



Efficient Quality Factor Prediction of Artificial Neural Network Based IsOWC System

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Abstract. This paper presents a novel approach utilizing an artificial neural network (ANN) for optical wireless communication (OWC) between satellites in geosynchronous earth orbit and lower earth orbit, covering a distance of 45000 km. The objective of this ANN based intersatellite optical wireless communication (IsOWC) system is to intelligently predict the quality factor considering different wavelengths. To enhance the transmission performance between these satellite systems, the mean squared error (MSE) is minimized using the Levenberg–Marquardt optimizer. Remarkably, after 25 epochs, the MSE value reaches an impressive 0.000373. The results demonstrate that the ANN-based learning outperforms other machine learning algorithms, exhibiting a significantly lower MSE. Furthermore, this system has a high convergence rate as well as resistant to outliers and overfitting. Even if the number of features is small, it can be predicted accurately. Such systems hold great promise for future wireless designs and integrations, spanning from satellite to terrestrial and underwater OWC systems.

Keywords: Optical Wireless Communication · Quality Factor · NRZ · Satellite Communication · Deep learning

1 Introduction

Over the last two decades, optical wireless communication (OWC) technology has increased dramatically due to its wide bandwidth, high data rate, requires less power, and easy implementation [1]. As a result, it has triggered research interest in 5G/6G and internet of things (IoT) applications that use light amplification by stimulated emission of radiation (LASER) as signal carriers [2]. Due to advancement in photonics based devices, semiconductor laser diode produces a monochromatic and coherent beam of optical light in the form of infrared, visible, and ultraviolet rays, all of which are part of the electromagnetic spectrum [3]. On the contrary to radio frequency (RF) bands, these optical frequency bands are very fancy for satellite communication and many other applications. In addition, these bands are easily implemented in the space link due to the absence of atmospheric turbulence (AT) [4].

Radio frequency (RF) based terrestrial systems garnered global attention in the past, showcasing notable achievements across various atmospheric turbulent channel models

[5]. Recently, the performance of these systems has been investigated by using advanced modulation and coding techniques, as well as diversity techniques in space, time, wavelength, and other approaches [6]. Nevertheless, the design of RF based communication system posed numerous challenges for these systems. As a result, there has been a shift towards adopting OWC-based space link systems to meet the demanding requirements of future wireless communication systems.

On the other hand, inter-satellite optical wireless communication (IsOWC) system is advocating as a promising application of OWC technology. In this system, two satellites revolve around the earth's axis within three different earth orbit paths, namely geostationary earth orbit (GEO), medium earth orbit (MEO), and lower earth orbit (LEO). Recently, the performance of IsOWC systems has been investigated using advanced techniques like wavelength division multiplexing (WDM) and multiple input multiple outputs (MIMO) [7]. But due to external chaos, the quality factor of the system has been degraded up to certain values. However, with continuous technological advancements, the performance of the IsOWC system has been further enhanced through the utilization of machine learning (ML) algorithms. Presently, more advanced ML algorithms are being integrated into IsOWC systems [8].

In this paper ANN based IsOWC system is investigated to intelligently predict the quality factor between two satellites. The input variables consist of the laser diode wavelengths, while the output variable is the quality (Q) factor. The optimization process aims to minimize the mean squared error (MSE) performance metric by gradually reaching a global minimum point, utilizing a very small learning rate.

2 System Model

The transmission setup of the proposed IsOWC system is shown in Fig. 1. The pseudo-random bit sequence generator generates a bit sequence of length 127 bits with a data rate of 2 Gbps, which is further encoded into pulse form through a non-return to zero pulses generator. The electrical pulse signal is modulated with a laser diode using a Mach-Zehnder modulator with 30 dB extinction ratio. The filtered electrical signal is analyzed through a bit error rate analyzer. The received power P_r for the IsOWC system can be expressed as [9]:

$$P_r = P_t \eta_t \eta_r \left(\frac{\lambda}{4\pi R} \right)^2 G_t G_r L_t L_r \quad (1)$$

where P_t , η_t , η_r , $(\lambda/4\pi R)^2$, λ , R , G_t , G_r , L_t , and L_r represent transmitted power, optical transmitter efficiency, optical receiver efficiency, free space path loss, operating wavelength, propagation distance, transmitter aperture gain, receiver aperture gain, transmitter pointing loss factor and receiver pointing loss factor, respectively. Moreover, scintillation is not considered in the present calculation due to the absence of atmospheric turbulence. The relationship between the diameter and aperture gain of an antenna is given as [10]

$$G = \left(\frac{\pi D}{\lambda} \right)^2 \quad (2)$$

putting Eq. (2) in (1), it can be expressed as:

$$P_r = P_t \eta_t \eta_r L_t L_r \left(\frac{D_t D_r}{2\pi \lambda R} \right)^2 \quad (3)$$

Equation (3) reveals that as the operating wavelength is decreased, the overall received optical power increases gradually, and therefore, the optical signal-to-noise (OSNR) ratio increases, which enhances the quality factor of the IsOWC system.

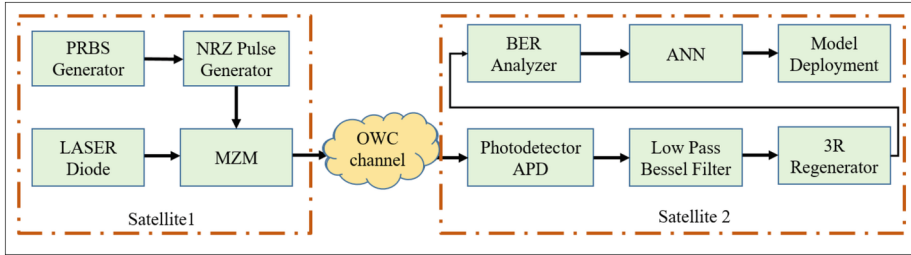


Fig. 1. Transmission set up of ANN-based IsOWC system

3 Machine Learning and Its Applications

3.1 Machine Learning

Machine learning (ML) is a straightforward algorithm that enables computers to learn autonomously, eliminating the need for explicit programming [11]. ML encompasses three main types of learning processes: i) supervised learning, ii) unsupervised learning, and iii) reinforcement learning. Supervised learning relies on labeled data, whereas unsupervised learning utilizes unlabeled data. On the other hand, reinforcement learning involves agents performing specific tasks in an environment and making decisions based on the outcomes. Furthermore, ML encompasses various statistical algorithms, including decision tree (DT), naive Bayes algorithm, gradient boosting algorithm, adaboosting algorithm, k-nearest neighbor (KNN), random forest (RF), and support vector machine (SVM), which are employed for prediction or classification purposes [12]. The entire ML process entails crucial steps such as feature extraction, data pre-processing, model training, validation, and model deployment, all of which are essential for developing a robust ML model [13].

Moreover, ML models has primarily relied on the feature selection method and data pre-processing techniques. Earlier, a variety of ML approaches were used to improve the IsOWC system's performance. In order to improve the performance of an IsOWC system for better optical wireless connectivity, this system has been shifted to advanced ML techniques. This is because the model is robust against outliers, and requires less time and memory space to complete its training process.

3.2 Deep Learning

DL is a subset of machine learning that build an intelligent machine capable of performing tasks that typically require human intelligence. It mainly focuses on regression and classification problems, image segmentation, and object detection [14].

The basic architecture of ANN contains single or multilayer perceptron (MLP) along with feed-forward and backpropagation paths. The single-layer perceptron of the ANN-based IsOWC system is shown in Fig. 2. MLPs are most commonly used for linear and non-linear data, which is motivated by the self-learning procedure, which is the same as biological neuron models [15].

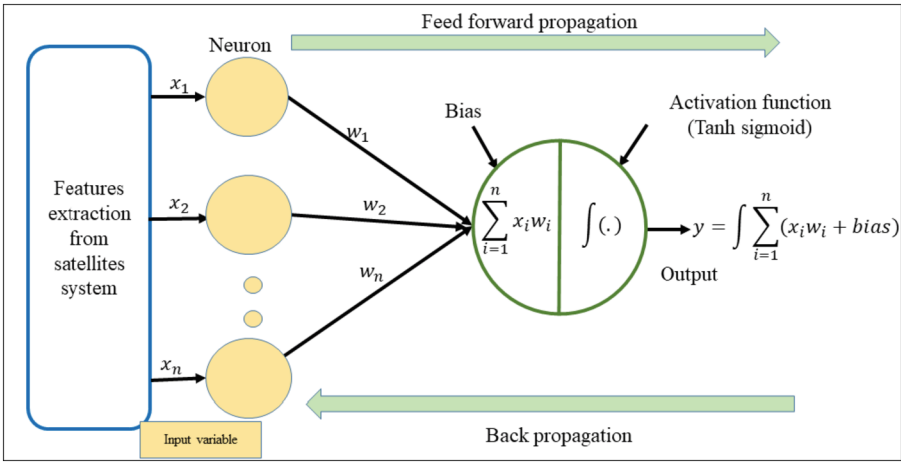


Fig. 2. Single layer perceptron (SLP) of an ANN-based IsOWC system

ANN model is widely used in regression and classification problems. While optimizing the error, the most important thing is to update weight and bias parameters. It converges to a global minimum point keeping the learning rate very low. Besides the use of ANN in the IsOWC system, the transmission performance of the IsOWC system will be further improved by using advanced algorithms like convolutional neural network (CNN), recurrent neural network (RNN), long-term short memory (LSTM), generative adversarial networks (GAN), transfer learning, vision transformers, and auto encoders.

4 Simulation Setup Description

4.1 Dataset Building

The supervised ANN based IsOWC systems are considered for the present investigation. The wavelength of laser diode, along with the Q-factor, is used for training the ANN model. Each variable contains 130 samples, where the wavelength ranges from 800 to 1600 nm and the Q- factor ranges from 5.01761 to zero. Out of 130 samples, 70% of samples are randomly selected for the training dataset, the remaining 15% for the testing dataset and the remaining 15% for validation dataset.

4.2 Performance Metric

Mean squared error (MSE) is commonly used metric for evaluating of regression of model. It quantifies the average squared difference between the predicted values and the actual values in a dataset. A lower MSE value indicates better model performance it means the predicted values are closer to the actual values on average. Therefore, the value of MSE directly reflects the performance of the system. For the proposed model, various parameter is taken for the simulation of an ANN based IsOWC system, as shown in Table 1.

Table 1. Parameters used for simulation of an ANN based IsOWC system

Parameter	Value
Number of ANN layer	03
Number of hidden neurons	10
Number of epochs	31
Optimizer	Levenberg-Marquardt (LM)
Performance metrics	Mean squared error (MSE)

5 Results and Discussions

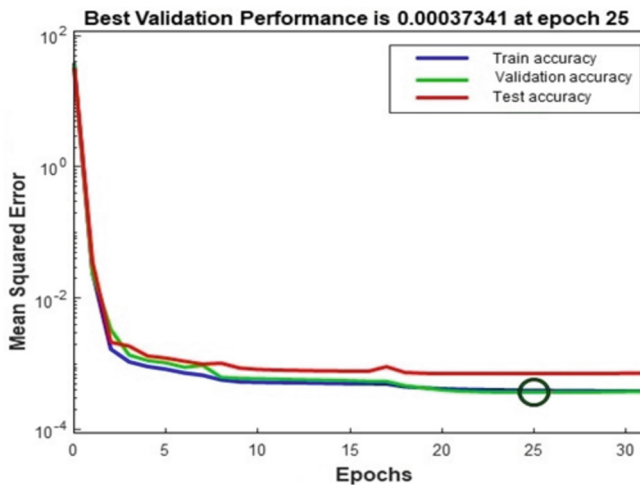


Fig. 3. Mean squared error vs. epochs of an ANN-based IsOWC system

The transmission performance of an IsOWC system is investigated using the ANN technique. Figure 3 shows the variations of MSE with epochs of training, validation, and testing accuracy of the given ANN based IsOWC system. It can be seen from Fig. 3 that the MSE value of different curves, i.e., the blue line (training accuracy), the green line (validation accuracy), and the red line (test accuracy), exponentially decreases as the number of epochs increases. After several iterations, the MSE value is obtained as 0.000373 with respect to the validation dataset, which clarifies that the model has predicted very well on the test or unseen datasets. After the four iterations of a proposed ANN model, the MSE value of the validation accuracy is slowly increased, and after that, it remains constant.

Afterwards, in order to investigate the coefficient of determination (R) analysis also known as R-squared among three training, validation, and testing parameter, the output predicted versus target graph is plotted as shown in Fig. 4. It can be observed from Fig. 4 that the overall (R) is obtained as 99.98%, which signifies that most of the datasets follow the best-fit line. Therefore, the model has shown that it strongly correlates with the target variable and predicted output.

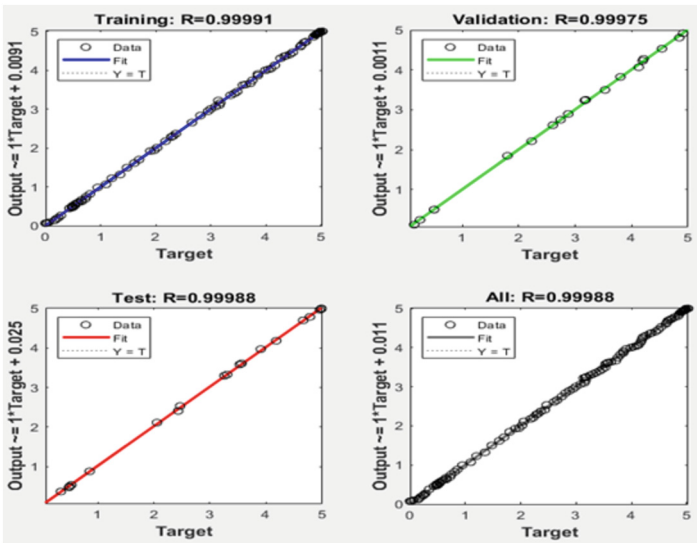


Fig. 4. Output vs. target for the different parameters of an ANN model (a) training parameter (upper left), (b) validation parameter (upper right), (c) test parameter (lower left), and (d) overall value of R (lower right)

Figure 5 shows the error histogram with 20 bins of different training, validation, and testing accuracy of the given ANN model. The error can be represented in histogram form with different rectangular sizes having a blue box (training accuracy), green box (validation accuracy), and red box (test accuracy). A zero-error line is set in the middle of the graph and signifies no error among these three parameters. In Fig. 5, one bin has a high number of instances showing that training and validation accuracy are very close to

the zero-error line, representing that the mean squared error value is optimized correctly to a significant level. Furthermore, the number of instances decreases on either side of the zero-error line.

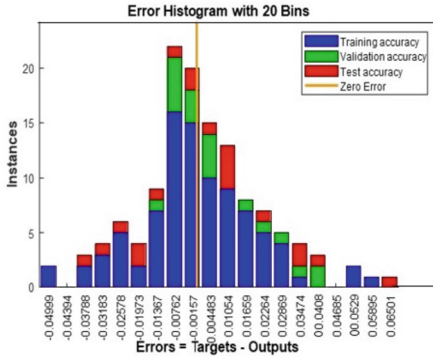


Fig. 5. Instances vs. errors of an ANN based IsOWC system

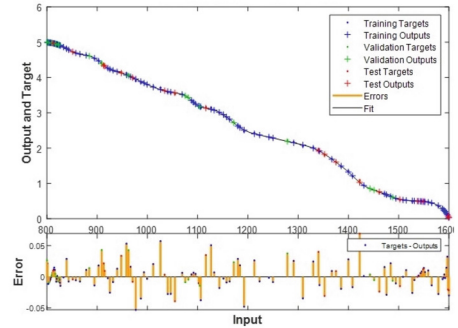


Fig. 6. Output and target vs. wavelength of training, validation, and test parameter (upper part) and error vs. input (lower part)

Figure 6 shows the fit function of the proposed ANN based IsOWC system. The training target and outputs (represented as a blue dot and plus sign), validation target and outputs (represented as a green dot and plus sign), and test target and outputs (represented as a light red dot and plus sign) follow the wavelength vs. quality factor graph. However, the error vs. input graph is plotted at the lower part of the function fit graph. It shows that at which wavelength the quality factor is maximum or minimum. Also, this graph shows three ranges of wavelength where the fit function is invalid, i) 900–1000 nm, ii) 1300–1350 nm, and iii) above 1600 nm. At these wavelengths, error is more which signifies that system has faced more disturbance due to the vibration of satellites or pointing error. It can be seen that the proposed ANN based IsOWC system performs better than the previous reported results [16].

6 Conclusion

The ANN based IsOWC system is used to intelligently estimate the quality factor without the requirement of channel state information. Depending on the wavelength selected, ANN based regression model assists in determining signal quality in the presence of atmospheric attenuation, transmission range, beam divergence, interference and crosstalk, and receiver sensitivity. Based on these findings, the suggested ANN approaches have a high potential for automating satellite communication systems. The LM optimizer occupies less memory and converges quicker than other optimizer.

Finally, these ANN based IsOWC will be integrated with underwater networks as well as terrestrial networks to satisfy the high expectations of 5G beyond communication and to develop a truly intelligent network.

References

1. Patnaik, B., Sahu, P.K.: Inter-satellite optical wireless communication system design and simulation. *IET Commun.* **6**(16), 2561–2567 (2012)
2. Kaur, N., Soni, G.: Performance analysis of inter-satellite optical wireless communication (IsOWC) system at 980 nm and 1550 nm wavelengths. In: 2014 International Conference on Contemporary Computing and Informatics (IC3I), pp. 1245–1250. IEEE, Mysore (2014)
3. Khalighi, M.A., Uysal, M.: Survey on free space optical communication: a communication theory perspective. *IEEE Commun. Surv. Tutorials* **16**(4), 2231–2258 (2014)
4. Majeed, M.H., Ahmed, R.K., Alhumaima, R.S.: Performance analysis of inter-satellite optical wireless communication (IsOWC) system with multiple transmitters/receivers. In: IOP Conference Series: Materials Science and Engineering, vol. 1076, p. 012052 (2021)
5. Sri, I.K., Srinivasulu, A.: Q-factor and BER performance analysis of inter-satellite optical wireless communication using 26 transponders. In: 2017 International Conference on Intelligent Communication and Computational Techniques (ICCT), pp. 165–168. IEEE, Jaipur (2018)
6. Tawfik, M.M., Sree, M.F.A., Abaza, M., Ghouz, H.H.M.: Performance analysis and evaluation of inter-satellite optical wireless communication system (IsOWC) from GEO to LEO at range 45000 km. *IEEE Photonics J.* **13**(4), 1–6 (2021)
7. Alom, M.Z., et al.: A state-of-the-art survey on deep learning theory and architectures. *Electronics* **8**(3), 292 (2019)
8. Tian, Q., et al.: Turbo-coded 16-ary OAM shift keying FSO communication system combining the CNN-based adaptive demodulator. *Opt. Express* **26**(21), 27849 (2018)
9. Sahu, P.P., Singh, M.: Multi channel frequency hopping spread spectrum signaling using code M-ary frequency shift keying. *Comput. Electr. Eng.* **34**(4), 338–345 (2008)
10. Kaur, S.: Analysis of inter-satellite free-space optical link performance considering different system parameters. *Opto-Electron. Rev.* **27**(1), 10–13 (2019)
11. Zhu, G., Liu, D., Du, Y., You, C., Zhang, J., Huang, K.: Toward an intelligent edge: wireless communication meets machine learning. *IEEE Commun. Mag.* **58**(1), 19–25 (2020)
12. Ghanem, Z., Alsaraira, A., Al-Tarawneh, L., Saraereh, O.A.: Comparative analysis of ml-schemes in OWC systems. *J. Electr. Eng. Technol. (IJEET)* **12**(8), 115–132 (2021)
13. Dahrouj, H., et al.: An overview of machine learning-based techniques for solving optimization problems in communications and signal processing. *IEEE Access* **9**, 74908–74938 (2021)
14. Minaee, S., Boykov, Y., Porikli, F., Plaza, A., Kehtarnavaz, N., Terzopoulos, D.: Image segmentation using deep learning: a survey. *IEEE Trans. Pattern Anal. Mach. Intell.* **44**(7), 3523–3542 (2022)
15. Tan, M.C., Khan, F.N., Al-Arashi, W.H., Zhou, Y., Lau, A.P.T.: Simultaneous optical performance monitoring and modulation format/bit-rate identification using principal component analysis. *J. Opt. Commun. Netw.* **6**(5), 441–448 (2014)
16. Algedir, A.A., Elganimi, T.Y.: Machine learning models for predicting the quality factor of FSO systems with multiple transceivers. In: 2020 2nd Global Power, Energy and Communication Conference (GPECOM), pp. 308–311. Izmir, Turkey (2020)