DWDM Transmission Systems and Networks: Experiments by Simulation

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ABSTRACT: *Laboratory practical training in high-end technical subjects at the level of university/technical institutes is often not feasible due to infrastructure limitations. However, the same objective can be effectively achieved by suitable design of simulation-based experimentation. The paper describes three representative experiments in the area of dense WDM transmission systems and networks.*

1 INTRODUCTION

It has been recognized that in today's fast changing and technology intensive society a need for trained man-power in high-end scientific and engineering areas is acutely felt. In many upcoming and new areas of advanced topics, experimental laboratory training is always not possible because of fund/ infrastructure limitations. However, through proper design of advanced-level simulation based experiments, students can be trained appropriately for an easy interface with the industries.

The main intent of this endeavor is to develop at-least twenty-five simulation based experiments in the core area of DWDM transmission systems and networks keeping in view that the cost of setting up of an experimental laboratory in this area is prohibitive. Because of space limitations, we are constrained to present only three representative simulation based experiments mentioned below.

1. Study of the impact of first-order group velocity dispersion (GVD) on a propagating pulse in a single mode fiber link.
2. Dispersion and nonlinearity management in a 4x40 Gbps WDM transmission link.
3. Routing and wavelength assignment in a WDM network

An interested reader may get additional information of other experiments from the authors

2 DESCRIPTION OF SIMULATION BASED EXPERIMENTS

We provide detailed step-by-step procedures for carrying out simulation-based experiments in the following.

2.1 EXPERIMENT 1: Study of the impact of first-order GVD on a propagating pulse in a single mode fiber link [1,2].

Table 1: System parameter definitions

β_2	Second order dispersion coefficient
β_3	Third order dispersion coefficient
γ	Non-linear coefficient
α	Attenuation coefficient at signal wave length
$2*T_o$	FWHM of Gaussian pulse
P_o	Peak power of the Gaussian pulse
h	Half the length of split step

2.1.1 SIMULATION STEPS

The system parameters used subsequently are defined in Table 1.

Step1: Optical pulse generation

The input is assumed as the unchirped Gaussian pulse envelope given by

$$U(0,T) = \sqrt{P_o}\exp\left[-\frac{1}{2}\left(\frac{T}{To}\right)^2\right]$$

where T_o is the half-width of the pulse (at 1/e intensity point).T is measured in a frame of reference moving with the pulse at the group velocity v_g i.e $T=(t-z/v_g)$. In order to generate the sampled signal, it is assumed that the pulse is spread over an interval 20To such that the sampling period Ts = 20To/N, N is the number of samples. The normalized sampled signal is given by

$$U(0,n) = \exp\left[-\frac{1}{2}\left(\frac{nT_s}{To}\right)^2\right] \text{ where n= -N/2 to (N/2)-1}$$

```
%Equivalent Matlab code
Ts=20*To/N;
k=-N/2:(N/2)-1;
Pulse=exp(-(k*Ts/To).^2/2);
```

Step2: Calculation of spectrum of the input pulse:

To find the spectrum of the sampled Gaussian pulse, we may use discrete Fourier transform (DFT). In simulation, we use FFT with length 2N by padding the pulse samples with N additional zeros thereby yielding 2N samples in the frequency domain and swap the spectrum samples from N+1 to 2*N with the samples of 1 to N.

```
%Equivalent Matlab code
Pulse(N+1:2*N)=0; % padding N zeros
Spectrum=fftshift( fft (Pulse,2*N) );
```

Step3: Calculation of fiber transfer function:

As the signal spectrum extends from –Fs/2 to Fs/2, we calculate the transfer function $H(f)$ from – Fs/2 to Fs/2 for a half the length of a step (h/2)

$$H(n+1) = \exp\left[\left(\frac{i}{2}\beta_2\left\{2\pi(nf_o - \frac{Fs}{2})\right\}^2 - \frac{i}{6}\beta_3\left\{2\pi(nf_o - \frac{Fs}{2})\right\}^3\right)\frac{h}{2}\right]$$

where n=0 to 2N-1 and f_o=Fs/(2*N)

```
%Equivalent Matlab code
k=0:2*N-1;
fo=Fs/(2*N);
TrF=exp(2*i*Beta2*h/2*pi*pi*(k*fo-Fs/2).^2.*exp(-i*Beta3*h/2*(2*pi*(k*fo-Fs/2)).^3/6);
```

Step 4: Multiplication of pulse spectrum and fiber transfer function:

In order to calculate the output pulse spectrum, we need to multiply input pulse spectrum and fiber transfer function. We already have those two complex sequences. So, we multiply them sample-by-sample and again unswap the spectrum.

```
%Equivalent Matlab code
 GVD_Spec=fftshift( Spectrum*TrF );
```

Step 5: Calculating the time domain optical pulse:

In the simulation, inverse Fourier transform will be implemented by IFFT algorithm, which yields the dispersed pulse in the time domain.

```
%Equivalent Matlab code
GVD=ifft(GVD_Spec,2*N);
```

Step 6: Calculating the non - linear phase response and loss of fiber

To calculate the non linear response first find the squared magnitude of the field which we got after GVD effect and then multiply with nonlinear parameter and step length 'h'. This will be the intensity-induced phase change (see Appendix A.1).

```
%Equivalent Matlab code
%CALCULATION OF SPM PART
PhiNl=(Gamma*(abs(GVD)).^2*h);
hspm =exp(i.*PhiNl);
Loss=exp(-Alpa*h/2)
```

Step 7: **Multilplying result of GVD part (step 1-5) and SPM and loss part (step6) is self-explanatory.**

```
%Equivalent Matlab code
Split_Step=GVD*hspm*Loss;
```

Step 8: Repeat the steps form 1 to 5 over the other half of the step. The steps form 1 to 7 gives the propagation only over a split-step. Carry out all the above steps so that entire length is covered passing the output of the preceding split-step to the following split-step.

2.1.2 SIMULATION RESULTS

Fig.1 shows the Gaussian pulse propagation in normal dispersion regime and Fig. 2 depicts the propagation in anomalous dispersion regime.

Input parameters:

$\beta_2 = 20ps^2/km$

$\beta_3 = 0.1ps^3/km$

$\gamma = 1.31W^{-1}km^{-1}$

To=100 ps

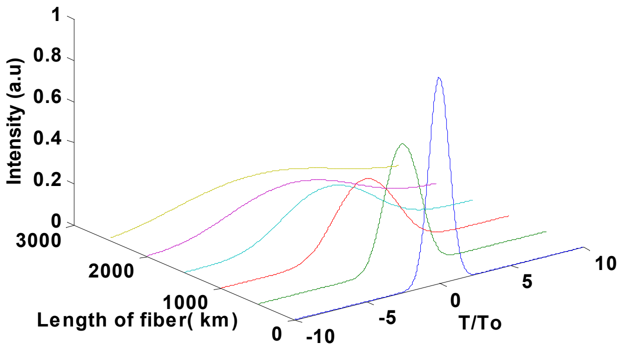


Figure 1. Propagation of Gaussian pulse in normal dispersion regime

Input parameters:

$\beta_2 = -20ps^2/km$

$\beta_3 = 0.1ps^3/km$

$\gamma = 1.31W^{-1}km^{-1}$

To=100 ps

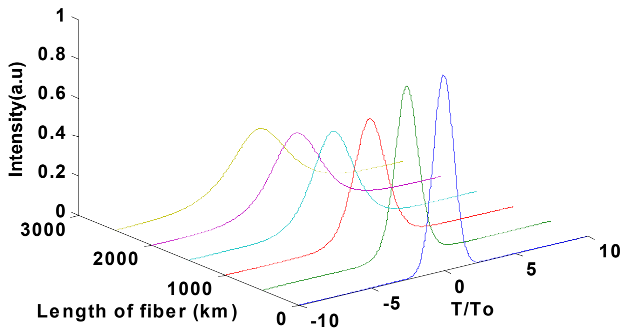


Figure 2. Propagation of Gaussian pulse in anomalous dispersion regime

2.2 EXPERIMENT 2: Simulation of a 4x40Gb/s multi-channel optical transmission system using optical phase conjugation (OPC) [3-5] with distributed Raman amplifier (DRA) [6-7] .

2.2.1 SIMULATION STEPS

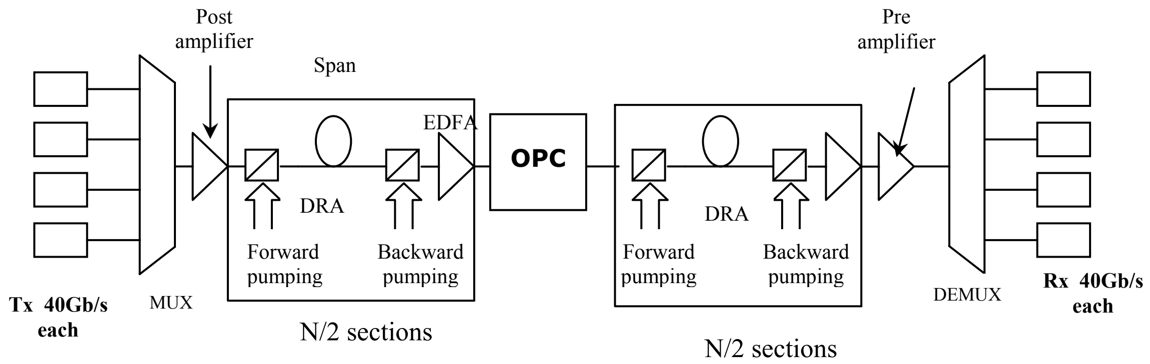


Figure 3: 4x40Gb/s transmission link with OPC-DRA compensator

Step 1: Optical signal generation (NRZ format).

Set the number of samples/bit (Nb) at least 32. Take separate pseudo random binary sequence (PRBS) of same length for each channel . If the pseudo-random sequence length is 'K', then total number of samples (N) is 'K*Nb'. Set the Nb samples to either '0' or '1' depending upon the binary value of the PRBS.

Step 2: Optical filtering

Filter the optical field of each channel through an optical Bessel filter of third order and bandwidth equal to1.5 times the signal bandwidth

Step 3: Definition of the relevant parameters in a span

Span length: l
Link length: L
Number of spans: L/l
Span loss: L_{span}

Step 4: Calculation of EDFA gain:

For a given span loss, the EDFA gain is adjusted to, $G_{EDFA} = \frac{L_{span}}{G_{forward} \cdot G_{backward}}$, where $G_{forward}$ and $G_{backward}$ are the forward and backward gains of DRA

Step 5: Split-Step Fourier method (SSF)

We replace α (see Appendix A.1) by $\alpha_{eq}(z)$ defined in [7] at every step of SSF used for WDM simulation and carry out the SSF over the entire span. Multiply the resultant signal with EDFA gain at the end of each span. Carry out the SSF method over each span over half the system length. The algorithm needed to simulate WDM to include the effects of second and third order dispersions, SPM, XPM is given in Appendix B.1

Step 6: Optical phase conjugation

We have got an array of complex field after carrying out SSF over half the system length. Let the signal can be expressed as A.exp(j $\Delta\phi$) , to conjugate the phase it is just enough to take complex conjugate of every sample of the optical field which results in A.exp(-j $\Delta\phi$).This phase again changed by $\Delta\phi$ resulting in total phase shift of zero[3-5].

Step 7: Carry out SSF over rest half of the system length as explained above

Step 8: Optical filtering

Pass the resultant optical field through an optical filter of 6th-order and of appropriate bandwidth (1.5*signal band-width), corresponding to the modulation format used. This filter selects the desired channel.

Step 9: Photo detection and electrical filtering:

The photocurrent generated by photo detector is proportional to the optical power incident, which is square of the optical field, the resultant photo-detected electrical signal is passed through a 3rd order Bessel filter of bandwidth equal to 70% of the bit rate.

Step 10: Eye opening penalty (EOP) measurement:

The EOP penalty is measured from the relation

$$EOP(dB)=10*\log_{10}(a/b)$$

where *'a'* is the eye opening for back to back connection i.e. length of fiber is zero and *'b'* is the measured eye opening when signal is passed through the fiber.

Step 11: Repeat the above process for various lengths of fiber and plot EOP (dB) vs. system length for three different modulation formats such as NRZ, RZ and suppressed carrier RZ (CS-RZ).

2.2.2 SIMULATION RESULTS

The simulation results are shown in Fig.4 and Fig.5 , which show the variation of EOP versus transmission length for three different modulation formats.

Table 2:Input parameters for 4x40 Gb/s WDM transmission simulation

Attenuation (α_s) at signal λ	0.22 Db/km
Attenuation (α_p)at pump λ	0.3 dB/km
Dispersion parameter (D) at 1550nm	16.6 ps/km/nm
Dispersion slope ($dD/d\lambda$)	0.08 ps/km/nm^2
Non-linear coefficient (γ)	1.3 W^{-1}.km^{-1}
Link Length (L)	320 km
Span length (l)	80km
Channel spacing	200GHz

2.3 EXPERIMENT 3: Routing and Wavelength Assignment (RWA) in a WDM network, using layered graph model [8,9].

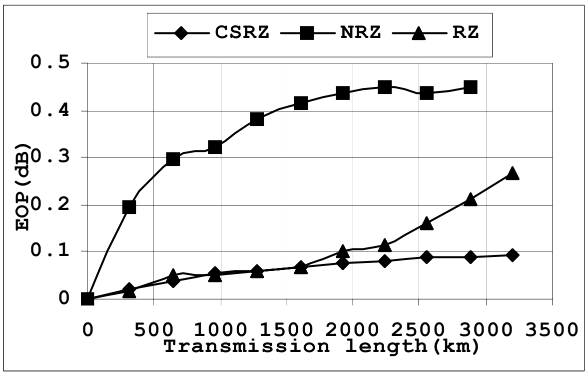


Figure 4: Comparison of EOP for different modulation formats with OPC-DRA scheme with Pavg =0dbm for 40Gb/s single channel system With total Raman gain=17.6 dB

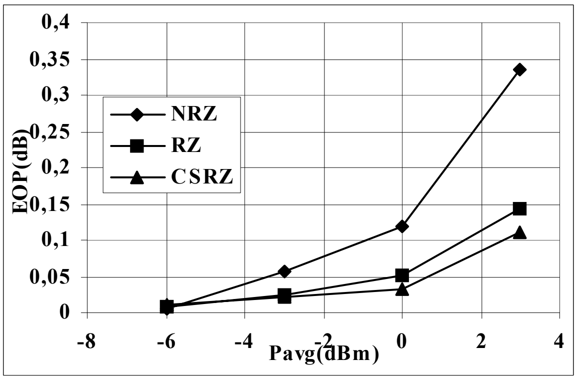


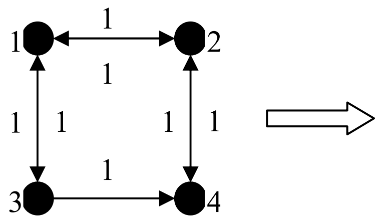
Figure 5: Comparison of different modulation formats in 4x40 Gb/s WDM transmission system with respect to EOP with only OPC compensation scheme by setting total Raman gain to 0 dB

Table 3: Input parameters

Parameter Name	Description	Status (For entire simulation)
Topology	Indicates the Number of nodes and their links with other nodes. Generally given in a data file. This is the physical topology of the network.	Fixed.
Average call holding time.	Indicates Average call holding time. Units are that of "time".	Fixed.
Total calls	Indicates total number of counted calls in simulation. Generally this value will be around 10,000.	Fixed.
Network load	The amount of traffic offered to network. Units are "Erlangs". From network load and call holding time, mean arrival rate will be calculated, which will be used to represent inter arrival process.	Variable.
No. of wavelengths	No. of wavelengths on each link in the system.	Fixed.
Cost of wavelength conversion.	This value is simulation dependent. When wavelength conversion is not available at a node, its value will be very high compared to link cost.	Fixed.

2.3.1 PROCEDURE TO INPUT THE NETWORK PHYSICAL TOPOLOGY

In a data file, the physical topology of the network was given as input. As an example, for a 4-node network shown below, the data file looks like as shown on the right hand side.




```
2 2 1 3 1
2 1 1 4 1
2 1 1 4 1
1 2 1
```

Fig.6: A 4-node network and the corresponding input data

In the above network, 1,2,3 and 4 denotes router nodes. The numbers next to each arc indicates the weight of the corresponding arc. In the topology matrix, each row (line) corresponds to a router node. Since four nodes are present in the network, four rows are present in the topology matrix. The first column value in each row indicates the number of outgoing links from that router node. Even numbered columns (2nd, 4th .Etc) indicate the router nodes to which the links are connected from that particular router node. Odd numbered columns (3rd, 5th .Etc) indicate the weights associated with the links connecting the particular node to the nodes in even numbered columns (2nd, 4th .Etc) respectively.

2.3.2 SIMULATION FLOWCHART

The following flowchart indicates the steps to be followed for the proposed task. The procedure mentioned below is valid irrespective of network topology.

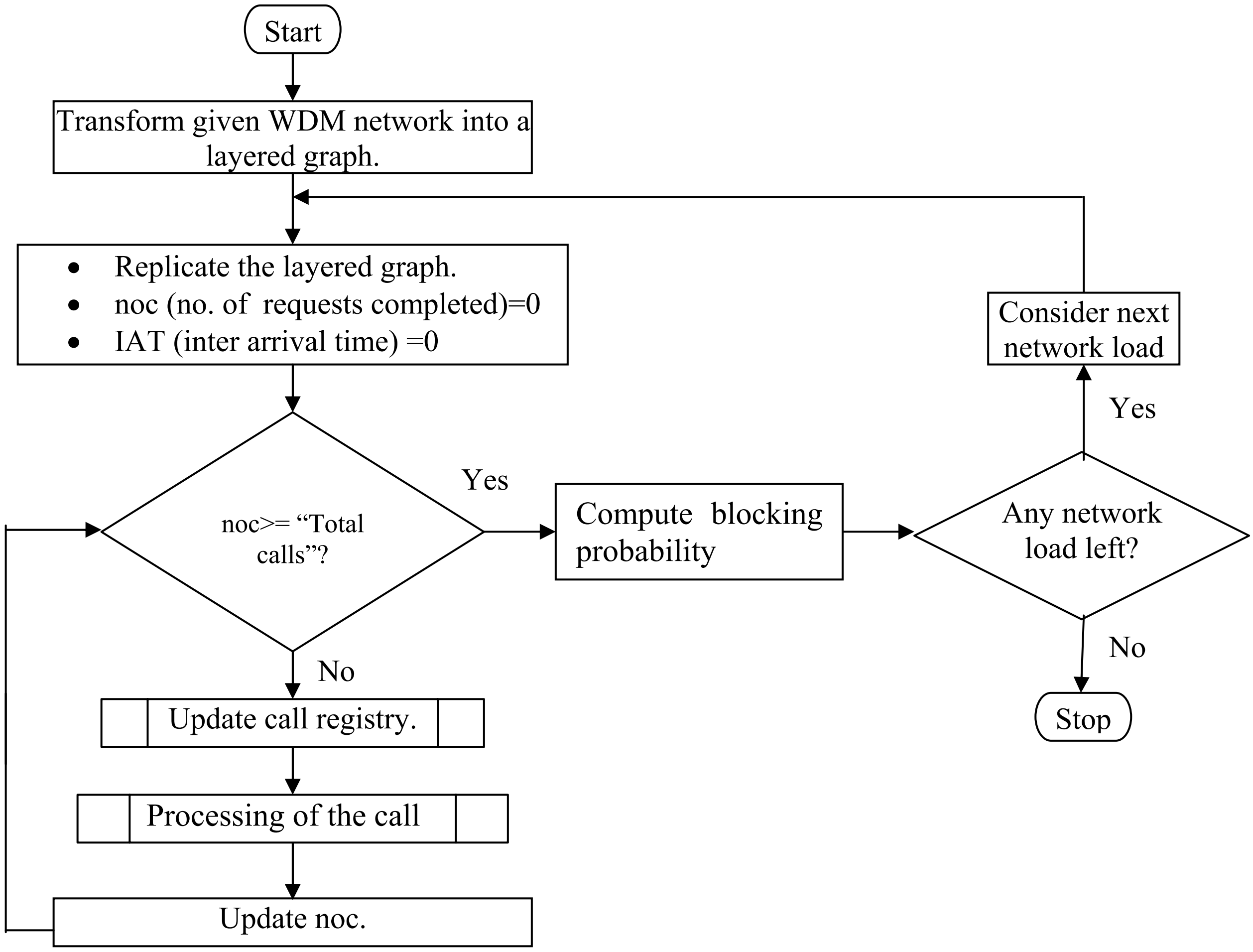


Figure 7: Simulation flow-chart

2.3.3 SIMULATION PROCEDURE

Step 1: Transformation of input network into layered graph.

The algorithm to transform a given network into layered graph is given in Ref. [8] and is not repeated here.

Step 2: Updating call registry and releasing the links.

In this function, holding time of every active call in the system will be updated and if any call holding time is completed, the resources allocated to the call will be released. Initially, no call is allocated. So no call is active. .

Step 3: Call generation and placement of the call.

A call request 'k' is characterized by { sk, dk , bk, hk },where sk and dk corresponds to source (ingress) and destination (egress) respectively and bk is the bandwidth required for the current call request and hk is the call holding time. Ingress and egress nodes are selected as per uniform distribution among all the nodes. Bandwidth of the call is equal to the capacity of one complete wavelength. It is assumed that *call holding times are exponentially distributed.* So with the given "mean holding time", exponential distribution is generated and each generated number is a call holding time. For placement of the call, the shortest path computation between source and destination is done using Dijkstra's algorithm. If the path is available, then the call request is admitted into the network and resources are allocated. If the path is not found, the request is blocked. It is assumed that call arrivals follow Poisson distribution with mean arrival rate λ. where,

$$\lambda = \frac{Network\ load}{Mean\ call\ holding\ time} \quad \text{and} \quad mean\ interarrival\ time = \frac{1}{\lambda}$$

Since arrival process follow Poisson distribution, interarrival times are exponentially distributed. So with the obtained "mean interarrival time", exponential distribution is generated. Each generated number is an inter-arrival time. A timer is set to the generated inter-arrival time. Next call is generated in the system after timer reaches to zero.

2.3.4 SIMULATION RESULTS

The results are obtained for a 24-node ARPANET. The number of wavelengths per fiber is 8 and 10. The capacity of each wavelength is normalized to one unit. The bandwidth of each call is one unit. Capacity of wavelength converter is also normalized to one unit. Weight of wavelength converter is 100 times more than the weight of wavelength link. Both Full wavelength conversion and no wavelength conversion cases are considered. Total 10,000 calls are simulated at each network load.

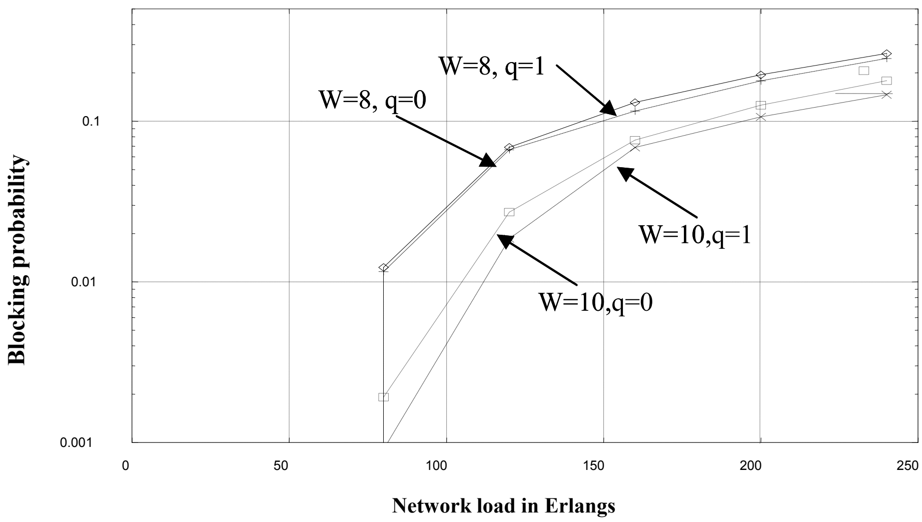


Fig. 8: Blocking probability versus the network load (Erlangs) for a 24-node network w = number of wavelengths, q=0 denotes without wavelength conversion and q =1 denotes with wavelength conversion.

3 CONCLUSION

In this paper we have described in detail simulation based three representative experiments in the topic of DWDM transmission systems and networks. These experiments can be easily adopted as simulation based experiments in the advanced level for both senior level UG and PG students. A significant number of high-end experiments can be planned and as many as twenty have been already developed. Such experiments with much-more E-learning facility can be of high value for students.

4 APPENDIX-A

A.1 Spilt-Step Fourier method (SSF)

The propagation of an optical pulse in single mode fiber can be described by[1]

$$i\frac{\partial A}{\partial z} = \frac{1}{2}\beta_2 \frac{\partial^2 A}{\partial T^2} + \frac{i}{6}\beta_3 \frac{\partial^3 A}{\partial T^3} - \gamma |A|^2 A - \frac{i}{2}\alpha A$$

where the parameters have their usual significance. One method that has been used extensively to solve the pulse propagation problem in nonlinear dispersive media is the split-step Fourier method (SSF) [1]. The essential steps to simulate the SSF method are provided in the following

1. Generate the input signal envelope (Gaussian/super Gaussian).→A(0,T)

2. Obtain the Fourier Transform of the input envelope. → A(z, ω)

$$A(z,\omega) = F[A(z,T)]$$

3. Calculate the transfer function for the length equal to half the step size

$$H(\omega) = \exp\left[\left(\frac{i}{2}\beta_2(\omega-\omega_o)^2 - \frac{i}{6}\beta_3(\omega-\omega_o)^3 - \frac{\alpha}{2}\right)\frac{h}{2}\right]$$

4. Multiply the signal obtained in Step2 with the transfer function. A(0, ω).H(ω)

$$A'(z + h/2, \omega) = A(z,\omega).H(\omega)$$

5. Calculate the inverse Fourier transform of the result of Step4 →.A(z,T)

$$A'(z + h/2, T) = F^{-1}\left(A'(z + h/2, \omega)\right)$$

6. Calculate the non-linear term $h_{spm}(T)$.

$$h_{spm}(T) = \exp\left(i\,\gamma\left|A'(z + h/2, T)\right|^2 h\right)$$

7. Multiply the results of step5 and step6:

$$A(z + h/2,) = A'(z + h/2,).h_{spm}(T).\exp(-\alpha h/2)$$

8.Repeat Step2 to Step5 over the other half (h/2.) of the step.
9.Repeat Step2 to Step7 for the span length.

APPENDIX-B

B.1 Pseudo code for simulation of a WDM system

for j = 1: No of channels,
for k =1: No of channels,
if (j ≠ k) then
*for f = -Fs/2:Fs/(2*N):Fs/2- Fs/(2*N),,*

$$H_{jk}(f) = 2\gamma_k \frac{\left(1 - \exp^{-\alpha_k(h/2)}.\exp^{j2\pi f d_{jk}(h/2)}\right)}{\left(\alpha_k - j2\pi f d_{jk}\right)}.\exp^{j2\pi f d_{jk}.h/2}$$

*for f = -Fs/2:Fs/(2*N):Fs/2- Fs/(2*N),*

$$H_{Disp,k}(f) = \exp\left[\left(\frac{i}{2}\beta_{2k}.(2\pi f - 2\pi f_o)^2 - \frac{i}{6}\beta_{3k}(2\pi f - 2\pi f_o)^3\right)\frac{h}{2}\right]$$

for Q =1:No of steps,
{
for k =1:No of channels,
{

$$A_k(z,f) = FFT\{A_k(z,T)\}$$

$$GVD_k(z + h/2, T) = IFFT\{A_k(z,\omega) * H_{Disp,k}(f)\}$$

$$\phi_{spm,k}(T) = \gamma\left|GVD_k(z + h/2, T)\right|^2 h$$

}

for k =1:No of channels,

$$SqMag_k = FFT\{\left|GVD_k(z + h/2, T)\right|^2\}$$

for j =1:No of channels,
for k =1:No of channels,
if (j ≠ k)

$$\phi_{XPM,j} = IFFT\left(\sum_{j\neq k} SqMag_k * H_{jk}(f)\right)$$

for k=1: No of channels,

$$A_k(z+h/2,T) = GVD_k(z+h/2,T) * \exp\left(i(\phi_{SPM,k} + \phi_{XPM,k})\right)$$

for k =1:No of channels,

{

$$A_k(z+h/2,\omega) = FFT\{A_k(z+h/2,T)\}$$

$$A_k(z+h,T) = IFFT\{A_k(z+h/2,\omega) * H_{Disp,k}(\omega)\}$$

}

}

The following are the definitions of various parameters used;

β_{2k} = Second-order dispersion coefficient of kth channel,

β_{3k} = Third-order dispersion coefficient of kth channel

α_k = Attenuation coefficient of kth channel

h = Split-step size

d_{jk} = Walk-off parameter

$A_k(z,T)$ =Complex envelope of kth channel at distance z

and ,

$$D = -\frac{2\pi c}{\lambda^2}\beta_2 \quad ; \qquad \frac{dD}{d\lambda} = \frac{4\pi c}{\lambda^3}\beta_2 + \left(\frac{2\pi c}{\lambda^2}\right)^2 \beta_3$$

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