PERFORMANCE EVALUATION OF SOLITON-BASED AND NON-SOLITON ALL-OPTICAL WDM SYSTEMS

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ABSTRACT
This paper presents a performance evaluation of soliton and non-soliton-based all-optical wavelength division multiplexed (WDM) networks assuming the existing infrastructure (e.g., fiber and other physical layer components). The performance evaluation is carried out using the quality (Q) factor, which is a measure of the signal-to-noise ratio, and indirectly, the bit error rate (BER) of the system. We first examine the performance of soliton and non-soliton transmission on multi-wavelength links consisting of multiple spans with EDFAs to compensate for fiber loss, and the results show that the soliton-based systems perform much better than the non-soliton systems for typical system parameters with the existing infrastructure for bit rates of up to 10Gbps per channel. We then present a sample WDM-based optical network with mesh topology, consider alternative routing and wavelength assignments, and show that the end-to-end Q factor of a soliton system is higher than that of a non-soliton system.

KEY WORDS
Optical networks, WDM, solitons, routing and wavelength assignment

1. Introduction

With the growing popularity of the all-optical networks for realizing high speed, low error communications, several techniques and standards have been proposed, aimed at improving the capacity of the all-optical networks. The wavelength division multiplexing (WDM) technique provides a solution to the ever-increasing demand for bandwidth and is fast replacing existing systems in providing high bit rates and very low bit error rates (BER's) of about 10^{-9}.

There are several routing and wavelength assignment (RWA) issues involved in such networks. In order to analyze and evaluate various RWA algorithms, it is desired to have a compact mathematical model for evaluating the Quality factor (Q factor) which reflects the performance of the WDM network. The performance of the all-optical WDM systems is limited by several physical layer impairments due to the quantum nature of light. These physical layer impairments include both linear and nonlinear effects and play a fundamental role in limiting the total capacity of the system.

In conventional fiber systems, the non-return to zero (NRZ) transmission format is widely used[1] and is preferred over the return-to-zero (RZ) format because of its more efficient use of the electronic bandwidth and timing jitter tolerance. The performance of both NRZ and RZ formats is limited by the nonlinear impairments that become prominent in multi-channel systems. However, nonlinear effects are not always detrimental to the performance of an optical system. For certain special pulse profiles, some nonlinear effects actually counteract the effects of the linear impairments and balance the signal distortion caused by them to maintain the shape of the pulse propagating in the fiber. Thus, the issue of pulse shape is central to the design of any all-optical communication system. These special pulses, known as solitons, have the ability to propagate without distortion to infinite distances or retain their shape periodically in ideal loss-less fibers. Studies show that the performance of a system improves significantly when solitons are used for fiber links with bit rates up to 20Gbps [2].

Most papers on solitons report the performance of systems using solitons for long-distance point-to-point links and the use of solitons for dynamically configured WDM networks has not been sufficiently addressed. Hence, we examine the feasibility of improving the system performance of a mesh topology WDM all-optical network using solitons while focusing on the performance evaluation of point-to-point links as well.

The research goal is to develop a mathematical model for evaluating the performance of the WDM all-optical networks by calculating the end-to-end Q factors for both soliton based and non-soliton pulse shapes. In section 2 we briefly introduce the theoretical models for calculating Q factors for systems using non-soliton pulses and present methods of calculating the Q-factor for soliton-based systems. Section 3 presents key results for Q-factor calculations for point-to-point links, where we use simulations to evaluate the effects of EDFA noise and spacing, channel separation and bit rate for soliton and non-soltion systems. Q-factor calculations for a simple WDM mesh network are discussed in section 4, where the effects of different route and wavelength selection are explored to illustrate network effects. Section 5 presents conclusions.

2. Soliton and non-Soliton Systems

The performance of a fiber optic system is evaluated in terms of a conveniently defined Q factor that reflects the BER of the system.] The Q factor is defined in general terms as

$$Q = \frac{I_1 - I_o}{d_1 - d_o} \tag{1}$$

where I_1 and I_2 are the mean currents for bit 1 and bit 0 respectively, and $\delta_1$and δ_o are the standard deviations for the bits 1 and 0 respectively. Since we denote a '0' bit with no signal in the bit slot, we can safely assume that

$$I_o = 0 \; and \; d_o = 0 \tag{2}$$

And if we assume that the responsivity of the detector R = $1AW^{-1}$, then

$$I_1 = RP = P \tag{3}$$

Hence the quality factor reduces to

$$Q = P / \delta_1 \tag{4}$$

It is customary to express Q in dB.

$$Q_{dB} = 10 \log_{10}\left(\frac{P}{d_1}\right) \tag{5}$$

The Q factor definition varies depending on the type of system under consideration. For soliton-based system, we calculate the standard deviation of the position fluctuations of the pulse in the bit slot whereas for a non-soliton system, we calculate the standard deviation of the amplitude fluctuations of the pulse envelope. The Q factor can be calculated by solving the non-linear Schrodinger equation (NLSE) [3]

The relationship between the Q factor and the BER varies with the modulation format and the detection scheme used at the receiver. For a Gaussian decision variable at the receiver, the Q factor is related to the BER as [4]

$$Q = \sqrt{2}\; erfc^{-1}(2BER) \tag{6}$$

A soliton is a specific pulse profile, which, when launched into a nonlinear optical fiber, maintains its shape as it travels down the fiber under ideal conditions. The existence of solitons in fiber systems and their advantages were first demonstrated in 1980[5] and by the late 1990's, they have become a potential candidate for modern long-haul optical systems. We have examined various kinds of solitons, propagation of these solitons through different nonlinear fibers and the effects of different fiber parameters, and have conducted performance evaluations of a soliton-based fiber link. We have also looked at the effects of amplified spontaneous emission (ASE) noise due to EDFAs on the performance of a soliton system. [3]. The discussion below is limited to the calculation of the impact of these effects on the Q factor.

Inter channel collisions and ASE noise introduced by EDFAs induce a timing jitter in the solitons propagating in a WDM system. This timing jitter causes the soliton to fluctuate in its bit slot and may eventually push it to an adjacent bit slot which causes a decoding error in at the receiver. This timing jitter is the dominating factor that determines the BER of a soliton-based system and the Q factor of a soliton system is determined by the variance of the soliton position in the bit slot. The Q factor for a soliton system is given by

$$Q = 10 \log_{10}\left(\frac{T_b}{\sigma_{ASE}} + \sigma_{XPM}\right) \tag{7}$$

where σ_{ASE} and σ_{XPM} are the standard deviations corresponding to the pulse fluctuations due to the ASE noise from the EDFAs and position fluctuations caused by the XPM (cross phase modulation) effect. In addition to the timing jitter, the ASE noise also causes energy fluctuations that slightly distort the shape of the solitons. However, the error caused by these amplitude fluctuations at the receiver is negligible as compared to that caused by the timing jitter. A soliton has the property of regaining its shape after an XPM-induced collision if the conditions are favorable, and hence is not affected by the amplitude fluctuations as much as by the timing jitter.

3. Results for Point-to-Point Links

One of the main objectives of our study is to evaluate the best performance of a soliton-based system using the fiber infrastructure that is already in place for non-soliton transmission and where the basic system components cannot be changed. We assume typical values for the fiber-related parameters and for amplifier spacing, while we vary values for pulse-related parameters to find the combination of parameter values yielding the best performance. We compare the Q factors calculated by assuming soliton and non-soliton pulses. In these simulations both SPM (self-phase modulation) and XPM effects are considered along with the linear GVD (group velocity dispersion) effect and attenuation in the fiber.

Simulations were run using PHOTOSS^{TM} software for various values of GVD, F_{ch}, NF, L_A and bit rates for both soliton and non-soliton pulses. In all the simulations, unless specified otherwise, the following values are assumed which are typical of existing fiber networks: α = 0.19dB/km, F_{ch} = 75GHz, L_A = 50kms, q_o = 5, γ = $2W^{-1}km^{-1}$. The non-soliton pulses used had Gaussian profiles.

3.1 Variation with the noise figure (NF) of the EDFAs on point-to-point links

The EDFA NF was varied from 2dB to 10dB with the GVD parameter β_2 assumed to be $-0.4ps^2/km$ and the bit rate fixed at 5Gbps. The Q factors for both soliton and non-soliton based links are plotted in figure 1.

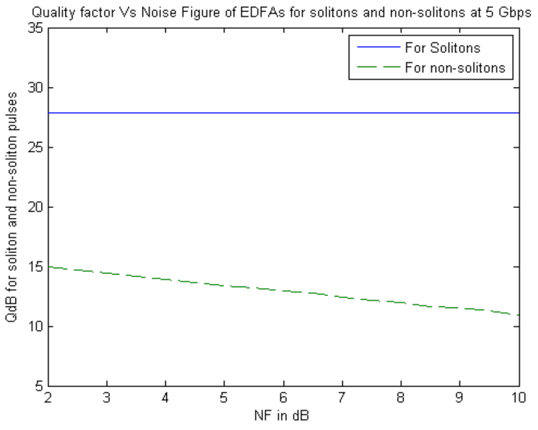

Figure 1: Q factor Vs NF of EDFAs for solitons and non-solitons at 5Gbps and $\beta_2 = -0.4\ ps^2/km$

Figure 1 shows that there is a significant difference of around 12dB between the Q factors for a NF of 5dB which is typical of EDFAs in current use. Here we have assumed only one other wavelength channel that interacts with the test channel. In WDM systems there are many such channels that propagate together and interact with each other which will decrease the overall Q factor. The above result also shows that there is not much dependence of the soliton Q factor with NF, whereas the non-soliton Q factor decreases rapidly with increase in NF.

3.2 Dependence of Q factor on the number of spans

Results of simulations for point-to-point links consisting of multiple spans are shown in figure 2, where the Q factor is plotted against the number of spans for both soliton and non-soliton pulses. In these simulations the GVD was characterized with $\beta_2 = -0.8 ps^2/km$. From figure 2 it is clear that at an increased GVD solitons perform much better than non-solitons for any number of spans. Also, the Q factors of both solitons and non-solitons tend to decrease by the same extent with the number of spans.

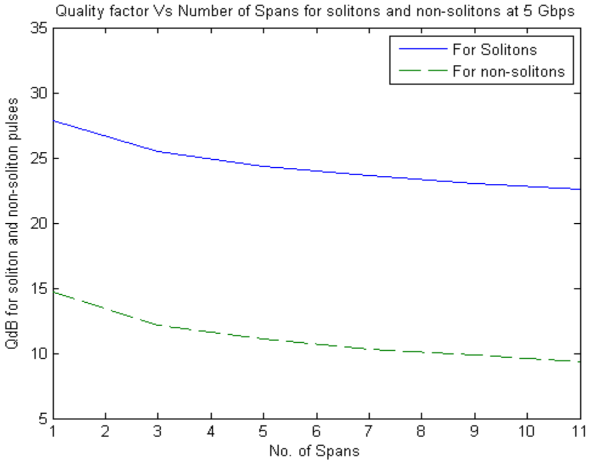

Figure 2: Q factor versus number of spans for solitons and non-solitons at 5Gbps and $\beta_2 = -0.8\ ps^2/km$

3.3 Variation of the Q factor with amplifier spacing, L_A and bit rate

Simulation results given in figure 3 show that as the amplifier spacing increases, the Q factor for both soliton and non-soliton-based pulses drops rapidly.

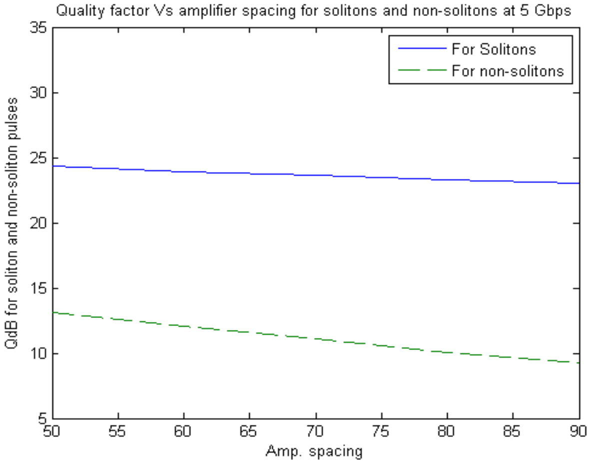

Figure 3: Q factor versus amplifier spacing for solitons and non-solitons at 5Gbps

When the amplifier spacing becomes large, loss-management is no longer effective and the solitons lose their shape, resulting in errors at the receiver. Even if the timing jitter is small, the effect of EDFAs placed far apart will distort the solitons and become the dominant source of error in the system. Hence, the Q factor calculated from the timing jitter alone will no longer reflect the true BER An increase in the system bit rate results in a decrease in the Q-factor for soliton-based transmission, as the timing jitter becomes relatively more pronounced. The results for 10 Gbps are shown figure 4

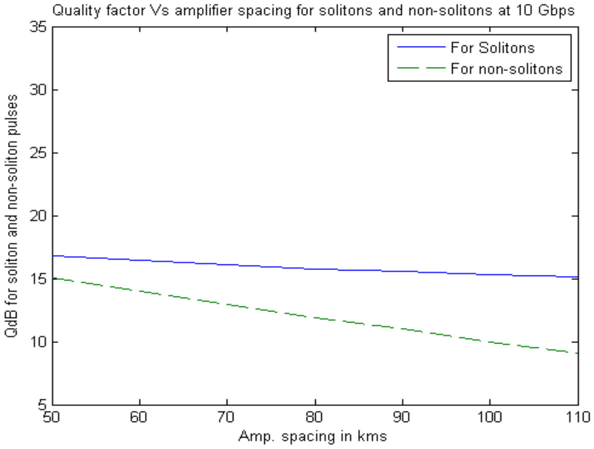

Figure 4: Result Q factor versus amplifier spacing or solitons and non-solitons at 10Gbps

The difference between the Q factors of soliton and non-soliton transmission decreases considerably with increased bit rate. This is because an increase in the bit rate decreases the bit-period and hence the soliton pulse can easily move into the adjacent bit slot for a given amount of jitter. Hence the timing jitter plays an important role at higher bit rates and the solitons perform worse than non-solitons, even when other conditions for soliton propagation are maintained

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3.4 Q factor versus channel spacing

The channel spacing plays an important role in the Q factor calculations for soliton transmission in WDM systems even at low power levels since it strongly affects the timing jitter independent of the power of the pulse. Simulations were run for different values of the channel spacing in a two-channel system for different spans and the results are plotted in figure 5.

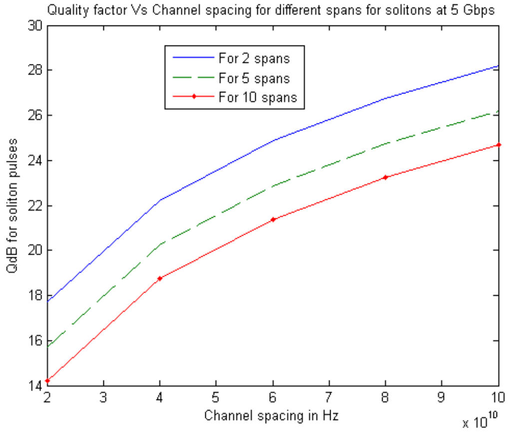

Figure 5: Q factor versus F_{ch} for solitons for different numbers of spans

The Q factor increases rapidly with an increase in the channel spacing. The channel spacing that is usually considered for a WDM network is 75GHz but can be as low as 50GHz. The drop in the Q factor for 75GHz channel spacing, associated with an increase from 2 spans to 10 spans is 4dB. Hence the signal can travel 1000-1500 km (corresponding to about 20-30 spans) without a significant drop in the Q factor.

4. Q Factor for a WDM network

A WDM network typically consists of multiple links interconnected to form a star, ring or mesh. In a mesh network, there may be several alternative source-destination paths and routing algorithms have been developed which take into account several factors such as the shortest possible distance, blocking probability etc, to select the best possible route[6][7]. As there are multiple wavelengths, there is an additional problem of wavelength assignment along with route selection, and routing and wavelength assignment algorithms (RWAs) have been devised to optimize selection [8]. In all-optical WDM networks, a single wavelength is used from the source to destination, unless wavelength converters are incorporated. Typically, network layer RWA algorithms do not take into account physical layer impairments [8]. However, in all-optical networks, linear and nonlinear impairments play a critical role in the route selection and the best route selected by a network layer RWA algorithm may not meet signal quality requirements. For example, if random wavelength assignment is used [7], wavelengths are randomly selected from the available set. If the XPM effect along the path is large for the selected set of wavelengths, then the signal quality is adversely affected leading to unacceptable BER. Hence an ideal RWA algorithm should take the quality factor of the light path into account when assigning wavelengths and paths. A mathematical model can be used to calculate the end-to-end Q factors between any two nodes in network.

Considerable research has been reported regarding the use of solitons and other pulse shapes in long-haul point-to-point systems [9][10][11]. Here, we analyze the performance of soliton pulses in mesh WDM optical utilizing the existing fiber infrastructure. In future all-optical networks, routing and wavelength assignments will be carried out dynamically to choose the best route for a connection request [6]. We explore the feasibility of using soliton pulses rather than conventional pulse shapes, to minimize physical layer impairments and achieve optimal end-to-end performance by comparing the Q factor for the same source-destination pair with a different routes and wavelengths.

To study the performance of soliton systems through Q factor calculations, we considered a mesh WDM network, shown in figure 6, with multiple wavelengths (channels) per link, and with multiple EDFAs per link. The amplifier spacing, L_A is indicated for each link. The red line indicates a possible route for the source-destination pair AE.

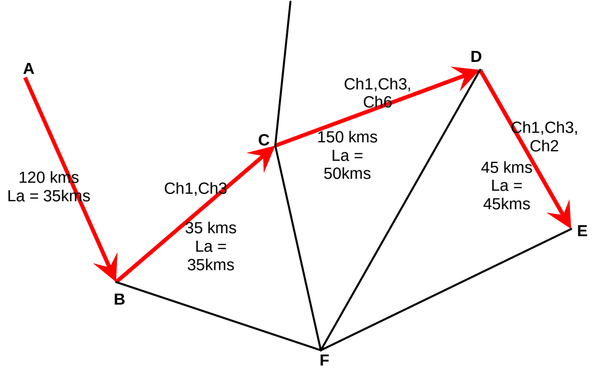

Figure 6. : Optical signal routed through path 1 in the sample WDM network assumed to be a part of a large backbone network.

This is an illustration of the effects of physical layer impairment and is part of a larger study of physical layer aware routing, and results of more extensive simulations will be reported elsewhere. In this example we considered three possible paths for a signal from A to reach E: ABCDE, ABCFE and ABFDE. The center frequency of the signal under consideration is 193.1THz, denoted as channel 3. In the first link between A and B, only channel

3 travels for all the three paths. In path 1, the signal is routed through ABCDE where it travels through some distance with channels 1, 6 and 2. Similarly in path 2, the signal is routed through ABFDE where the signal travels with channels 2, 7, 5 and 1. Finally, in path 3 the signal is transmitted through nodes ABCFE, where it counters channels 1, 4, 5 and 7.

The Q factors were calculated for the three paths and plotted against the noise figure (NF) of the EDFAs present on the spans. We assume that all the amplifiers have the same NF and that amplifier gain compensates for the fiber loss in each span. We also assume typical network characteristics such as a constant dispersion profile for the fiber throughout the network with a second order GVD of -0.5ps^2/km, an attenuation constant of 0.19dB/km, a nonlinear coefficient of 2W^{-1}km^{-1}, pulse width parameter T_o of 20ps and a bit rate of 5Gbps. The power of the pulse has to be maintained at 0.625mW for the fundamental soliton to sustain in the fiber. The frequencies of the channels from 1 through 7 are 193THz, 193.05THz, 193.1THz, 193.15THz, 193.2THz, 193.25THz and 193.3THz with a channel spacing of 50GHz.

Simulations were run for both soliton and non-soliton pulses and the NF of the EDFAs was varied over a range including typical values of 4-5dB. Figure 7 shows the resulting Q factor versus NF for path1 for the soliton and non-soliton cases. Results for the other paths are similar.

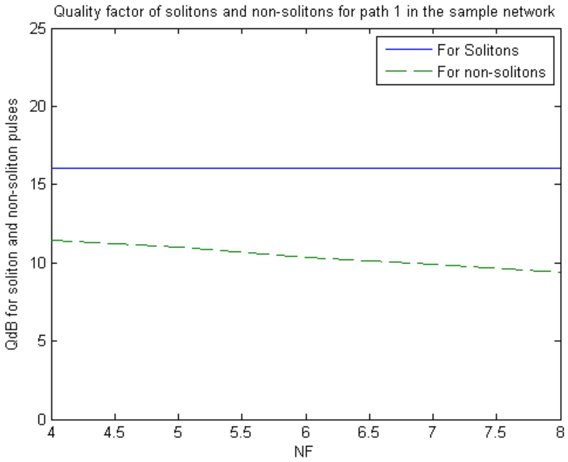

Figure 7: Variation of Q with EDFA NF for path 1, for solitons and non-soliton pulses

For each of the paths, the soliton-based pulses show greater end-to-end Q-factor than the non-soliton pulses. Also, the Q factor of the non-soliton pulses is adversely affected by the increase in NF whereas the Q factor pf the soliton pulses is unaffected.

Figure 8 compares the Q factors for soliton pulses for the three paths and shows that path 3 gives best performance, while path 2 giving the worst performance. The difference in Q factor between path 2 and the other paths is significant, while path 2 is the shortest of the three paths (335km). Hence it is apparent that for soliton-based WDM systems, the effects of co-propagating channels and amplifier spacing are major considerations, rather than path length, in the best route.

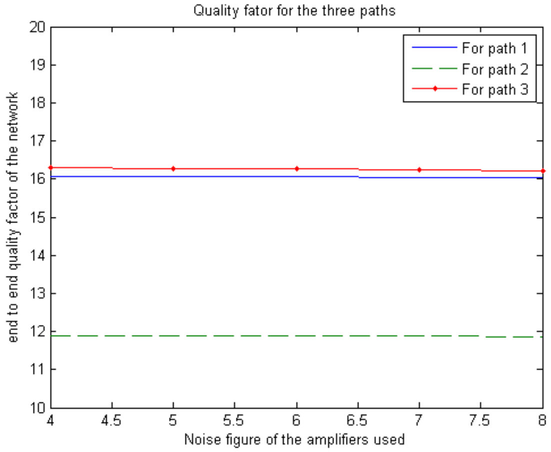

Figure 8: Result showing a comparison of Q factors of the three paths in the network for soliton pulses

The effect of co-propagating channels can be more clearly demonstrated by considering the case where one more channel is added to one of the paths, in this case path 3. Suppose, at the node F, channel 2 instead of going to D, is routed to E. Results, given in figure 9, show a considerable decrease in the Q factor for path 3. This is due to the additional effect of the adjacent channel (channel 2) which interacts strongly with channel 3. Hence an ideal routing algorithm must be globally aware of the surrounding links to make the best possible wavelength assignment and path decision.

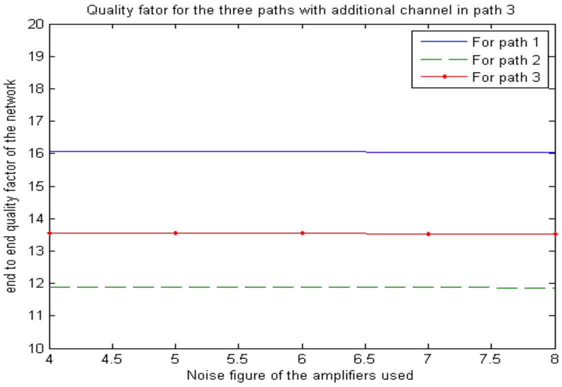

Figure 9: Comparison of Q factors of the three paths for soliton pulses and an additional wavelength on path 3.

5. Conclusion

Our results show that the Q factor for point-to-point soliton systems decreases rapidly and comes very close to the Q factor values of non-soliton systems with increased bit rate. The difference in the Q factors between soliton and non-soliton systems reduces from over 13dB at 5Gbps to about 4dB at 10Gbps for an amplifier spacing of 70km. A further increase in bit rate results in a cross over at about 17Gbps, where the Q factor of non-soliton systems exceeds that of soliton systems, for the parameters assumed in this study. There is considerable research aimed at understanding where this cross-over of the Q factor curves occurs. Some papers have reported a cross-over at bit rates as high as 40Gbps [12]. The reason for the cross-over is that the Q factor of a soliton depends primarily on timing jitter. As the bit rate of the channel increases, the soliton pulse can easily shift into its adjacent bit-slots and the Q factor decreases rapidly. This imposes a limit on the overall capacity of a WDM system since the channel spacing cannot go too small as inter channel collisions will result. Further research is needed to examine the relationship between bit rate and channel spacing in soliton-based transmission and to establish the trade offs for WDM networks. These factors need to be included in RWA algorithms to assure optimal route and wavelength selection in soliton-based systems.

Acknowledgements

This work was supported by the NSF under grant CNS 0830958: NeTS-NBD: Physically Aware Agile Networking

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