

Analysis and Simulation of Dense Wavelength Division Multiplexing For Optical Transmission Networks

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Abstract: A Dense Wavelength Division Multiplexing (DWDM) system is a high-speed optical transmission system that simultaneously transports optical signals of different wavelengths over a single optical fiber. DWDM was developed as a next generation optical signal transport technology after traditional Time Division Multiplexed (TDM) systems offering much greater potential capacities. TDM is the most popular technology in the electrical networks, but it cannot utilize the available bandwidth, because it is limited by the speed of the time-multiplexing and demultiplexing components. That technology uses electrical components, which restrict potential resources of optical fibers. Theoretically DWDM technology gives indefinitely many services by using optical fibers. The number of services is dependent on many factors such as channel spacing between channels, number of channels, bit rate, input power, optical fiber effective area and optical fiber length. This paper provides an analysis & simulation of Dense Wavelength Division (DWDM) technology for the optical transmission systems. This paper provides a method to develop a more powerful comprehensive simulation program using MATLAB to simulate the different parts of the DWDM systems in order to provide some ways to minimize the impact of linear and non-linear effect (attenuation, dispersion, self-phase modulation (SPM), cross phase modulation (XPM) and stimulated Raman scattering (SRS)) on transmission quality.

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1. Introduction

Digitally encoded voice and data traffic signals were initially deployed over copper and radio bearers but over the past 20 years, these have been almost entirely replaced by optical fiber systems. Although radio continues to play a key role in many applications, copper is now largely confined to the local access network, whose replacement entirely by fiber remains difficult to justify economically in the short term.

Notwithstanding the choice of bearer, the definition of the digital multiplexing standards reflected the hierarchical network structure of the voice switched network, with 64 Kbits/s voice channels first multiplexed into a 2Mbits/s primary rate signal, which forms the basic building block of today's transport network. Subsequent multiplexing to higher rates followed, based on the ITU recommendations for PDH (Plesiochronous Digital Hierarchy) transport, resulting in the standardized aggregate 8 Mbit/s, 34 Mbit/s and 140 Mbit/s line systems. As digital processing and detection techniques advanced, so did the maximum aggregate transport rates, reaching 565 Mbit/s (equivalent to almost 8000 telephone channels) over a single fiber by early 1980s [3].

Around that time, the limitations of PDH were being questioned, culminating in the introduction of the SDH synchronous multiplexing structures. The

benefits of this new, synchronous enabled individual constituent payloads to be readily extracted from an aggregate signal, without the need for complete demultiplexing of the entire signal. In addition, the introduction of additional management and control bytes within the synchronous transport frame provided an unprecedented mechanism for monitoring performance and reconfiguring traffic paths, under remote network management control. The combination of these two features radically changed the nature of the transport network, enabling traffic to be provisioned and routed without the time and resource costs of visit to site, and laying the foundation for the flexible and resilient networks demanded by today's telecommunication users.

The benefits of SDH quickly apparent, resulting in the rapid adoption of these technologies in world markets, to the extent that they have all but replaced PDH.

Multiplexing as demand for bandwidth accelerated in the latter part of the 1990s, the limitations in the installed base of optical fiber, particularly on long-haul intercity routes, became pressing. At that time, the available SDH equipment was limited in capacity by the current electricity processing technology to an optical line rate of 40 Gbit/s per fiber [3].

To accommodate traffic growth rates of several hundred per cent per year in large part triggered by the

growth of the internet. The concept of putting several individual optical signals down a common, shared fiber using wave division multiplexing (WDM) was introduced. In WDM, each of potentially scores of lasers launches a unique color of light into a single shared fiber, with each laser carrying its own unique data stream. Although first applied to multiple SDH streams, the principle can be applied to carrying non-SDH traffic, opening up the potential for each fiber to carry a number of colored lasers or wavelength each independently carrying SDH, IP any other service.

Dense wavelength division multiplexing (DWDM) (Figure 1) was first introduced in large volume in North America by the long-haul [4], inter-exchange carriers for point to point routes. For the highest fiber capacity there is no real rival to DWDM. However, for aggregating traffic between the user and high capacity core, consolidation and grooming of traffic is essential in order to achieve optimum utilization of transmission plant in the access and regional network layers [1].

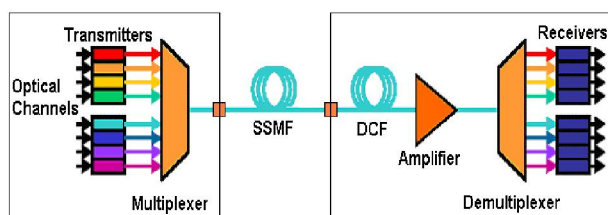


Figure 1. Structure of DWDM transmission system

When a network design is sketched out for the first time, many issues might require further optimization. One of the most important tools for designing and optimizing networks is simulation. Simulation uses interconnected mathematical models of components to predict the performance of a system as a whole. By incorporating a simulation within an optimization loop, the system's performance can be optimized for a particular scenario. This means designing to meet future upgrades without major reconfiguration of the network. The simulation of optical fiber links has only become common place over the past years. This is partly because researchers, who calculated conservative design rules that guaranteed the operation of a system in a well-defined set of circumstances, initially developed many commercial systems. In addition, a single manufacturer supplied the whole link from transmitter, through fiber, to receiver to guarantee performance through thorough testing. Of course, simulation of performance has been performed to design specialized links, such as submarine systems, for far longer. These systems were costly to prototype and operated as state of the art, saving design effort and lowering risk by simulations was well worth the

effort. With the advent of DWDM systems, manufacturers began using commercial and systems electronically, and to make proposals to service providers. This boost in the commercial tool market was initially driven by the nonlinearity of optical fibers, which although small, causes significant cross talk along a long haul link, where optical amplifiers keep the power levels high. However, as the performance of systems increased and a need arose to reduce costs particularly for access systems, many new problems could be identified and solved using simulation [2].

2. The History of DWDM

The laying of new fiber was once the only way to cope with fiber exhaust in Telecommunication networks. A cost and labor intensive process, the main drawback of this solution was its inability to enable network operators to provide new services. At the beginning of the 1980s, time division multiplexing (TDM) made it possible to increase the bit-rate [5]. With TDM, the capacity of a single fiber could be increased by slicing time into smaller intervals and thereby multiplexing the different signals.

In TDM systems, each telecommunication fiber is able to transport an optical signal from a single laser (Figure 2). This optical signal is converted into an electrical signal, regenerated (electrical reshaped, retimed and reamplified) and finally transformed back into an optical signal again encountering losses. High bit-rate transmissions via TDM however proved to be challenging.

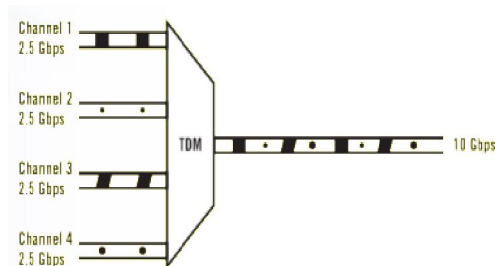


Figure 2. Time Division Multiplexing (TDM)

Wavelength division multiplexing (WDM), the simultaneous transmission of multiple signals at different wavelengths over a single fiber proved to be more reliable alternative.

The first networks deploying WDM technology at the end of 1980s [5], multiplexed signals from the lasers of two very different wavelengths (a technology now referred to as Coarse WDM). The disadvantage of this technique was that the multiplexed signal had to be separated each time being electrically regenerated.

Nowadays modern CWDM system is used for short range transmissions where no regeneration is required. They transmit up to 16 channels between 1310 and 1610 nm, thus making CWDM a cost effective solution. During the 1990s, networks were designed to send up to four different signals over one fiber at different wavelengths within the same optical window. This is an application however necessitating the use of narrow lasers. In order to increase the number of services, the channel spaces can be moved closer together creating Dense WDM or DWDM (Figure 3) as it is commonly known. This technology economically increases transport capacity through the utilization of existing fiber routes and terminal equipment.

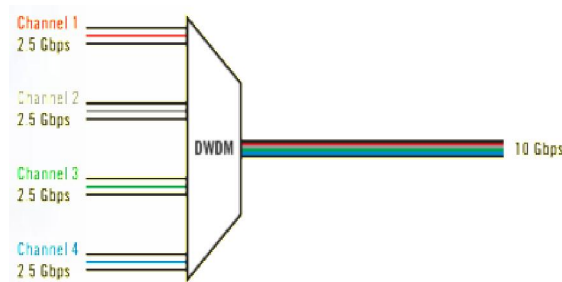


Figure 3. Dense Wavelength division multiplexing (DWDM)

While debate continues as to whether DWDM or TDM is best suited for the expansion of existing fiber networks, it has become clear that only solutions incorporating both technologies will give service providers the flexibility and capacity to future requirements (Figure 4). These requirements could for example enable them to:

- Maintain different dedicated wavelengths for different customers.
- Lease individual wavelength as opposed to entire fibers.
- Expand portions of their networks (for example, where multiple rings intersect between two nodes)

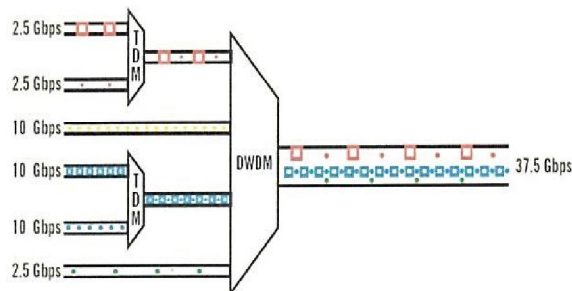


Figure 4. Increased capacity by combining TDM with DWDM

3. Implementation of the simulation program for DWDM program

The implementation of the simulation software with GUI (Graphical User Interface) using MATLAB is described. The purpose of the program is to simulate a DWDM system with its physical characteristics. The illustrated system in Figure 1 has been simulated.

3.1 Input parameters

The following parameters can be selected by the user:

➤ Fiber Characteristics

Attenuation, Dispersion, Slope, Nonlinear Index, Effective area and Fiber length.

➤ Signal Characteristics

Bit rate, Power, Number of bits, Samples per bit and Signal Shape.

➤ DWDM System Characteristics

Number of channels, Channel spacing and Carrier frequency.

➤ Nonlinear Effects

Self-phase modulation, Cross phase modulation and Stimulated Raman Scattering.

As an option, the user can activate the dispersion compensation fiber (DCF) and the amplifier individually. If the DCF is activated, a dispersion compensation fiber will be added to the Standard Single Mode Fiber (SSMF) with the same fiber length. If the DCF is used then the attenuation of the DCF will be taken into consideration.

3.2 The flow charts

In the following as shown in Figure 5, the structure of the simulation program is illustrated in form of a flow chart. The GUI (Graphical User Interface) is the main program, which calls the calculation and output subprograms. The flow chart of "calculation" subprogram is shown in Figure 6. The flow chart of "output" subprogram is shown in Figure 7. Another subprogram, which is called by the subprogram "calculation", is the "signal generator". The flow chart of "signal generator" subprogram is shown in Figure 8. Another function provided by the subprogram "display input signal shape" which illustrates graphically in the control monitors the chosen pulse with the defined signal characteristics and parameters. The subprogram "display input signal shape" is nearly identical to the subprogram "signal generator". The only difference is the subprogram "display input signal shape" will be used to show only the form of one single bit and not the entire input signal in the control monitor. The flow chart of "signal generator" subprogram is shown in Figure 9.

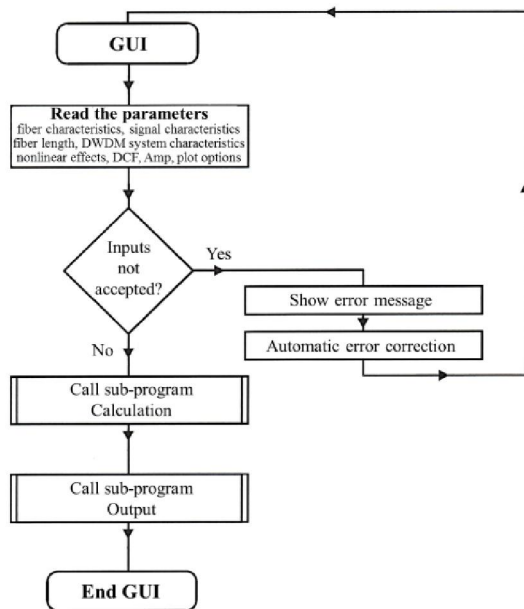


Figure 5. Flow Chart of main program

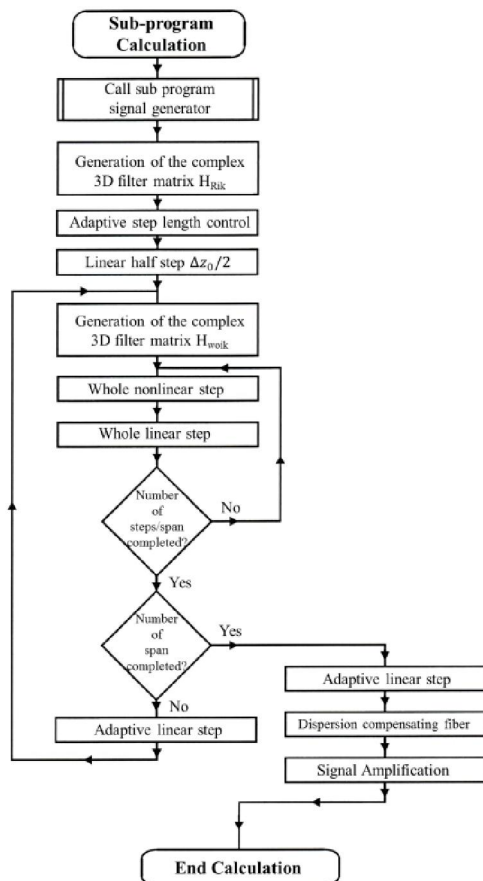


Figure 6. Flow Chart of subprogram "calculation"

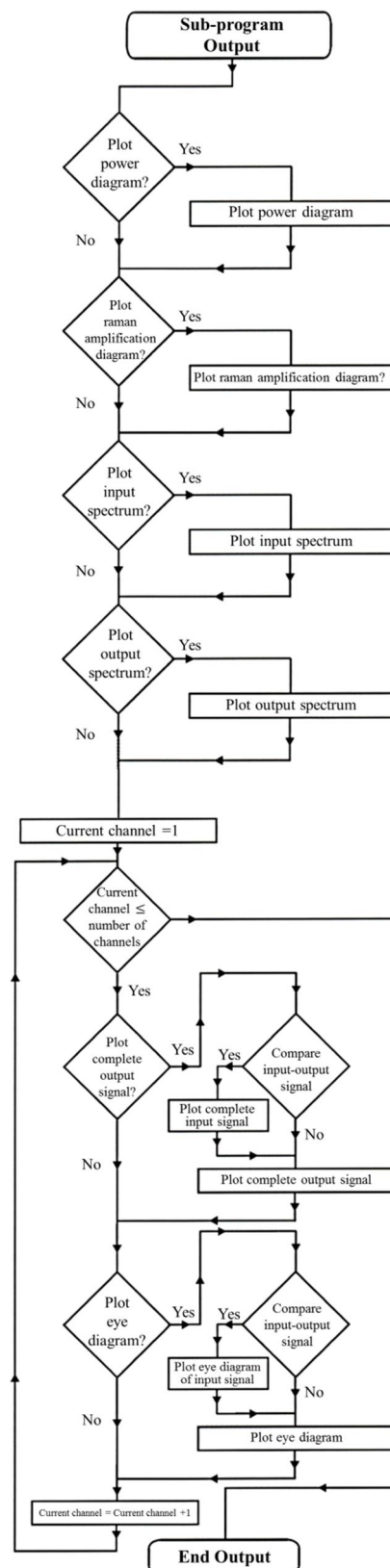


Figure 7. Flow Chart of subprogram "output"

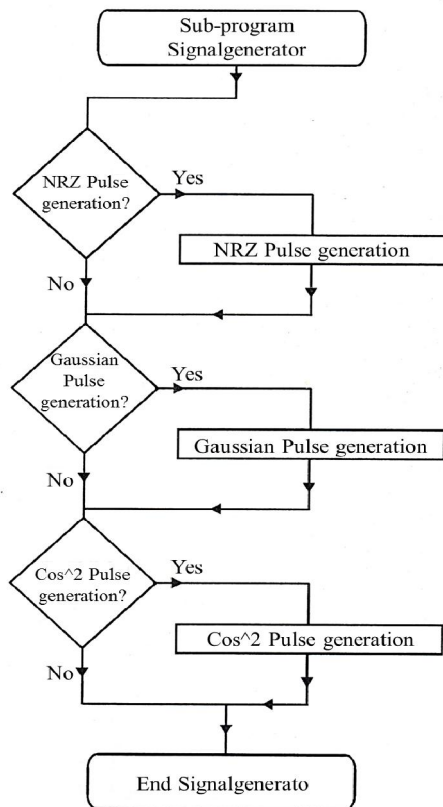


Figure 8. Flow Chart of subprogram “signal generator”

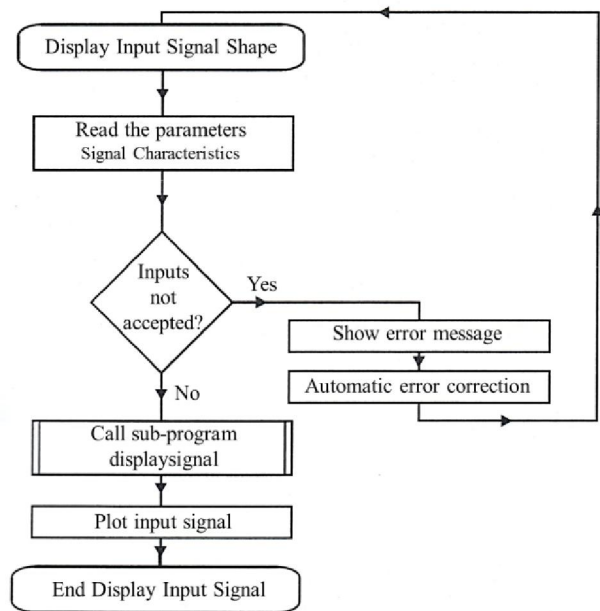


Figure 9. Flow Chart of subprogram “display input signal shape”

3.3 Graphical illustration of the results

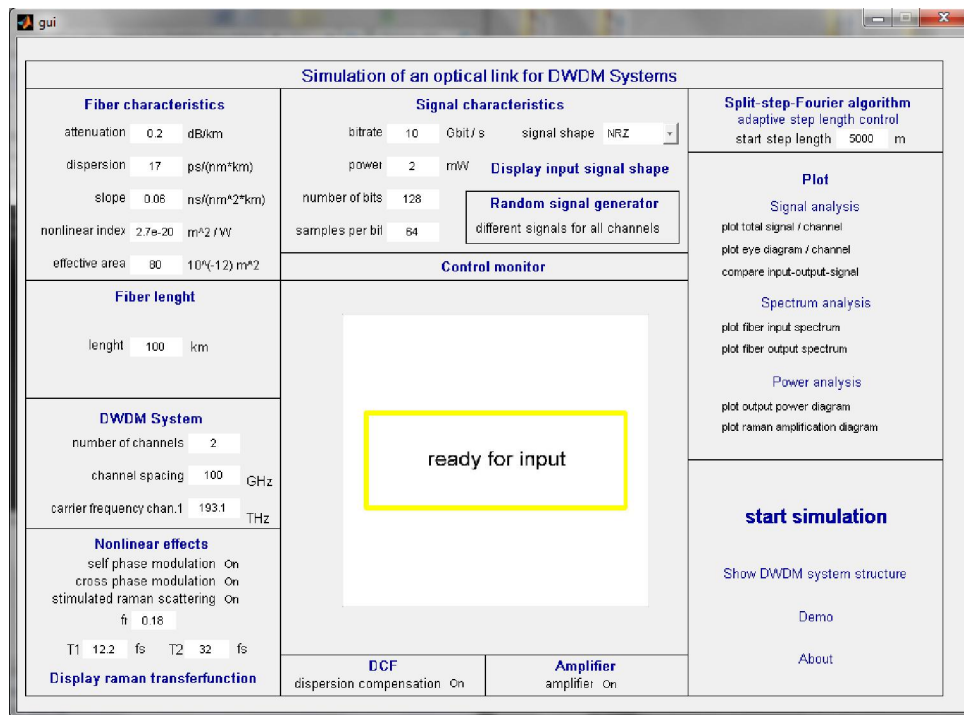


Figure 10. Interface of the simulation software

To be able to illustrate the simulated results graphically, the following output options are available:

- Plot (graphical depiction)
- Signal analysis
- Plot total signal/channel
- Plot total eye diagram / channel
- Compare input-output signal
- Spectrum analysis
- Plot input spectrum
- Plot output spectrum
- Power analysis
- Plot output power diagram
- Plot Raman amplification diagram

3.4 The functions of the graphical user interface

The graphical user interface is subdivided into the following windows as shown in Figure 10:

- Fiber Characteristics
- Signal Characteristics
- Fiber Length
- DWDM System Characteristics
- Nonlinear Effects
- DCF
- Amplifier
- Split Step Fourier Algorithm
- Plot
- Control Monitor

3.4.1 The function buttons

Figure 11 illustrates the function buttons located in the lower right corner of the main window.



Figure 11. Function Buttons

➤ Start Simulation

This function starts the main program which is shown in Figure 5.

➤ Show DWDM System Structure

This button opens the show window in Figure 12, which illustrates the structure of the simulated DWDM transmission link.

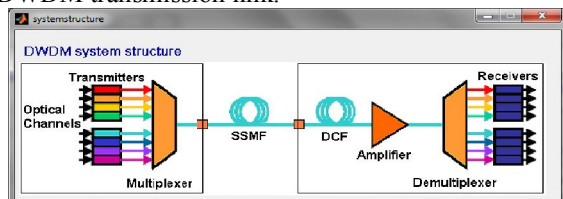


Figure 12. DWDM SYSTEM Structure Window

➤ Demo

This Demo shows two channels of 10Gbit/s DWDM system with a fiber length of 100 km. The channels have a carrier frequency of 193.1 THz and 193.15 THz. For both channels, one pulse will be transmitted in the form of a Gaussian pulse (RZ). The propagation of the two pulses through the fiber will be illustrated graphically.

The attenuation and dispersion can be selected to be taken into consideration as linear effects, while nonlinear effects are unconsidered. Figure 13 shows the demo window.

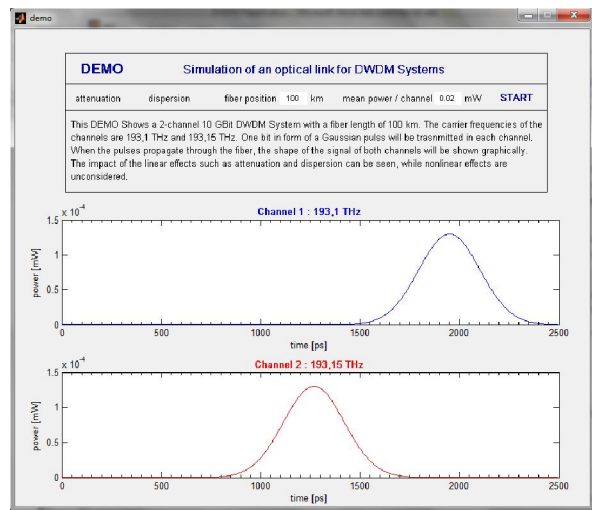


Figure 13. Demo Window

3.4.2 Possibilities of graphical illustration

3.4.2.1 The control monitor

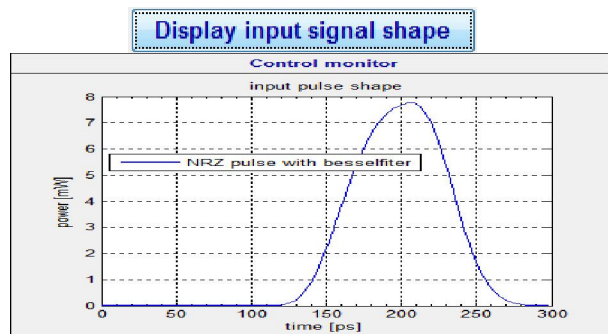


Figure 14. Graphical Illustration of the input pulse

In the middle of the user interface (Figure 10) we find the control monitor. This control monitor provides a depiction of the input pulse as shown in Figure 14. Also it can be used to show the Raman transfer function if the “display Raman transfer function” button is pressed as shown in Figure 15.

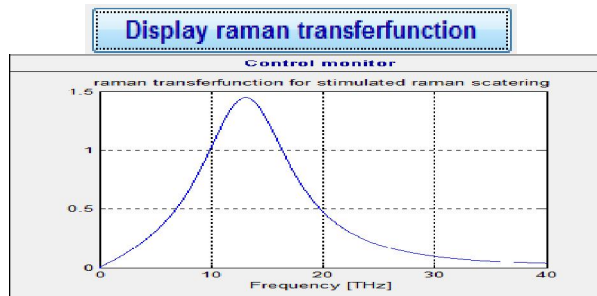


Figure 15. Graphical Illustration of the Raman Transfer Function

Furthermore, the actual status of the simulation program is shown in the control monitor as shown in Figure 16.

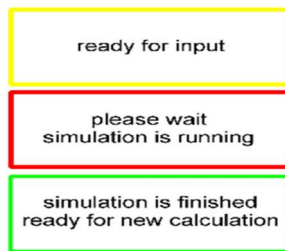


Figure 16. Simulation status in control monitor

3.4.2.2 The possibilities of the graphical illustration of the simulation result

If the option plot total signal/channel is selected, the entire output signal at the end of the fiber will be shown in the time domain. Power and phase will be shown in two separated graphs as shown in Figure 17. For every channel a separated window will be opened with the channel number and the carrier frequency shown in the headline.

By selecting the option plot total eye diagram/channel the eye diagram at the end of the fiber will be depicted graphically as shown in Figure 18. Here, as in plot total signal/channel, a separated window will be opened for every channel and channel number and carrier frequency will be given in the headline.

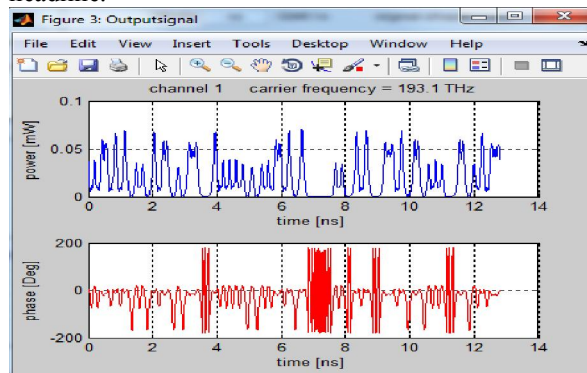


Figure 17. Graphical depiction of the power and phase of the output signal

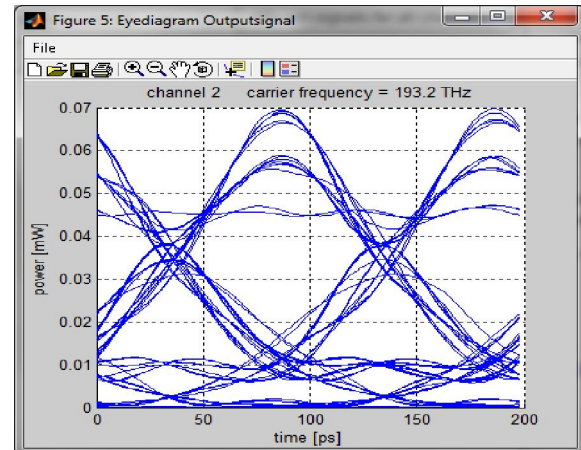


Figure 18. Graphical depiction of the eye diagram of the output signal

In digital communication the eye diagram is used to visualize how the waveform used to send multiple bits of data can potentially lead to errors in the interpretation those bits. This is the so-called problem of inter symbol interference. If the eye diagram becomes much more open that means the transmission of the data less prone to errors due to linear and nonlinear effects and if the lines become thicker and shaggy the system performance is degraded.

To be able to compare the output signals to the input signals, the option compare input-output signal can be selected. This option plots the power and phase of signal per channel and also plots eye diagram per channel for the input and output signals.

In addition to the plotting of the signals in time domain as shown in Figure 19, it is possible to plot the spectrum of frequency of the input and output signals by selecting the options plot input spectrum and plot output spectrum as shown in Figure 20 and Figure 21.

The output power and the Raman amplification for every DWDM channel can be plotted in form of a bar chart. The option plot output power diagram opens a window which shows the output power for every DWDM channel (Figure 22). If the option plot Raman amplification diagram is selected, the Raman amplification of the DWDM channels will be plotted (Figure 23).

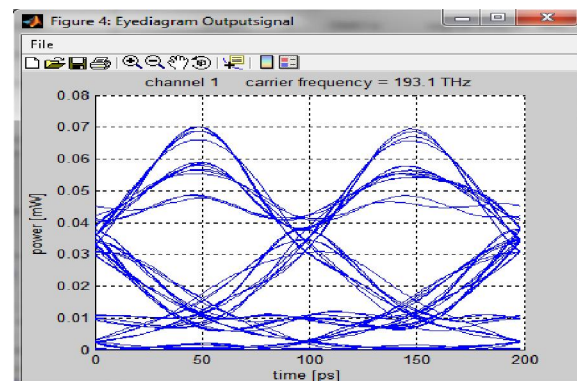
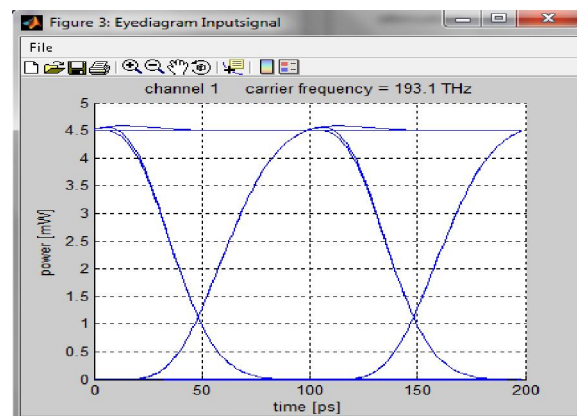
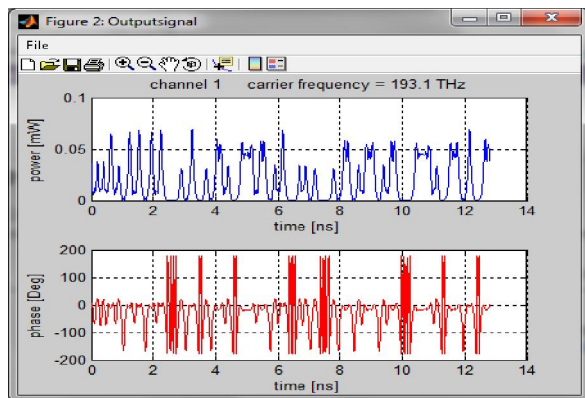
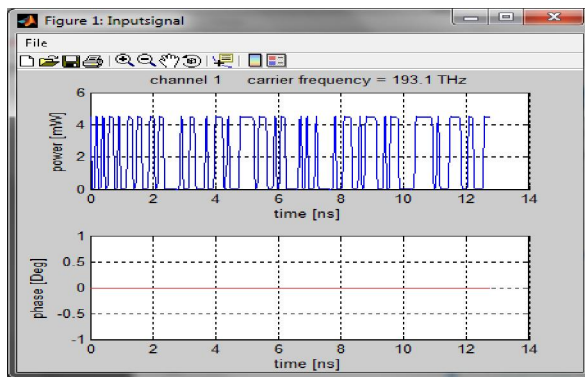


Figure 19. The graphical comparison between input and output signals

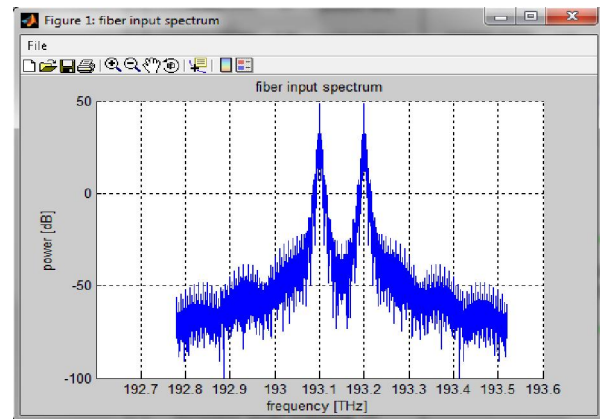


Figure 20. Graphical illustration of the input spectrum

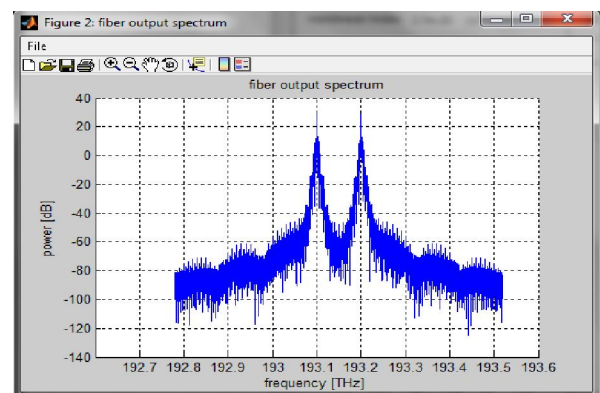


Figure 21. Graphical illustration of the output spectrum

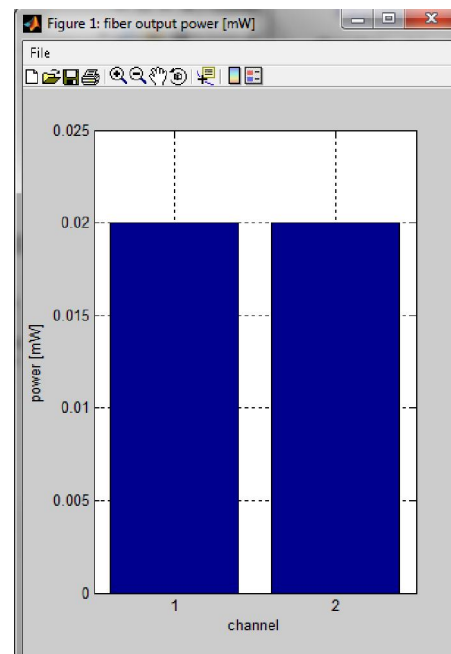


Figure 22. Graphical illustration of the output power

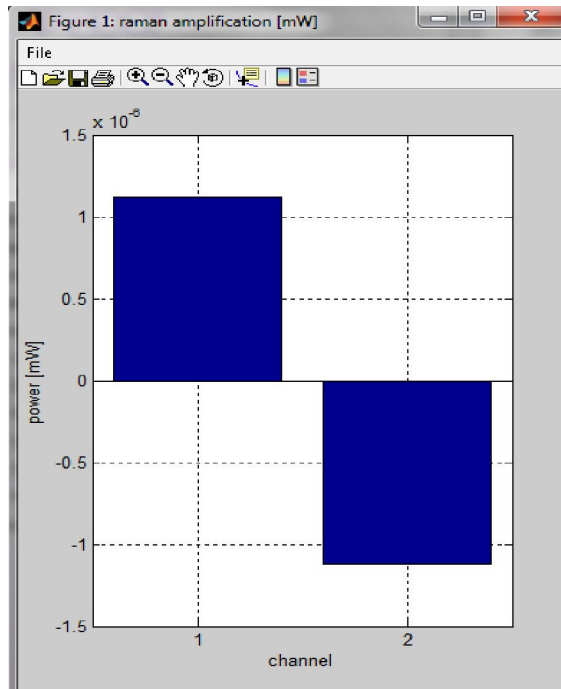


Figure 23. Graphical illustration of the Raman amplification

4. Simulation result

The developed software is used to find the impact of the signal & system characteristics on the limiting factors. The following relations has been studied and evaluated:

- The relation between the attenuation and the fiber length.
- The relation between the dispersion and the fiber length and bit rate.
- The relation between the self-phase modulation (SPM) and the input power level, bit rate and effective area.
- The relation between the cross phase modulation (XPM) and the channel spacing, number of channels input power level, bit rate and effective area.
- The relation between the stimulated Raman Scattering (SRS) and the number of channels, input power level and effective area.

4.1 Impact of the fiber length on the attenuation

The performance of a system with fiber length of 100 km is compared to a system with fiber length of 500 km, we found that there is big difference in signal level and we also found that the performance of the system is improved compared to the system without amplifier.

4.2 Impact of the fiber length on the dispersion.

The performance of a system with fiber length of 100 km is compared to a system with fiber length of 500 km, we found that there is big difference in

system performance between two cases; we found that the performance of the system is degraded when the fiber length is increased and this is shown by the eye diagrams. Then we simulated a system with fiber length of 500 km with dispersion compensation fiber (DCF), we found that the performance of the system is improved compared to the system without DCF.

4.3 Impact of the bit rate on the dispersion.

The performance of a system with bit rate of 2.5 Gbit/s is compared to a system with bit rate of 10 Gbit/s, we found that there is big difference in system performance and this illustrated by the eye diagrams, we found that the performance of the system is degraded when the bit rate is increased. Then we simulated a system with bit rate of 10 Gbit/s with dispersion compensation fiber (DCF), we found the performance of the system is improved compared to system without DCF.

4.4 Impact of the input power on self phase modulation

The performance of a system with input power level of 2 mW is compared to a system with input power level of 20 mW, we found that there is big difference in system performance and this illustrated by the eye diagrams and also we found that the performance of the system is degraded when the input power level is increased.

4.5 Impact of bit rate on self phase modulation

The performance of a system with bit rate of 10 Gbit/s is compared to a system with bit rate of 40 Gbit/s, we found that there is difference in system performance and we also found that the performance of the system is degraded when the bit rate is increased.

4.6 Impact of the effective area on self phase modulation

The performance of a system with effective area of $80 \times 10^{-12} \text{ m}^2$ is compared to a system with effective area of $10 \times 10^{-12} \text{ m}^2$, we found that there is difference in system performance and also we found that the performance of the system is degraded if we use fiber with smaller effective area.

4.7 Impact of the channel spacing on the cross phase modulation

The performance of a system with channel spacing of 20 GHz is compared to a system with channel spacing of 100 GHz, we found that there is big difference in system performance and we also found that the performance of the system is degraded when the channel spacing is decreased.

4.8 Impact of the number of channels on the cross phase modulation

The performance of a system has 4 channels is compared to a system has 16 channels; we found that there is difference in system performance and we also

found that the performance of the system is degraded when the number of channels is increased.

4.9 Impact of the input power on the cross phase modulation

The performance of a system with input power level of 2 mW is compared to a system with input power level of 20 mW, we found that there is big difference in system performance; we found that performance of the system is degraded when the input power level is increased.

4.10 Impact of the bit rate on the cross phase modulation

The performance of a system with bit rate of 10 Gbit/s is compared to a system with bit rate of 40 Gbit/s, we found that there is difference in system performance and we also found that the performance of the system is degraded when the bit rate is increased.

4.11 Impact of the effective area on the cross phase modulation

The performance of a system with effective area of $80 \times 10^{-12} \text{ m}^2$ is compared to a system with effective area of $10 \times 10^{-12} \text{ m}^2$, we found that there is difference in system performance and we also found that the performance of the system is degraded when we used fiber with smaller effective area.

4.12 Impact of the number of channels on the stimulated Raman scattering

The performance of a system has 4 channels is compared to a system has 32 channels, we found that there is difference in system performance and output power and we also found that the performance of the system is degraded when the number of channels is increased especially for the channel with highest frequency.

4.13 Impact of the input power on the stimulated Raman scattering

The performance of a system with input power level of 2 mW is compared to a system with input power level of 20 mW, we found that there is big difference in system performance and we also found that the performance of the system is degraded when the input power level is increased.

4.14 Impact of the effective area on the stimulated Raman scattering

The performance of a system with effective area of $80 \times 10^{-12} \text{ m}^2$ is compared to a system with effective area of $10 \times 10^{-12} \text{ m}^2$, we found that there is difference in system performance and this illustrated by the eye diagrams, we also found that the performance of the system is degraded when use fiber with smaller effective area.

Table 1 provides an overview of the limiting factors affected by DWDM systems parameters.

Table 1. Parameters affecting limiting factors

Parameter	Atten.	CD	SPM	XPM	SRS
Channel spacing				•	
Number of channels				•	•
Channel power			•	•	•
Channel bit rate		•	•	•	
Fiber length	•	•			
Fiber effective area			•	•	•

Here the most important parameters have been taken into consideration. Empty spaces in the table above do not necessarily mean the impairment is not effected by the parameter at all.

5. Result & Discussion

Comprehensive and successful MATLAB software has been developed, in order to assist the simulation of the different parts of the DWDM systems. The simulation ability of the developed software for the linear and nonlinear effects (attenuation, dispersion, self-phase modulation (SPM), cross phase modulation (XPM) and stimulated Raman Scattering (SRS)) have been successfully utilized. This developed simulation technique has the capacity of easing, simplifying and speeding up the design procedures.

The most attractive thing of the developed software is the graphical user interface (GUI) which has the ability of easing the selection of different characteristics of the proposed system. This developed software enable the user to select the fiber characteristics such as attenuation, dispersion, slope, nonlinear index, effective area and fiber length, and to select the signal characteristics such as bit rate, power, number of bits, samples per bit and signal shape and to select the DWDM system characteristics such as number of channels, channel spacing and carrier frequency.

The program included subprograms for signal generation, display input signal, calculation and output to give the designer the flexibility to modify any part of the simulation program independent of others. It is also used to find the impact of the characteristics of the DWDM systems on the linear and nonlinear effect in order to overcome them. From the simulation results we found that the attenuation depends on the length of the fiber. If the length of the fiber is increased the attenuation level will also be increased due to, for example, material absorption and impurities. Therefore we should use amplifiers on certain distances to minimize the attenuation effect for long distances.

From the simulation results we found that the dispersion depends on the fiber length and bit rate. If

the length of the fiber is increased the dispersion level will also be increased, and if the bit rate is increased the dispersion effect will also be increased. Therefore, dispersion compensation fiber DCF should be used on certain distances to overcome the dispersion effect at high bit rates and long distances.

From the simulation results we found that the SPM depends on the input power level, bit rate and effective area. If the input power level or bit rate are increased the SPM effect will also be increased, and if the effective area of the fiber is decreased the SPM will be increased. Therefore input power level, bit rate and the used bit rate and the effective area of the used fiber should be carefully designed to overcome the SPM effect.

From the simulation results we found that the XPM depends on the channel spacing, number of channels, input power level, bit rate and effective area. If the channel spacing is increased the XPM effect will be decreased, and if the number of channels or input power level or bit rate is increased the XPM effect will also be increased. Therefore the channel spacing, number of channels, input power level, bit rate and the effective area of the used fiber should be carefully designed to overcome the XPM effect.

From the simulation results we found that the SRS depends on the number of channels, input power level and effective area. If the number of channels or input power level is increased the SRS effect will also be increased and if the effective area of the fiber is decreased the SRS effect will be increased. Therefore the number of channels, input power level and effective area of the used fiber should be carefully designed to overcome the SRS effect.

From the simulation results we concluded that in order to improve the DWDM systems performance at high bit rate with big number of channels for long distances we should use amplifiers and dispersion compensation fibers on certain distances, and it's recommended to use lowest possible input power, using wide enough channel spacing and using optical

fiber cables with large enough effective area to minimize the impact of the limiting factor on the transmission quality.

6. Conclusion

Useful MATLAB software has been developed, in order to assist the simulation of the different parts of the DWDM systems. The simulation ability of the developed software for the linear and nonlinear effects (attenuation, dispersion, self-phase modulation (SPM), cross phase modulation (XPM) and stimulated Raman Scattering (SRS)) have been successfully utilized. This developed simulation technique has the capacity of easing, simplifying and speeding up the design procedures. The most attractive thing of the developed software is the graphical user interface (GUI) which has the ability of easing the selection of different characteristics of the proposed system.

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