z} + \frac{I}{v_2} \frac{\partial I_2}{\partial t} = (-gI_1 - \alpha)I_2 \quad \text{Eq. 2}$$

Where z is the distance along the fiber, g is the Raman gain (loss) coefficient and v is the group velocity of each channel in the fiber. Assuming $\lambda_2 < \lambda_1$ (channel 2 is designated as pump channel and channel 1 as probe channel).

By neglecting the SRS term, gI_2 on the right hand side Eq. 1 of and solving for I_1 ; then substituting I_1 into Eq.2 and solving for I_2 are gets [10, 15]:

$$P_2(0, \mu_2) = P_2(0, \mu_2)e^{-\alpha z} \cdot \exp \left[-\frac{g}{A_{eff}} \int_0^z P_1(0, \mu_2 + d_{12}z')e^{-\alpha z'} dz' \right] \quad \text{Eq. 3}$$

$$P_2(0, \mu_2) \approx P_2(0, \mu_2) e^{-\alpha z} \cdot \left[1 - \frac{g}{A_{eff}} \int_0^z P_1(0, \mu_2 + d_{12} z') e^{-\alpha z'} dz' \right] \quad Eq. 4$$

Where $d_{12} = \left| \frac{1}{v_1} - \frac{1}{v_2} \right|$ is the group velocity mismatch between the pump and signal channels and $\mu_2 = t - \frac{z}{v_2}$

A similar approach can be used to solve for I_1 by neglecting the SRS term, $-gI_1$ on the right hand side of Eq.2 and solving for I_2 , then substituting I_2 into Eq.1 to get [10, 15]

$$P_1(0, \mu_1) \approx P_1(0, \mu_1) e^{-\alpha z} \cdot \left[1 + \frac{g}{A_{eff}} \int_0^z P_2(0, \mu_1 + d_{12} z') e^{-\alpha z'} dz' \right] \quad Eq. 5$$

6) Analysis of SCM in Presence of OBI

There are M numbers of subcarrier multiplexing (SCM) in a given optical channel, having the same average power. Each of these fields can be represented by [11, 12]:

$$e_i(t) = \sqrt{S_i(t)} \quad Eq. 6$$

Where S_i the intensity modulation by an RF is signal of center frequency f_i and can be represented by [11-15]:

$$S_i = 1 + m(t) \cos(2\pi f_i t) \quad Eq. 7$$

Where $m(t)$ is NRZ data signal with bit period T_b .

The total field in an optical channel is the sum of M fields and can be represented as [11, 20]:

$$e_{in}(t) = \sum_{i=1}^M e_i(t) \quad Eq. 8$$

The electric field at the output of the fiber is given by:

$$e_o(t) = |e_{in}(t) * h_f(t)| e^{-\alpha L} \quad Eq. 9$$

Where α is the fiber attenuation coefficient, L is the fiber length and $h_f(t)$ represents the fiber impulse response.

The photodetector (PD) converts this field into an electrical signal proportional to the field intensity.

$$i_s(t) = \{\sum_{i=1}^M e_o^2(t)\} \quad \text{Eq.10}$$

$$i_c(t) = \{2 \sum_{i=1}^M \sum_{l=i+1}^M e_i(t) e_l(t)\} \quad \text{Eq.11}$$

Here $i_c(t)$ contributes nonzero beat interference terms. The output of the PD is passed through a pre-amplifier followed by a band pass filter. If any of the spectral components of $i_c(t)$ falls within the bandwidth of any of the M users BPF, it will cause OBI.

$$\begin{aligned} i_s(i) &= \int_{-\infty}^{+\infty} i_{s(i)}(t) e^{-jft} \\ &= 2\pi\delta(f) + \left(\frac{T}{2}\right) \\ &\quad * [\text{sinc } T(f - f_i) + \text{sinc } T(f + f_i)] e^{\left(-\frac{jfT}{2}\right)} \end{aligned} \quad \text{Eq. 12}$$

Where f_i represents the required subcarrier frequency.

The power spectrum of the i-th subscriber's signal component can be expressed as:

$$\begin{aligned} P_s(i)(f) &= [i_s(i)(f)]^2 \\ &= 4\pi^2\delta(f) + \left(\frac{T^2}{4}\right) \\ &\quad * [\text{sinc}^2 T(f - f_i) + \text{sinc}^2 T(f + f_i)] e^{\left(-\frac{jfT}{2}\right)} \end{aligned} \quad \text{Eq. 13}$$

Using band pass filter, output signal power of the required sub-carrier can be calculated as [11-15]:

$$P_i(\text{sig}) = \int_{f_i - \frac{B}{2}}^{f_i + \frac{B}{2}} P_{s(i)}(f) df = \int_{f_i - \frac{B}{2}}^{f_i + \frac{B}{2}} \left(\frac{T^2}{4}\right) * [\text{sinc}^2 \tau(f - f_i)] df \quad \text{Eq. 14}$$

Where B is the specified bandwidth of the subcarrier or bandwidth of the BPF.

This $P_i(\text{cross})$ is the source of the OBI.

$$\text{SNR} = \frac{P_i(\text{sig})}{P_i(\text{cross})} \quad \text{Eq. 15}$$

$$\text{BER} = 0.5 \text{erfc}(\sqrt{2X\text{SNR}}) \quad \text{Eq.16}$$

7) Four-Wave Mixing Crosstalk in SCM Externally Modulated Optical Link

Four-wave mixing crosstalk is one of the major limiting factors in SCM/WDM optical fiber communications systems that use narrow channel spacing, low chromatic dispersion and high optical channel power. The time-averaged optical power $P_{ijk}(L, \Delta\beta)$ generated through the FWM process for the frequency component f_{ijk} is written as [22].

$$P_{ijk}(L) = \frac{1024\pi^2}{n^4\lambda^2c^2} (DX_{1111})^2 \left(\frac{P_i P_j P_k}{A_{eff}^2} \right) \left| \frac{e^{(i\Delta\beta - \alpha)L} - 1}{\{i\Delta\beta - \alpha\}} \right|^2 \quad Eq. 17$$

where X_{1111} is the third-order nonlinear susceptibility, (which is related to n_2 nonlinear refractive (m^2/W)). The generated wave efficiency η , with respect to phase mismatch $\Delta\beta L$ [10, 22]

$$\eta = \frac{P_{ijk}(L, \Delta\beta)}{P_{ijk}(L, \Delta\beta=0)} = \left| \frac{e^{(i\Delta\beta - \alpha)L} - 1}{L_{eff}\{i\Delta\beta - \alpha\}} \right|^2 = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2} \left[1 + \frac{4e^{-\alpha L} \sin^2(\frac{\Delta\beta L}{2})}{(1 - e^{-\alpha L})^2} \right] \quad Eq. 18$$

where $\Delta\beta$ is the propagation constant difference written as

$$\frac{2\pi\lambda^2}{c} \Delta f_{ik} \Delta f_{jk} \left[D + \frac{\lambda^2 S}{2c} (\Delta f_{ik} + \Delta f_{jk}) \right] \quad Eq. 19$$

Assuming the equivalent frequency separation $\Delta f = (\Delta f_{ik} * \Delta f_{jk})^{1/2}$ Eq. 20

$$\Delta\beta = \frac{2\pi\lambda^2}{c} \Delta f^2 \left[D + \frac{\lambda^2 S}{2c} (\Delta f) \right] \quad Eq. 21$$

The time-average optical power generated through the FWM process can be modified in terms of generated wave efficiency as [10, 22]

$$P_{ijk}(L) = \frac{1024\pi^6}{n^4\lambda^2c^2} (DX_{1111})^2 \left(\frac{P_i P_j P_k}{A_{eff}^2} \right) L_{eff}^2 \eta \quad Eq. 22$$

Using $D = 6$ (none of frequencies are the same).

8) Dual Parallel Linearized External Modulators

The basic configuration of optical dual parallel linearization technique is shown below in figure [5].

Figure 5: Dual parallel MZ modulator in [6].

By providing less optical power and higher RF drive power to the secondary modulator, the secondary modulator has higher OMI and greater distortion. By providing more optical power to the primary MZ modulator, the third-order distortion products created in the secondary modulator can be made to cancel the distortion products from the primary modulator with a small cancellation of the fundamental signal, result with MATLAB in fig [14-16].

$$\begin{aligned} \frac{P_{out}}{P_{in}} &= A \cos^2 \left[\frac{\frac{\pi V(t)}{V_{\pi}} - \frac{\pi}{2}}{2} \right] + (1-A) \cos^2 \left[\frac{B \frac{\pi V(t)}{V_{\pi}} - \frac{3\pi}{2}}{2} \right] \\ &= \frac{1}{2} \left(1 + A \sin \frac{\pi V(t)}{V_{\pi}} - (1-A) \sin \frac{B \pi V(t)}{V_{\pi}} \right) \end{aligned} \quad Eq. 23$$

where A is the splitting ratio of the input power divider and B is the ratio of RF drive power. Assuming $V(t)$ is a multi-sinusoidal signal, using trigonometric identities and Bessel functions, the amplitude of the fundamental carrier with frequency ω_k can be expressed as [10]:

$$\frac{P_{\omega k}}{P_{in}} = A J_1 \left(\frac{\pi A}{V_{\pi}} \right) J_0 \left(\frac{\pi A}{V_{\pi}} \right)^{N-1} - (1-A) J_1 \left(B \frac{\pi A}{V_{\pi}} \right) J_0 \left(B \frac{\pi A}{V_{\pi}} \right)^{N-1} \quad Eq. 24$$

And the amplitude of the third-order intermodulation component of the frequency $\omega_i + \omega_j + \omega_k$ can be expressed as

$$\frac{P_{\omega_i+\omega_j+\omega_k}}{P_{in}} = AJ_1\left(\frac{\pi A}{V_\pi}\right)^3 J_0\left(\frac{\pi A}{V_\pi}\right)^{N-3} - (1-A)J_1\left(B\frac{\pi A}{V_\pi}\right)^3 J_0\left(B\frac{\pi A}{V_\pi}\right)^{N-3} \quad Eq. 25$$

The third-order intermodulation product can be cancelled when

$$A = \frac{J_1\left(B\frac{\pi A}{V_\pi}\right)^3 J_0\left(B\frac{\pi A}{V_\pi}\right)^{N-3}}{J_1\left(\frac{\pi A}{V_\pi}\right)^3 J_0\left(\frac{\pi A}{V_\pi}\right)^{N-3} + J_1\left(B\frac{\pi A}{V_\pi}\right)^3 J_0\left(B\frac{\pi A}{V_\pi}\right)^{N-3}} \quad Eq. 26$$

9) Results

Figure 6: Plot of the optical bit interference (OBI) vs channel number for input power, $P_i = 1$ dB, 10 dB and 20 dB.

Figure 7: Plot of the signal to interference ratio (SIR) vs channel number for input power, $P_i = 1$ dB, 10 dB and 20 dB.

Figure 8: Plot of the bit-error-rate (BER) vs channel number for input power, $P_i = 1$ dB, 10 dB and 20 dB.

Figure 9: Channel number vs. BER.

10) Discussion

The number of channels can be increased without significant penalty if the input power is kept low. The number of channels can also be increased if the bandwidth is taken more for more carrier separation.

- Parameters of Design Consideration [10, 16]

- Bandwidth: 890 MHz – 960 MHz.
- Channel Spacing: 200 KHz.
- Modulation: QPSK modulation.
- Line Coding: NRZ input data.
- Interchannel Spacing and number of Channels: 250 KHz.
- Noise: Noise other than OBI is not considered.

Figure 10: Power spectrum of 10 channels at 7 MHz separation carrier wave.

Figure 11: Power Spectrum of 10 channels at 7 MHz separation carrier wave.

Figure 12: Power spectrum of 10 channels at 7 MHz separation carrier wave.

Figure 13: Spaced frequency vector with NumUnique Pts points. And the magnitude of fft of x and scale the fft so that it is not a function of the length of x .

Figure 14: DPMZ power divider ratio vs. OMI (optical modulation index).

Figure 15: C/CTB performance with B=2 and A=0.87, 0.88 & 0.89.

Figure 16: Carrier to third & fifth order distortion vs. OMI.

11) Source Code

```
%C. MATLAB Code for Channel vs SNR & BER
clc
clear all
close all
p=[1 5 10 20];
snr1=[27.78 22.40 19.44 15.23 13.60 11.04 8.53 6.61 5.25 4.86];
snr10=[25.36 20.60 17.87 14.46 12.60 10.26 7.83 6.29 5.10 4.64];
snr20=[22.9497 18.7589 16.2029 13.2505 11.5074 9.5336 7.052 5.7121
5.0435 4.2542];
channel=[11 21 29 41 47 57 71 83 94 107];
BER1=[2.10E-23 1.93E-13 4.53E-10 1.79E-07 6.09E-06 7.95E-05 2.68E-04
0.0017 0.0019 0.0021];
BER5=[5.55E-21 1.75E-12 1.70E-09 1.67E-06 9.57E-06 5.65E-05 3.30E-04
0.0018 0.0024 0.004];
BER10=[3.64E-18 2.90E-11 1.10E-08 1.14E-05 8.81E-05 3.54E-04 9.42E-04
0.004 0.0054 0.003];
BER20=[3.31E-14 1.95E-09 7.79E-07 7.96E-05 5.75E-04 1.12E-03 5.38E-03
0.0057 0.0043 0.0039];
```



```

OBI1=[-40.63 -35.24 -32.29 -28.07 -26.47 -23.89 -21.41 -19.44 -18.24
-17.54];
OBI5=[-25.63 -20.53 -17.69 -14.13 -12.06 -9.93 -8.06 -5.39 -4.26 -
3.56];
OBI10=[-18.21 -13.44 -10.70 -7.28 -5.42 -4.06 -1.64 0.88 1.77 2.43];
OBI20=[-9.77 -5.55 -2.98 1.23 2.7 3.75 5.44 7.50 7.81 8.52];
ber11=[2.10E-23 5.55E-21 3.64E-18 3.31E-14];
ber21=[1.93E-13 1.75E-12 2.90E-11 1.95E-09];
hold on
plot(channel,OBI20);
title('OBI Vs Channel');
xlabel('Channel (Number)');
ylabel('OBI (dB)');
axis([10 108 -45 10])
grid on
figure(2)
plot(channel,snr1);
hold on
plot(channel,snr10);
hold on
plot(channel,snr20);
title('SIR Vs Channel');
xlabel('Channels (Number)');
ylabel('SIR (dB)');
%axis([889 925 0 2])
grid on
figure(3)
semilogy(channel,BER1);
hold on
semilogy(channel,BER5);
hold on
semilogy(channel,BER10);
hold on
semilogy(channel,BER20);
title('Channel Vs BER');
xlabel('Channels (Number)');
ber29=[4.53E-10 1.70E-09 1.10E-08 7.79E-07];
ber41=[1.79E-07 1.67E-06 1.14E-05 7.96E-05];
ber47=[6.09E-06 9.57E-06 8.81E-05 5.75E-04];
ber57=[7.95E-05 5.65E-05 3.54E-04 1.12E-03];
ber71=[2.68E-04 3.30E-04 9.42E-04 5.38E-03];

```

```

ber83=[0.0017 0.00180 0.004 0.0057];
ber94=[0.0019 0.0024 0.0054 0.0043];
ber107=[0.0021 0.004 0.003 0.0039];
figure(1)
plot(channel,OBI1);
hold on
plot(channel,OBI5);
hold on
plot(channel,OBI10);
ylabel('OBI ');
%axis([889 925 0 2])
grid on
figure(4)
semilogy(p,ber11);
hold on
semilogy(p,ber21);
hold on
semilogy(p,ber29);
hold on
semilogy(p,ber41);
hold on
semilogy(p,ber47);
hold on
semilogy(p,ber57);
hold on
semilogy(p,ber71);
hold on
semilogy(p,ber83);
hold on
semilogy(p,ber94);
hold on
semilogy(p,ber107);
title('Channel Vs BER');
xlabel('Channels (Number)');
ylabel('BER ');
%axis([889 925 0 2])
grid on

```

```

%% A.  MATLAB Code for 10 Channels
clc
clear all
close all
% Sampling frequency
Fs = 65536;
% Time vector of 1 second
t = 0:1/Fs:1;
f=8900:70:9600;
for i=1:65537
    y(i)=20;
end
for i=1
    for j=1:11
        for k=1:65537
            s(j,k)=1+y(i,k).*cos(2*pi*t(i,k)*f(i,j));
        end
    end
end
for i=1:65537
    x10(i)=0;
    y10(i)=0;
end
for i=1:11
    for j=1:65537
        x(i,j)=s(i,j).^2;
    end
end
for i=1:65537
    for j=1:11
        x10(1,i)=x10(1,i)+x(j,i);
    end
end
for i=1:65537
    for j=1:11
        for k=2:11
            if j<k
                y10(1,i)=2.*s(j,i).*s(k,i)+y10(1,i);
            end
        end
    end
end
% Use next highest power of 2 greater than or equal to length(x) to
calculate FFT.
nfft= 2^(nextpow2(length(x10)));
% Take fft, padding with zeros so that length(fftx) is equal to nfft
fftx10 = fft(x10,nfft);
ffty10 = fft(y10,nfft);
% Calculate the numberof unique points
NumUniquePtsx10 = ceil((nfft+1)/2);
NumUniquePtsy10 = ceil((nfft+1)/2);
% FFT is symmetric, throw away second half
fftx10 = fftx10(1:NumUniquePtsx10);
ffty10 = ffty10(1:NumUniquePtsy10);
% Take the magnitude of fft of x and scale the fft so that it is not
a function of the length of x
mx10 = abs(fftx10)/Fs;

```

```

my10 = abs(ffty10)/Fs;
% Take the square of the magnitude of fft of x.
%mx = mx.^2;
% Since we dropped half the FFT, we multiply mx by 2 to keep the same
energy.
% The DC component and Nyquist component, if it exists, are unique
and should not be multiplied by 2.
if rem(nfft,2) % odd nfft excludes Nyquist point
    mx10(2:end) = mx10(2:end)*2;
else
    mx10(2:end -1) = mx10(2:end -1)*2;
end
if rem(nfft,2) % odd nfft excludes Nyquist point
    my10(2:end) = my10(2:end)*2;
else
    my10(2:end -1) = my10(2:end -1)*2;
end
% This is an evenly spaced frequency vector with NumUniquePts points.
fx10 = ((0:NumUniquePtsx10-1)*Fs/nfft)/10;
fy10 = ((0:NumUniquePtsy10-1)*Fs/nfft)/10;
%Generate the plot, title and labels.
figure(1)
plot(fx10,mx10);
title('Power Spectrum of 10 channels at 7 MHz seperation Carrier
Wave');
xlabel('Frequency (MHz)');
ylabel('Power');
axis([925 962 0 25])
grid on
F=f/10;
areamx10=0;
areamy10=0;
si=0;
ei=0;
sil=0;
eil=0;
si=find(fx10==(925-0.1));
ei=find(fx10==(925+0.1));
df=fx10(si:ei);
dmx=mx10(si:ei);
areamx10=trapz(df,dmx);
sil=find(fx10==920.4);
eil=find(fx10==922.6) ;
df=fx10(sil:eil);
dmy=mx10(sil:eil);
areamy10=trapz(df,dmy) ;
snr10=areamx10/areamy10;
snr10db=20.*log10(snr10) ;
ber10=0.5*erfc(sqrt(2*snr10)) ;

title('Power Spectrum of 10 channels at 7 MHz seperation Carrier
Wave');
xlabel('Frequency (MHz)');
ylabel('Power');
axis([889 925 0 2])
grid on
figure(2)
plot(fx10,mx10);
title('Power Spectrum of 10 channels at 7 MHz seperation Carrier
Wave');
xlabel('Frequency (MHz)');

```

```

ylabel('Power');
axis([925 962 0 2])
grid on
figure(3)
plot(fy10,my10);
title('Power Spectrum of 10 channels at 7 MHz separation Carrier
Wave');
xlabel('Frequency (MHz)');
ylabel('Power');
axis([889 925 0 25])
grid on
figure(4)
plot(fy10,my10);
f=8900:6.5:9600;
for i=1:65537
    y(i)=0.01;
end
for i=1
    for j=1:108
        for k=1:65537
            s(j,k)=1+y(i,k).*cos(2*pi*t(i,k)*f(i,j));
        end
    end
end
for i=1:65537
    x100(i)=0;
    y100(i)=0;
end
for i=1:108
    for j=1:65537
        x(i,j)=s(i,j).^2;
    end
end
for i=1:65537
    for j=1:108
        x100(1,i)=x100(1,i)+x(j,i);
    end
end
for i=1:65537
    for j=1:108
        for k=2:108
            if j<k
                y100(1,i)=2.*s(j,i).*s(k,i)+y100(1,i);
            end
        end
    end
end
end

```

```

%Program 3: Dual Parallel Linearized MZ Modulator
clear all;
close all;

index=0;
index1=0;
index2=0;
index3=0;
%Modulation Index
mod1=[0.01:0.0005:0.05],[0.051:0.005:0.11]];
mod2=mod1;
m=mod2;

M=mod1.*sqrt(78);
M1=mod2.*sqrt(78);

B=[2,2.5,3];
for n=1:length(B)
    index=index+1;
    A1(index,:)=(B(n)*(mod1./2)).^3;
    A2(index,:)=exp(-B(n)^2*(M.^2)./4);
    A3(index,:)=(mod1./2).^3;
    A4(index,:)=exp(-(M.^2)./4);
end

for n=1:length(B);
    index1=index1+1;

    A(index1,:)=(A1(n,:).*A2(n,:))./((A3(n,:).*A4(n,:))+(A1(n,:).*A2(n,:)));
end

CONV_IMD=128./(3*m.^4*78^2);
CONV_IMD5=(m./2).^8*(78^4/12);

figure(1)
plot(mod1,A);grid;hold;
title('Figure 4-6 DPMZ Power Divider Ratio vs. OMI');
xlabel('Optical Modulation Index m');
ylabel('Power Divider Ratio(A)');
h = legend('B=2','B=2.5','B=3');
axis([0.01,.1,0.8,1])

a=[0.88,0.93,0.96];
b=[2,2.5,3];

for n1=1:length(b)
    index2=index2+1;
    IMD1(index2,:)=a(n1).*(m./2).^3;
    IMD2(index2,:)=exp(-(M1.^2)./4);
    IMD3(index2,:)=(1-a(n1)).*(b(n1).^3*(m./2).^3);
    IMD4(index2,:)=exp(-b(n1).^2*(M1.^2)./4);
    C1(index2,:)=a(n1).*(m./2);
    C2(index2,:)=exp(-(M1.^2)./4);
    C3(index2,:)=(1-a(n1)).*(b(n1).*(m./2));
    C4(index2,:)=exp(-b(n1).^2*(M1.^2)./4);
    IMD5_1(index2,:)=a(n1).*(m./2).^5;
    IMD5_2(index2,:)=exp(-(M1.^2)./4);
    IMD5_3(index2,:)=(1-a(n1)).*(b(n1).^5*(m./2).^5);
    IMD5_4(index2,:)=exp(-b(n1).^2*(M1.^2)./4);
end

```

```

test_imd5(index2,:)=(b(n1).^4)*(m./2).^8*(78^4/12);
end

total_IMD=(IMD1.*IMD2)-(IMD3.*IMD4);
total_IMD_5=(IMD5_1.*IMD5_2)-(IMD5_3.*IMD5_4);
total_C=(C1.*C2)-(C3.*C4);
CTB=(total_IMD./total_C).^2*(3*78^2/8);
CTB_5=(total_IMD_5./total_C).^2*((78^4)/12);
CTB_IMD5=CTB+test_imd5;

figure(2)
plot(m, 10*log10(1./CTB));grid;hold
plot(m, -10*log10(1./CONV_IMD), 'r');
figure(3)
plot(m, -10*log10(CTB(1,:)), 'b');grid;hold
plot(m, -10*log10(test_imd5(1,:)), 'b. ');
plot(m, -10*log10(CTB(2,:)), 'r');
plot(m, -10*log10(test_imd5(2,:)), 'r. ');
plot(m, -10*log10(CTB(3,:)), 'k');
plot(m, -10*log10(test_imd5(3,:)), 'k. ');
axis([0.01, .1, 0, 120])
title('Figure 4-11 Carrier to Third & Fifth order distortion vs. OMI');
xlabel('Optical Modulation Index m');
ylabel('C/CTB & C/CIR5(dB)');
h = legend('Case I: Third Order Distortion', 'Case I: Fifth Order Distortion', 'Case II: Third Order Distortion', 'Case II: Fifth Order Distortion', 'Case III: Third Order Distortion', 'Case III: Fifth Order Distortion');

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References

- [1] R. Hui, B. Zhu, R. Huang, C. Allen, K. Demarest, D. Richards, "Subcarrier Multiplexing for High-speed Optical Transmission," *Journal of Lightwave Technology*, vol. 20, no. 3, March 2002.
- [2] R. Olshansky, "Optimal Design of Subcarrier Multiplexed lightwave systems employing linearized external modulators," *Journal of Lightwave Technology*, vol. 10, no.3 March, 1992.
- [3] G Keiser, *Optical fiber Communication*, Boston, 2000.
- [4] W. Way, *Broadband Hybrid Fiber/Coax Access System Technologies*, San Diego, CA: Academic, 1999.
- [5] G. Smith, D. Novak, Z. Ahmed, "Overcoming Chromatic-Dispersion Effects in Fiber-Wireless Systems Incorporating External Modulators," *IEEE Transactions on Microwave Theory and Techniques*, vol. 45, no. 8, August 1997.
- [6] J. Brooks, G. Maurer, R. Becker, "Implementation and Evaluation of a Dual Parallel Linearization System for AM-SCM Video Transmission," *Journal of Lightwave Technology*, vol. 11, no. 1, January 1993.
- [7] FCC Standard and Regulations: Section 76.605 "Multichannel Video and Cable Television Service".
- [8] J. Chiddix, H. Laor, D. Pangrac, L. Williamson & R. Wolfe, "AM Video on Fiber in CATV systems: Need and Implementation", *IEEE Journal on Selected Areas in Communications*, vol. 8, no. 7, September 1990.
- [9] S. Bigo, S. Gauchard, A. Bertaina, & J. Hamaide, "Experimental Investigation of Stimulated Raman Scattering Limitation on WDM Transmission Over Various Types of Fiber Infrastructures," *IEEE Photonics Technology Letters*, vol. 11, no. 6 June 1999.
- [10] M Phillips & D. Ott, "Crosstalk Due to Optical Fiber Nonlinearities in WDM CATV Lightwave Systems," *Journal of Lightwave Technology*, vol 17, no. 10, Oct. 1999.
- [11] Simon Haykin, *Communication Systems* (John Wiley & Sons Inc., 4 Editions.)
- [12] Simon Haykin, *Digital Communications* (Wiley India Edition, 1st Edition.)
- [13] Lathi B.P., *Modern Digital and Analog Communication Systems* (Oxford University Press, 3rd Edition.)
- [14] Yang S. & Yao J.G., Impact of Crosstalk Induced Beat Noise on the size of Semiconductor Laser Amplifier Based Optical Space Switch Structures, *IEEE Photonics Technology Letters*, Vol. 4. , No. 7, July 1996.
- [15] Gyselings Tim, Morthier Geert & Baets Roel, Crosstalk Analysis of Multiwavelength Optical Cross Connects, *Journal of Light wave Technology*, Vol. 17, No. 8, August 1999.

- [16] Mizuochi Takashi, Kitayama Tadayoshi, Shimizu Katshuhiro & Ito Atsuyoshi, Interferometric Crosstalk-Free Optical Add/Drop Multiplexer Using Mach-Zehnder Based Fiber Gratings, *Journal of Light wave Technology*, Vol 16, No. 2, February 1998.
- [17] Phase Modulation in Wikipedia, Available: http://en.wikipedia.org/wiki/phase_modulation
- [18] Timercon website [online]. Available: <http://en.timercon.com/BER/>.
- [19] Accumulated noise in yahoo answer. Available: http://en.answer.com/topic/accumulated_noise/ (2002) The IEEE website. [Online] Available: http://ieee_xplore.com/topic/effect_of_crosstalk_on_wdm_mux-demux/
- [20] Crosstalk topics. Available: <http://www.crosstalkamerica.com/>.
- [21] Modulation in Wikipedia. Available: <http://en.wikipedia.org/wiki/Modulation>
- [22] N. Shibata, R. Braun, R. Waarts, "Phase Mismatch Dependence of Efficiency of Wave Generation Through Four-Wave Mixing in a Single-Mode Optical Fiber," *IEEE Journal of Quantum Electronics*, vol QE-23, no. 7, July 1987.
- [23] E. E. Elsayed and B. B. Yousif, "Performance evaluation and enhancement of the modified OOK based IM/DD techniques for hybrid fiber/FSO communication over WDM-PON systems," *Opt. Quantum Electron.*, vol. 52, no. 9, 2020, doi: 10.1007/s11082-020-02497-0.
- [24] B. B. Yousif, E. E. Elsayed, and M. M. Alzalabani, "Atmospheric turbulence mitigation using spatial mode multiplexing and modified pulse position modulation in hybrid RF/FSO orbital-angular-momentum multiplexed based on MIMO wireless communications system," *Opt. Commun.*, vol. 436, pp. 197–208, 2019, doi: 10.1016/j.optcom.2018.12.034.
- [25] A. M. Mbah, J. G. Walker, and A. J. Phillips, "Outage probability of WDM free-space optical systems affected by turbulence-accentuated interchannel crosstalk," *IET Optoelectron.*, vol. 11, no. 3, pp. 91–97, 2017, doi: 10.1049/iet-opt.2016.0057.
- [26] B. B. Yousif and E. E. Elsayed, "Performance Enhancement of an Orbital-Angular-Momentum-Multiplexed Free-Space Optical Link under Atmospheric Turbulence Effects Using Spatial-Mode Multiplexing and Hybrid Diversity Based on Adaptive MIMO Equalization," *IEEE Access*, vol. 7, pp. 84401–84412, 2019, doi: 10.1109/ACCESS.2019.2924531.
- [27] E. E. Elsayed and B. B. Yousif, "Performance enhancement of hybrid diversity for M-ary modified pulse-position modulation and spatial modulation of MIMO-FSO systems under the atmospheric turbulence effects with geometric spreading," *Opt. Quantum Electron.*, vol. 52, no. 12, 2020, doi: 10.1007/s11082-020-02612-1.
- [28] Ebrahim E. Elsayed, Bedir B. Yousif, and Mahmoud M. Alzalabani, "Performance enhancement of the power penalty in DWDM FSO

- communication using DPPM and OOK modulation", *Optical and Quantum Electronics*, vol. 50 (7), pp. 282, (26 June 2018).
- [29] Ansari, N., Zhang, J.: 'Media access control and resource allocation for next generation passive optical networks' (Springer, 2013)
- [30] Ebrahim E. Elsayed and Bedir B. Yousif, "Performance enhancement of the average spectral efficiency using an aperture averaging and spatial-coherence diversity based on the modified-PPM modulation for MISO FSO links", *Optics Communications*, vol. 463, pp. 125463, (15 May 2020).

Compliance with ethical standards

Conflict of interest: The author declares that there is no conflict of interest regarding the manuscript. The author is responsible for the content and writing of this article. The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.