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

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Research Article

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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.](image)

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.](image)
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].

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 \( \lambda_1 \) and \( \lambda_2 \) [10, 15].

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

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

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 \( I_2 \) gets [10, 15]:

\[
P_2(0, \mu_2) = P_2(0, \mu_2)e^{-az}. \exp \left[ -\frac{g}{A_{eff}} \int_0^z P_1(0, \mu_2 + d_{12}z')e^{-az'}dz' \right] \quad \text{Eq. 3}
\]
\[ P_2(0, \mu_2) \approx P_2(0, \mu_2)e^{-\alpha z}\left[1 - \frac{g}{A_{eff}} \int_0^Z P_1(0, \mu_2 + d_{12}z')e^{-\alpha z'}dz'\right] \text{Eq. 4} \]

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

A similar approach can be used to solve for \( l_1 \) by neglecting the SRS term, \(-gL_1\) on the right hand side of Eq.2 and solving for \( l_2 \), then substituting \( l_2 \) into Eq.1 to get [10, 15]

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

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]:

\[ e_i(t) = \sqrt{S_i(t)} \quad \text{Eq. 6} \]

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

\[ S_i = 1 + m(t) \cos(2\pi f_i t) \text{Eq. 7} \]

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]:

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

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

\[ e_o(t) = \left|e_{in}(t) * h_f(t)\right|e^{-\alpha L} \quad \text{Eq. 9} \]

Where \( \alpha \) 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.
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.

$$i_s(i) = \int_{-\infty}^{+\infty} i_s(t) e^{-jft}$$

$$= 2\pi \delta(f) + \left(\frac{T}{2}\right) * \left[ \text{sinc} T (f - f_i) + \text{sinc} T (f + f_i) \right] e^{\left(\frac{jft}{2}\right)}$$ \hspace{1cm} \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:

$$P_s(i)(f) = [i_s(i)(f)]^2$$

$$= 4\pi 2\delta(f) + \left(\frac{T^2}{4}\right) * \left[ \text{sinc}^2 T (f - f_i) + \text{sinc}^2 T (f + f_i) \right] e^{\left(\frac{jfr}{2}\right)}$$ \hspace{1cm} \text{Eq. 13}

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

$$P_{i(sig)} = \int_{f_i - B/2}^{f_i + B/2} P_s(i)(f) \, df = \int_{f_i - B/2}^{f_i + B/2} \left(\frac{T^2}{4}\right) * \left[ \text{sinc} 2 \tau (f - f_i) \right] \, df$$ \hspace{1cm} \text{Eq. 14}

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

This $P_i$ is the source of the OBI.

$$\text{SNR} = \frac{P_{i(sig)}}{P_{i(cross)}}$$ \hspace{1cm} \text{Eq. 15}

$$\text{BER} = 0.5 \text{erfc} \left(\sqrt{2X\text{SNR}}\right)$$ \hspace{1cm} \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 in as [22].

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

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

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

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

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

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

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

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

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

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].

\[
P_{\text{out}} \frac{P_{\text{in}}}{P_{\text{in}}} = A \cos^2 \left( \frac{\pi V(t)}{V_{\pi}} - \frac{\pi}{2} \right) + (1 - A) \cos^2 \left( B \frac{\pi V(t)}{V_{\pi}} - \frac{3\pi}{2} \right)
\]

\[
= \frac{1}{2} \left( 1 + A \sin \frac{\pi V(t)}{V_{\pi}} - (1 - A) \sin \frac{B\pi V(t)}{V_{\pi}} \right)
\]

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 \( \omega_k \) can be expressed as [10]:

\[
P_{\omega_k} \frac{P_{\text{in}}}{P_{\text{in}}} = A J_1 \left( \frac{\pi A}{V_{\pi}} \right) I_0 \left( \frac{\pi A}{V_{\pi}} \right)^{N-1} - (1 - A) J_1 \left( B \frac{\pi A}{V_{\pi}} \right) I_0 \left( B \frac{\pi A}{V_{\pi}} \right)^{N-1}
\]

Eq. 24
And the amplitude of the third-order intermodulation component of the frequency \(\omega_i + \omega_j + \omega_k\) can be expressed as

\[
P_{\omega_i+\omega_j+\omega_k}/P_{in} = A J_1\left(\frac{\pi A}{V_N}\right)^3 J_0\left(\frac{\pi A}{V_N}\right)^{N-3} - (1 - A) J_1\left(\frac{\pi A}{V_N}\right)^3 J_0\left(\frac{\pi A}{V_N}\right)^{N-3}\]

Eq. 25

The third-order intermodulation product can be cancelled when

\[
A = \frac{J_1\left(\frac{\pi A}{V_N}\right)^3 J_0\left(\frac{\pi A}{V_N}\right)^{N-3}}{J_1\left(\frac{\pi A}{V_N}\right)^3 J_0\left(\frac{\pi A}{V_N}\right)^{N-3} + J_1\left(\frac{\pi A}{V_N}\right)^3 J_0\left(\frac{\pi A}{V_N}\right)^{N-3}}
\]

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.
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 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); hold on
plot(channel,snr20); hold on
plot(channel,snr20); hold on
plot(channel,snr20); hold on
plot(channel,snr20); hold on
plot(channel,snr20); hold on
plot(channel,snr20); hold on
plot(channel,snr20); hold on
plot(channel,snr20); hold on
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;
% Sampling rate
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;
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 number of unique points
NumUniquePtsx10 = ceil((nfft+1)/2);
NumUniquePtsy10 = ceil((nfft+1)/2);
% FFT is symmetric, throw away second half
fftx10 = ffftx10(1:NumUniquePtsx10);
ffty10 = fffty10(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.
% Although 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 separation 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;
si1=0;
ei1=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);
si1=find(fx10==920.4);
ei1=find(fx10==922.6);
df=fx10(si1:ei1);
dmy=mx10(si1:ei1);
areamy10=trapz(df,dmy);

snr10=areamx10/areamy10;
ber10=0.5*erfc(sqrt(2*snr10)) ;

figure(2)
plot(fx10,mx10);
title('Power Spectrum of 10 channels at 7 MHz separation Carrier Wave');
xlabel('Frequency (MHz)');

figure(1)
plot(fx10,mx10);
title('Power Spectrum of 10 channels at 7 MHz separation Carrier Wave');
xlabel('Frequency (MHz)');

figure(2)
plot(fx10,mx10);
title('Power Spectrum of 10 channels at 7 MHz separation 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=1:108
    for k=1:65537
        s(j,k)=1+y(i,k).*cos(2*pi*t(i,k)*f(i,j));
    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
%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);
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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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.