Journal of Advanced Research in Applied Sciences and Engineering Technology 43, Issue 1 (2025) 251-262

SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied
Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Optical Add-Drop Multiplexers: Enhancing High Transmission Bit Rates in Next-Generation Communication Networks

Dunya Zeki Mohammed[1,*]

[1] College of Engineering, Gilgamesh Ahliya University, Baghdad, Iraq

ARTICLE INFO

Article history:
Received 1 December 2023
Received in revised form 18 January 2024
Accepted 20 February 2024
Available online 8 April 2024

Keywords:

Optical add-drop multiplexers (OADM); Dense wavelength division multiplexing (DWDM); Artificial neural networks (ANNs); High-speed optical networks

ABSTRACT

The development of optical networks in the telecommunications sector is becoming much closer by considering the help of an Optical Add Drop Multiplexer (OADM) based on a novel technology called Wavelength Division Multiplexing (DWDM). The objective of the current study to examine high transmission bit rates for next-generation optical communication networks using the technology of OADM Based on DWDM. Artificial neural networks (ANNs) were developed via MATLAB software to predict three main parameters in this filed such as transmitted signal power (P_T), transmitted signal bandwidth ($B.W_{sig}$), and transmission bit rate capacity (B_{sh}) at different fiber cable lengths, such as L=200, 250, and 300 km. The ANNs results showed that, standard error (SE) for predicting P_T as a function of the number of transmitted channels (N_{ch}) was 0.115 mW, 0.095 mW and 0.077 mW, for 200, 250 and 300 km, respectively. Additionally, the SE for predicting $B.W_{sig}$ was 0.067 GHz, 0.051 GHz and 0.040 GHz for 200, 250 and 300 km, respectively. Lastly, the SE for predicting B_{sh} was 1.665, 1.311 Gbit/sec and 1.076Gbit/sec for 200, 250 and 300 km, respectively. The SE for predicting P_T as a function of the Signal Wavelength (λ) was 0.116, 0.096 and 0.079 mW for 200, 250 and 300 km, respectively. Additionally, the SE for predicting $B.W_{sig}$ was 0.067, 0.052 and 0.052 GHz for 200, 250 and 300 km, respectively. Lastly, the SE for predicting B_{sh} was 1.688, 1.417 and 1.110 Gbit/sec for 200, 250 and 300 km, respectively. The low SE in ANNs demonstrated the efficiency, motivating further advancements in optimizing network performance for high-bit-rate transmission.

1. Introduction

The basics of the communications network is founded based on using fibre optic cables, which are considered the primary component of carriers' interoffice networks [1-5]. In this regard, the technology of Time-division multiplexing (TDM) is broadly implemented by carriers to transfer the big data at a rate of 2.4 Gbit/s on a single cable, while some use equipment to expand the transfer rate up to 10 Gbit/sec. Still, the prompt advance of Cyberspace and the revolution in high bandwidth purposes have resulted in capacity requirements beyond classic TDM limitations. Additionally, the relatively inadequate bandwidth that existed when optical fibre was first established in the 1980s is

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[*] *Corresponding author.*
E-mail address: dunyazaki@gau.edu.iq

https://doi.org/10.37934/araset.43.1.251262

slowly decreasing. In this context, a novel technique called Dense Wavelength Division Multiplexing (DWDM) is installed in order to increase the capacity of a single fibre to achieve the expanded bandwidth requirements. DWDM techniques will possibly increase a single fibre's capacity by 16 times, specifically to 40 Gbit/s. This high-tech allows data carriers to develop transmission optical networks that will achieve the requirement for transmitted capacity in upcoming devices at a significantly lower cost than deploying new fibre when paired with OADMs [6-9].

In Wavelength Division Multiplexing (WDM)-based optical access networks, adding and removing a specific WDM channel at each subscriber's node requires a wavelength-selective optical add/drop filter [10-12]. The technology of DWDM has been used in these WDM-based optical networks for the purpose of optimizing the available transmission bandwidth. In it worth to mention that, in DWDM-based optical networks, add/drop filters supposed to be achieved under three conditions such as:

i. temperature stability
ii. a small spectral bandwidth
iii. strong reflection merits [13,14].

These critical points inspired the companies and researchers proposing novel technologies for the add/drop filter. Some commercial optical add/drop filters were proposed after a careful of research such as Fiber Bragg gratings, thin-film interference filters, circulators, and Mach-Zehnder interferometers. Despite the high-tech advances of Add/drop filters and related devices; however, they are not applicable for DWDM-based optical access networks because of their high budget [15,16].

Ultimately, point-to-point links in optical data transport will be replaced by transparent meshed optical networks in the long run. Besides, the capacity per fibre required a significant increase in the transfer rate to meet the growing demand for bandwidth. It is in doubt how more wavelengths per fibre can improve the capacity rate, faster bit rates per wavelength, or a combination of the two approaches. Optical time division multiplexing (OTDM) must be utilized for transferring data in the range of 80, 160 Gbit/s or more per wavelength because electronic processing at such high frequencies is not feasible. But, in the upcoming years, it is significant to protect the developments in transparent networks to be used for WDM whereas applying OTDM with WDM technology [17-19].

As per the above literature review, it is essential to focus on applying OADM approach based on DWDM as a novel high-tech for the future direction of the research. In this study, Artificial Neural Networks (ANNs) were developed using previous experimental dataset in order to forecast three critical parameters in this field called: transmitted signal power (P_T), transmitted signal bandwidth ($B.W_{sig}$), and transmission bit rate capacity (B_{sh}) versus the number of Transmitted Channels and signal wavelength. The three targets were predicted under three fibre cable lengths such as (L=200, 250, and 300 km) for better understanding. The integration of ANNs into OADM-based DWDM shows a new perspective on optimizing and predicting fundamental boundaries within next-generation optical communication networks.

2. Methodology

The experimental datasets for the current objective were collected from a previous study published in 2012 [20]. To predict three separate output variables, such as transmitted signal power (PT), transmitted signal bandwidth ($B.W_{sig}$), and transmission bit rate capacity (B_{sh}), at three different experimental conditions, such as L=200, 250, and 300 km (representing the fiber cable length), artificial neural networks (ANNs) were developed using the experimental dataset. OADM-based-DWDM is considered as fundamental component in optical networks that use wavelength division multiplexing. As per Figure 1, this technique adds flexibility and increases efficiency to the network by allowing the selective addition and dropping of specific wavelengths at intermediate points along the optical path. In the meantime, the concepts of application and implementation of ANNs are outlined in the next section.

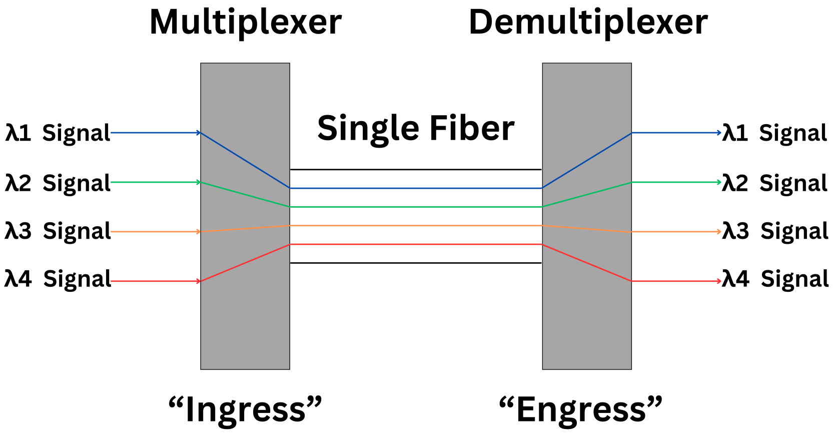


Fig. 1. Technology of OADM based on DWDM

Human neurons inspired McCulloch and Pitts [21] to develop the first artificial neural network (ANN) concept in 1943 [22-24]. As per Eq. (1), the ANN algorithms can solve the non-linear relationship between sets of input-output variables. In the meantime, to predict non-linear objectives such as P_T, $B.W_{sig}$, and B_{sh}, the multi-layer perceptron (MLP) is a modern feedforward artificial neural network (ANN) comprised of fully connected neurons with a non-linear activation function.

$$y = f(\sum_{i=1}^{n} x_i W_i + b) \tag{1}$$

As per Figure 2, an MLP architecture involves three layers (input, hidden, and output), each of which has several computing units (neurons). It performs to find the optimal values of weights (W) and biases (b) to obtain the best correlation between the input parameters and output parameters (P_T, $B.W_{sig}$, and B_{sh}).

As above, y represents the output variable, such as (P_T), $B.W_{sig}$, and B_{sh}, f is the activation function, W_i is the weight, x_i is the input variables such as N_{ch}, λ, and L, b is the bias term, and n is the number of neurons.

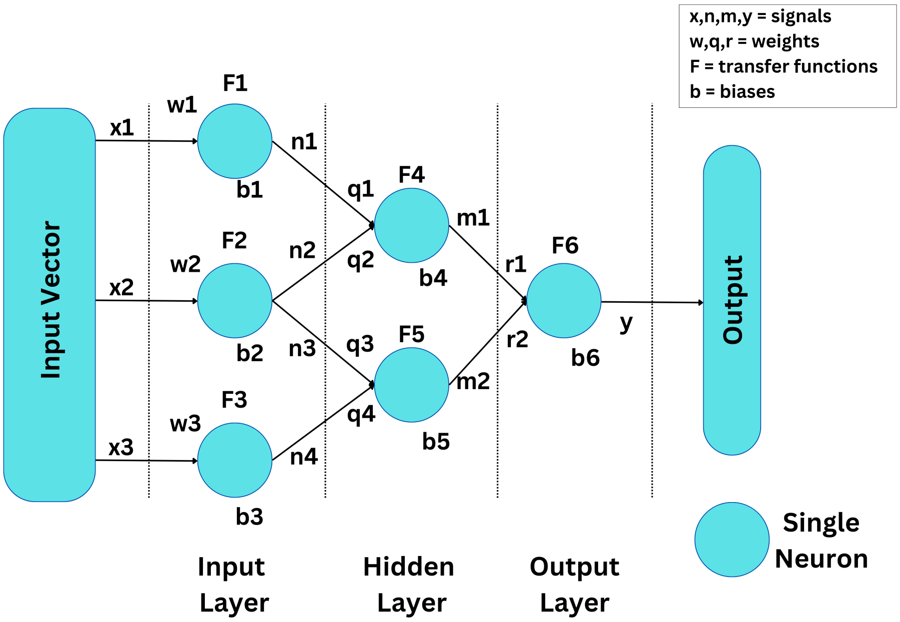
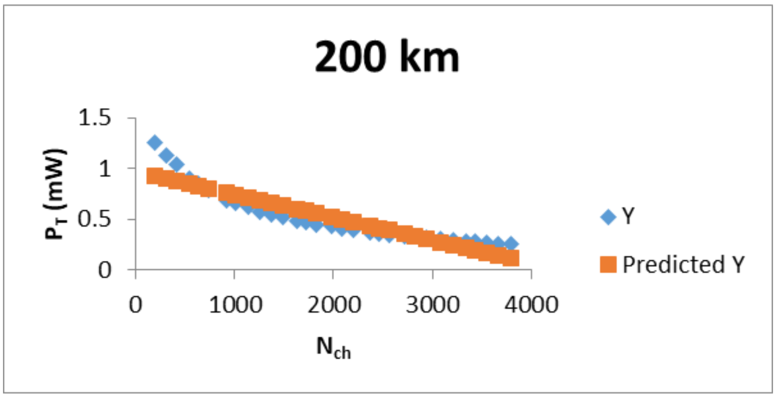


Fig. 2. Illustration of artificial neural networks (ANNs)

3. Results and Discussion

The experimental and ANNs results transmitted signal power (P_T) variations are shown in Figure 3 for three different testing conditions of fibre cable lengths (200, 250, and 300 km). Figure 3 shows that the P_T values decrease at different fibre cable lengths (L) as the number of transmitted channels (N_{ch}) increases. Moreover, the P_T values decrease at a constant N_{ch} as L increase. Meanwhile, the ANN algorithm revealed the following performance metrics such as (Multiple R= 0.910, R^2= 0.828, Adjusted R^2= 0.822, and Standard Error (SE)= 0.115mW) for the testing condition of L=200 km, (Multiple R= 0.921, R^2= 0.847, Adjusted R^2= 0.841 and SE= 0.095 mW) for the testing condition of L=250 km and (Multiple R= 0.921, R^2= 0.848, Adjusted R^2= 0.843 and SE= 0.077 mW) for the testing condition of L=300 km, respectively.



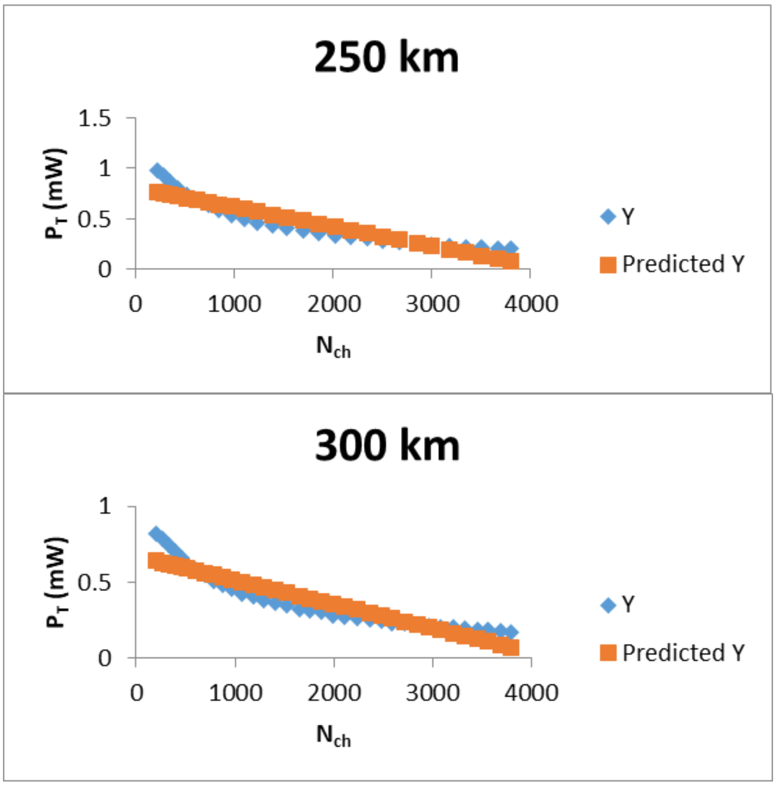
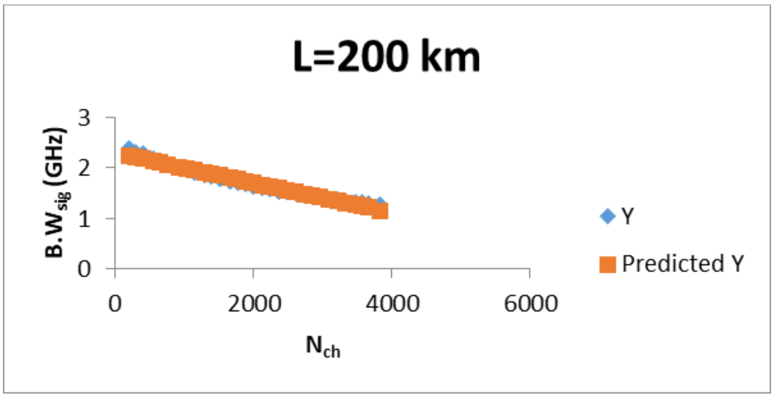


Fig. 3. Experimental and ANN of P_T versus N_{ch}

Figure 4 illustrates the differences in transmitted signal bandwidth ($B.W_{sig}$) using experimental and ANN values against the N_{ch} for three different testing conditions of fiber cable lengths, including 200, 250, and 300 km. As per Fig. 4, the $B.W_{sig}$ values decrease by changing the testing condition of L as the N_{ch} increases. Moreover, the $B.W_{sig}$ values decrease at a constant N_{ch} as L increase. Meanwhile, ANN algorithm revealed the following performance metrics such as (Multiple R= 0.980, R^2= 0.961, Adjusted R^2= 0.960 and SE= 0.067 GHz) for the testing condition of L=200 km, (Multiple R= 0.982, R^2= 0.965, Adjusted R^2= 0.963 and SE= 0.051 GHz) for the testing condition of L=250 km and (Multiple R= 0.983, R^2= 0.967, Adjusted R^2= 0.965 and SE= 0.040 GHz) for the testing condition of L=300 km, respectively.



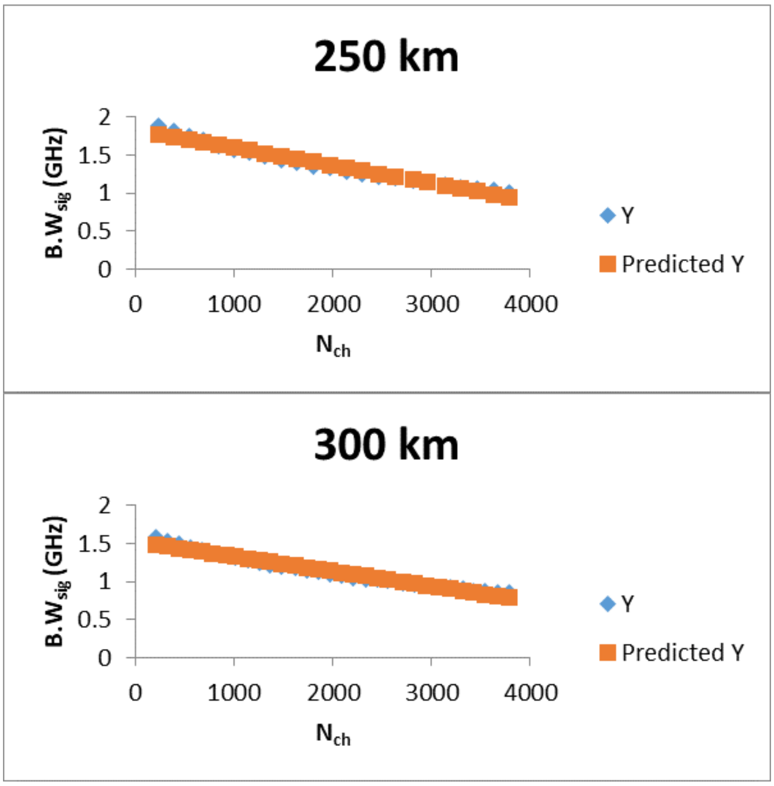
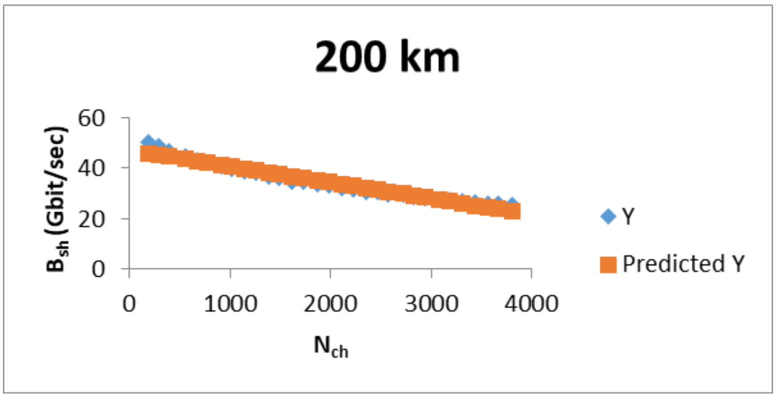


Fig. 4. Experimental and ANN of B.W$_{sig}$ versus N$_{ch}$

Figure 5 depicts experimental and ANN model variations of Transmitted Bit Rate Capacity (B$_{sh}$) versus N$_{ch}$ for three different testing conditions of fibre cable lengths such as: 200, 250, and 300 km. The figure below shows that, the B$_{sh}$ values decrease at different L as more N$_{ch}$ is used. As L increases, B$_{sh}$ at a constant N$_{ch}$ decreases. Meanwhile, ANN algorithm revealed the following performance metrics such as (Multiple R= 0.974, R^2= 0.948, Adjusted R^2= 0.946 and SE= 1.665 Gbit/sec) for the testing condition of L=200 km, (Multiple R= 0.975, R^2= 0.951, Adjusted R^2= 0.949 and SE= 1.311 Gbit/sec) for the testing condition of L=250 km and (Multiple R= 0.976, R^2= 0.952, Adjusted R^2= 0.950 and SE= 1.076 Gbit/sec) for the testing condition of L=300 km, respectively.



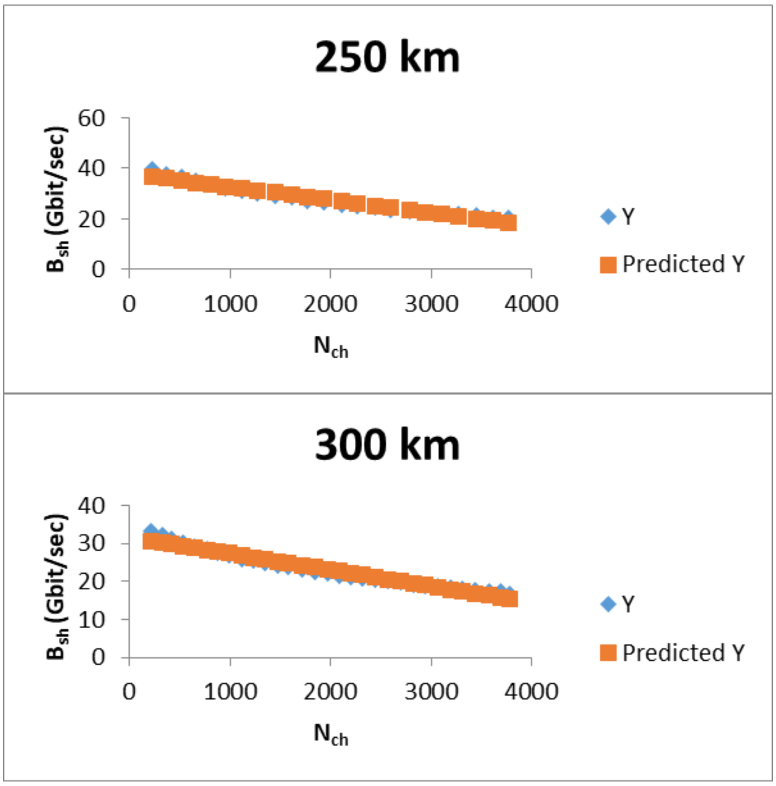
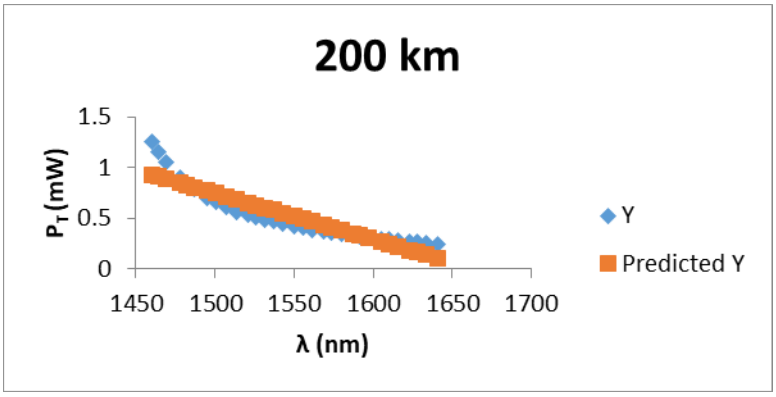


Fig. 5. Experimental and ANN of B_{sh} versus N_{ch}

Figure 6 shows that when the wavelength of an optical signal (λ) gets longer, the P_T values decrease for different operating conditions of L. As L increases, so does the P_T at a constant λ. Meanwhile, ANN algorithm revealed the following performance metrics such as (Multiple R= 0.910, R^2= 0.829, Adjusted R^2= 0.823 and SE= 0.116 mW) for the testing condition of L=200 km, (Multiple R= 0.920, R^2= 0.847, Adjusted R^2= 0.841 and SE= 0.096 mW) for the testing condition of L=250 km and (Multiple R= 0.919, R^2= 0.845, Adjusted R^2= 0.840 and SE= 0.079 mW) for the testing condition of L=300 km, respectively.



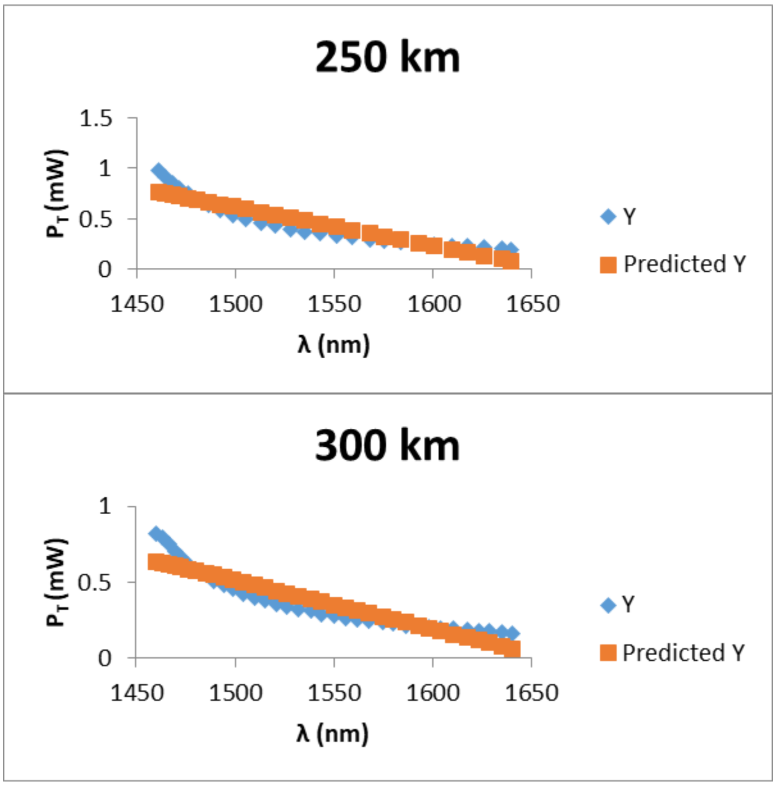
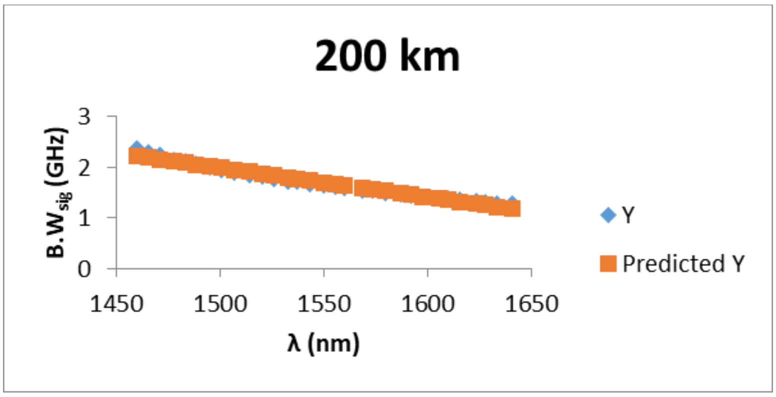


Fig. 6. Experimental and ANN variations of P_T against λ

Figure 7 shows that, when using a longer wavelength λ, the $B.W_{sig}$ decreases at different operating conditions L. As the L increases, so does the $B.W_{sig}$ at a constant λ. Meanwhile, ANN algorithm revealed the following performance metrics such as (Multiple R= 0.979, R^2= 0.959, Adjusted R^2= 0.957 and SE= 0.067 GHz) for the testing condition of L=200 km, (Multiple R= 0.981, R^2= 0.963, Adjusted R^2= 0.962 and SE= 0.052 GHz) for the testing condition of L=250 km and (Multiple R= 0.981, R^2= 0.963, Adjusted R^2= 0.962 and SE= 0.052 GHz) for the testing condition of L=300 km, respectively.



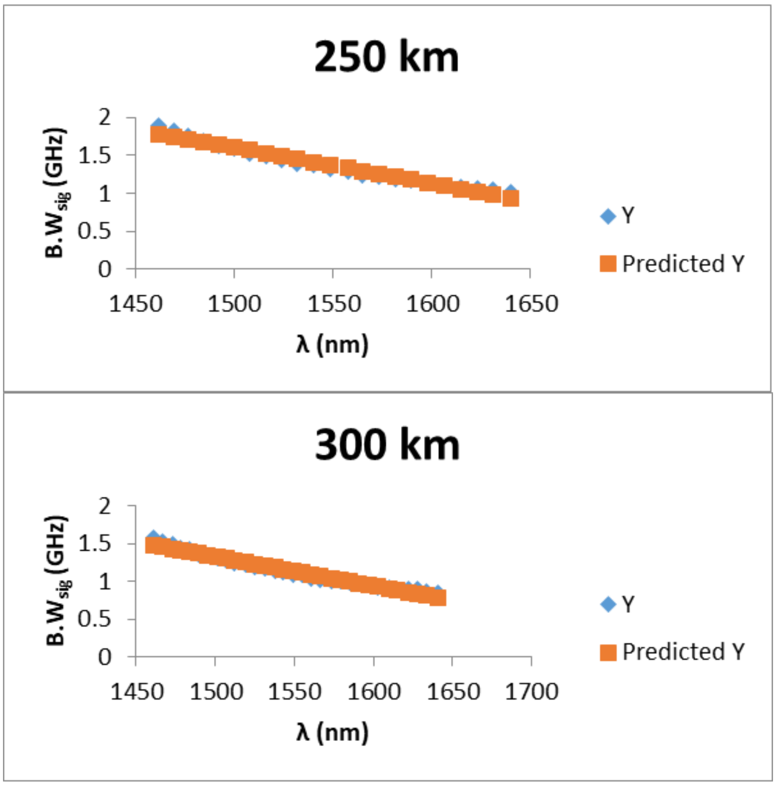
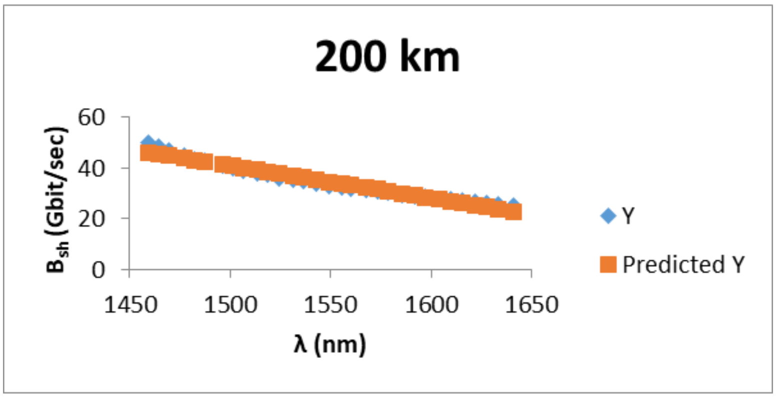


Fig. 7. Experimental and ANN variations of B.W$_{sig}$ against λ

Figure 8 shows that when the wavelength λ rises, the B_{sh} decreases for different operating conditions of L. Also, as L increases, the B_{sh} at a constant λ decreases. Meanwhile, ANN algorithm revealed the following performance metrics such as (Multiple R= 0.973, R^2= 0.947, Adjusted R^2= 0.946 and SE= 1.688 Gbit/sec) for the testing condition of L=200 km, (Multiple R= 0.971, R^2= 0.942, Adjusted R^2= 0.940 and SE= 1.417 Gbit/sec) for the testing condition of L=250 km and (Multiple R= 0.974, R^2= 0.948, Adjusted R^2= 0.946 and SE= 1.110 Gbit/sec) for the testing condition of L=300 km, respectively.



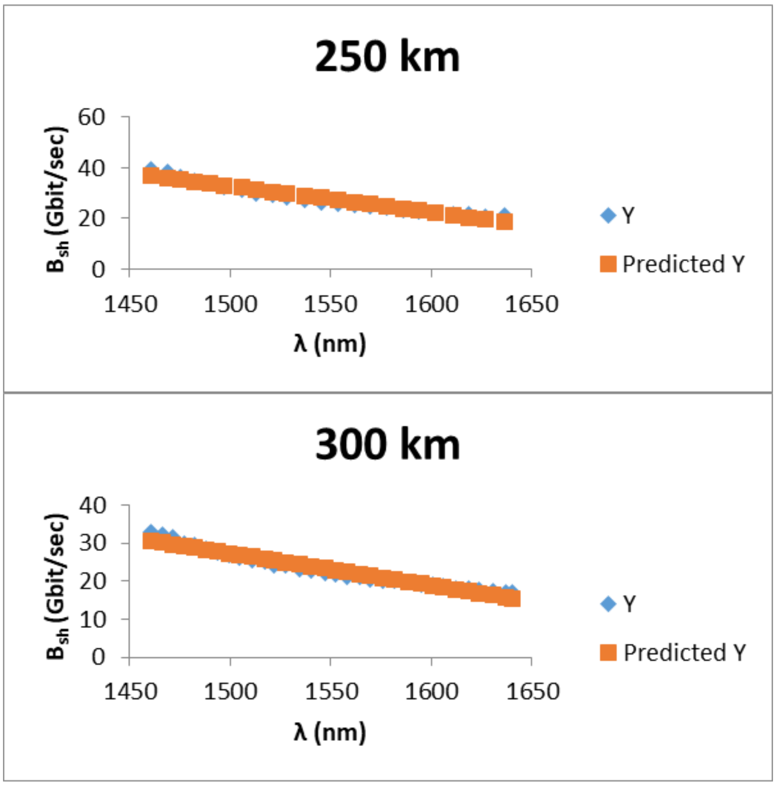


Fig. 8. Experimental and ANN variations of B_{sh} against λ

4. Conclusions

This study aimed to adapt DWDM-based OADM technology to next-generation optical communication networks to achieve high transmission bit rates. Artificial Neural Networks (ANNs) were successfully applied to predict three critical parameters in this technology, including transmitted signal power (P_T), transmitted signal bandwidth ($B.W_{sig}$), and transmission bit rate capacity (B_{sh}), at varying fiber cable lengths such as (L=200, 250, and 300 km). The following conclusions can be listed as:

i. The ANN analysis revealed SE for P_T predictions versus N_{ch}, with values of 0.115 mW (for the case of L=200 km), 0.095 mW (for the case of L=250 km), and 0.077 mW (for the case of L=300 km). Similarly, $B.W_{sig}$ predictions exhibited SE of 0.067 GHz (for the case of L=200 km), 0.051 GHz (for the case of L=250 km), and 0.040 GHz (for the case of L=300 km), while B_{sh} predictions demonstrated SE of 1.665 Gbit/sec (for the case of L=200 km), 1.311 Gbit/sec (for the case of L=250 km), and 1.076 Gbit/sec (for the case of L=300 km).
ii. Considering the prediction of P_T based on λ, SE was determined to be 0.116 mW (for the case of L=200 km), 0.096 mW (for the case of L=250 km), and 0.079 mW (for the case of L=300 km). Correspondingly, $B.W_{sig}$ predictions yielded SE of 0.067 GHz (for the case of L=200 km), 0.052 GHz (for the case of L=250 km), and 0.052 GHz (for the case of L=300 km), while B_{sh} predictions had SE of 1.688 Gbit/sec (for the case of L=200 km), 1.417 Gbit/sec (for the case of L=250 km), and 1.110 Gbit/sec (for the case of L=300 km).

This work has drawbacks, such as focusing on specified cable lengths and depending on certain literature data, yet it successfully applies OADM-based DWDM for high transmission rates. For a deeper understanding of next-generation optical communication networks, further research might investigate more intricate situations, expand the scope of the study by investigating larger cable lengths, and modify the datasets.

Acknowledgment

This research was funded by Gilgamesh Ahliya University, Baghdad, Iraq.

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