

# The Role of Machine Learning and Deep Learning Approaches to Improve Optical Communication Systems

Weam M. Binjumah

Applied College of Taibah University, Madina, Saudi Arabia

Email: wjommaa@taibahu.edu.sa

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## Abstract

In recent years, there has been a revolution in the way that we transmit information through optical communication systems, allowing for fast and high-capacity data transmission using optical communication systems. Due to the growing demand for higher-capacity and faster networks, traditional optical communication systems are reaching their limits due to the increasing demand for faster and higher-capacity networks. The advent of machine learning and deep learning approaches has led to the emergence of powerful tools that can dramatically enhance the performance of optical communication systems with significant efficiency improvements. In this paper, we provide an overview of the role that machine learning (ML) and deep learning can play in enhancing the performance of various aspects of optical communication systems, including modulation techniques, channel modelling, equalization, and system optimization methods. The paper discusses the advantages of these approaches, such as improved spectral efficiency, reduced latency, and improved robustness to impairments in the channel, such as spectrum degradation. Additionally, a discussion is made regarding the potential challenges and limitations associated with using machine learning and deep learning in optical communication systems as well as their potential benefits. The purpose of this paper is to provide insight and highlight the potential of these approaches to improve optical communication in the future.

## Keywords

Machine Learning, Deep Learning, Optical Communication, Design Science Research, Literature Review

## 1. Introduction

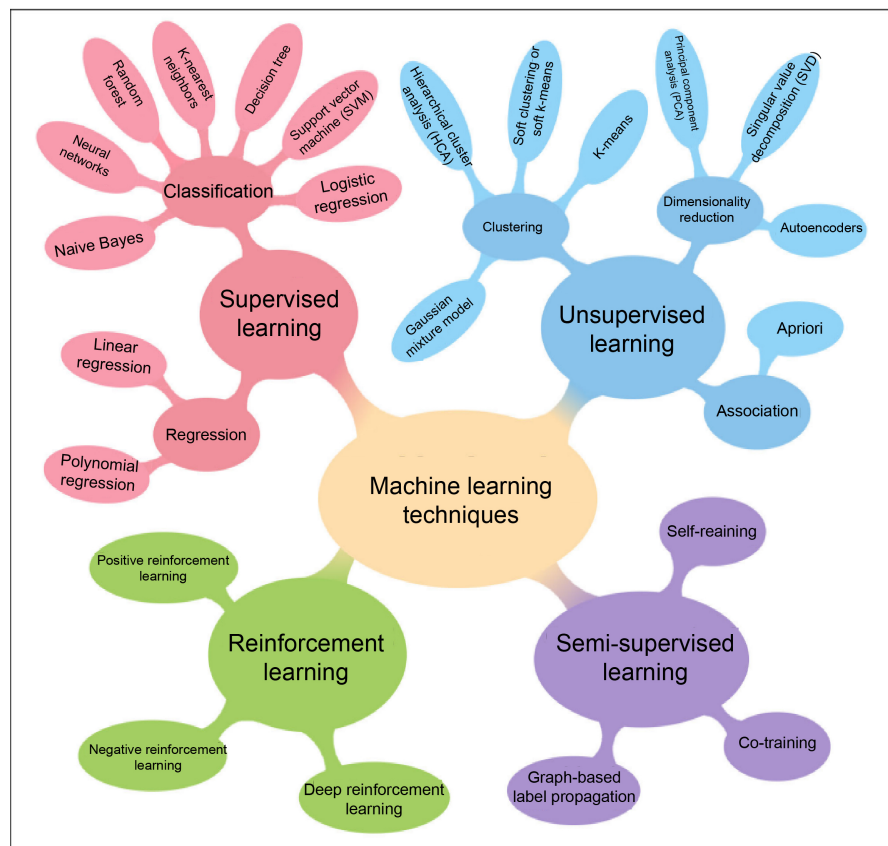
The optical connection, also referred to as the optical telecommunication, is the use of light to transmit information at a distance. Depending on the kind of device you are using, it can either be a visual process or an electronic process. Several millennia have passed since the earliest forms of optical communication were established, while in 1880, the photophone was invented as the first electrical device that could perform this function [1] [2]. There are three main components in an optical communication system: a transmitter that encodes a message into an optical signal, a channel that transmits the optical signal, and a receiver that reassembles the message from the optical signal it receives. As opposed to electronic equipment, an electronic receiver uses signs and signals that are interpreted or received by the eye, as opposed to electronic equipment. These signals can be simple (such as a beacon fire) or complex (such as lights that flash in Morse code sequences or use colour codes). Optical communication offers several advantages over traditional electrical communication methods, including increased bandwidth, reduced signal degradation, and energy efficiency. With its wide range of applications and future trends, optical communication is poised to play an increasingly important role in shaping the future of information transmission [3] [4].

Optical communication uses light to transmit data over long distances, providing a faster and more efficient alternative to traditional radio frequency-based communication systems. One of the key challenges in optical communication is optimizing the system performance for data transmission. This is where machine and deep learning come into play. Machine learning techniques, such as artificial neural networks, can be used to model and optimize the performance of optical communication systems [5]. These algorithms are trained to learn patterns and relationships in the data, enabling them to make accurate predictions and recommendations. **Figure 1** displays the different kinds of the machine learning which may assist to overcome the optical communication challenges.

### 1.1. Supervised Learning

Datamining is a sub-category of machine learning, which uses labelled data to train algorithms to classify information or predict results [7]. Input data is incorporated into the model through weight adjustments so that the algorithm works correctly [7]. A supervised machine learning approach is used in cases where you already know what you will teach the machine ahead of time. In order for the algorithm to achieve the desired results, it is necessary to take it through a large training data set, examine it, and adjust the parameters until the desired results are achieved. By adjusting its own parameters in response to a loss function, the algorithm measures its accuracy in order to minimize the error as much as possible. A final test of the trained machine is to allow it to make predictions based on a validation set, which is a new set of unseen data that has not been seen before [7]. There are two types of algorithms which are used in supervised

learning, namely regression algorithms and classification algorithms, as shown in **Figure 1**.



**Figure 1.** Machine learning techniques [6].

- **Regression algorithms:** This type of regression procedure is used to determine the correlations between a variable and its dependent variable in the presence of independent variables [8]. In the mathematical world, an algorithm is a technique which allows you to summarize and study how two continuous quantitative variables interact with each other statistically [9]. The purpose of this is to be able to predict or explain a particular numerical value based on the data that was collected previously. This type of analysis can be conducted using different algorithms, but linear regression and polynomial regression tend to be the most commonly used algorithms for this kind of analysis [9].
- **Classification algorithms:** Classification algorithms are algorithms that predict or explain the value of a class based on some property of the class. In essence, they are using an algorithm to assign a classification to the test results so that they can interpret them properly looking at the information they collected throughout the test [6]. It is crucial for the classification process to recognize specific associations within a data set of data that has been analysed, and to be able to make conclusions about how these entities should be classified and labelled over the course of the analysis. It is well known that

algorithmic processes are one of the most effective ways of understanding classification algorithms in the field of computer science, and one of the best examples of this can be found in the spam or junk mail detector. There are several types of algorithms that can be used to determine whether a message is actually an email or not.

## 1.2. Unsupervised Learning

An example of unsupervised learning is a method for learning without the need for a person to monitor the model as the model explores a data set. Therefore, the training process is characterized by a data set without any labels or classifications that have been previously defined [10]. Using only statistical properties as a basis to assess the hidden information, the algorithm tries to identify patterns that relate different variables in order to identify hidden information that may not have been spotted before they are scanned [6]. According to **Figure 1**, there are three major types of unsupervised learning algorithms: clustering, association, and dimensionality reduction<sup>1</sup>.

- **Clustering algorithms:** It is a technique that is mainly used to identify the structures or patterns within unlabeled data collections and to develop a system based on how similar or different they are in relation to one another [11]. Grouping algorithms are commonly used to identify a large number of groups of data such as k-means, soft clustering, hierarchical cluster analysis, and Gaussian mixture models.
- **Association algorithms:** Associative algorithms are rule-based tools used for finding hidden relationships among variables in a particular dataset that may not be immediately obvious from looking at the data alone. It is therefore possible to consider it as a method of analyzing data [11].
- **Dimensionality reduction algorithms:** ML's algorithms can work much more efficiently when there is more data, but it can also have a negative impact on the performance of the algorithm if there is too much data. An algorithm that reduces the dimension of a data set is one that is used when a data set has a great deal of information in it, hence the need for some major reductions in dimensions. By means of these algorithms, the number of data entries is reduced to a suitable size during the operation, while still managing to preserve the integrity of the data set at the same time [11].

## 1.3. Semi-Supervised Learning

The idea of semi-supervised learning is an important subcategory of machine learning. As part of the training stage, rather than labeling the entire analysed data set, only a small portion of the data is reviewed, hand-labeled, and then used to train a model by combining it with other data. Lastly, this trained model is able to correctly classify all the features that exist in a larger unlabelled data set that has not been labelled by humans [12]. There are two types of learning techniques: semi-supervised learning and supervised learning. It has been shown that semi-

supervised learning is a more flexible method of learning than unsupervised learning and can be used for a wide range of classification, regression, clustering, and even association problems. Due to the fact that semi-supervised learning uses a small amount of labelled data as well as a large amount of unlabelled data, it is less computationally intensive and takes less time to prepare data than supervised learning [12].

#### **1.4. Reinforcement Learning**

The idea of reinforcement learning is a subcategory of machine learning in which machines have the capability of interacting with environments. In a learning agent, behavior is learned by performing tasks and seeing the results of the actions they perform in a given environment. As a result of every good action that the agent takes, he or she receives positive feedback; as a result of every bad action that the agent takes, he or she receives negative feedback or a penalty. If the machine repeats the process thousands of times, it over time becomes more and more skilled as it learns and becomes more proficient [13]. There is one significant difference between reinforcement learning and traditional supervised learning and that is that in supervised learning; the answer is found in the training data. It is therefore possible to train the model with the correct solution as a result. In contrast to this, reinforcement learning is not a response, but rather an agent that decides what to do based on what happens, in order to respond or perform a task at hand. There are some significant differences between reinforcement learning and unsupervised learning in terms of the objectives that it pursues [14].

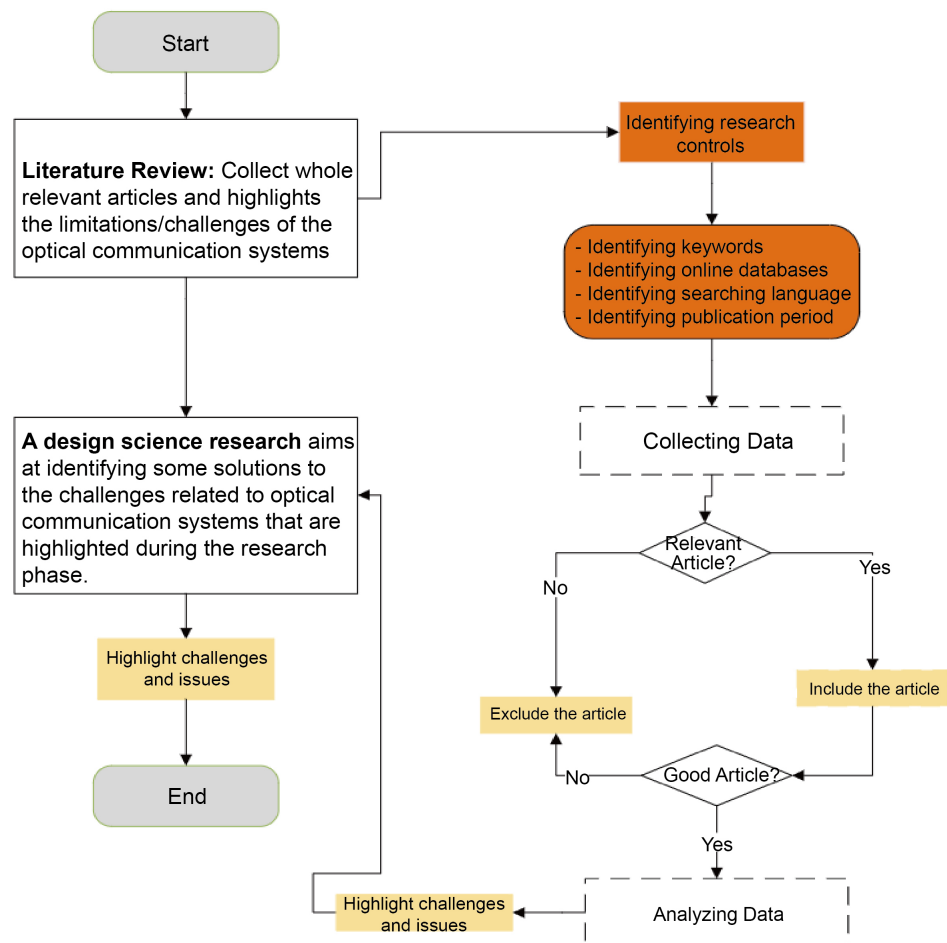
Furthermore, there are a number of specific application cases and practical effects of machine learning and deep learning methods in optical communication systems that are: channel characterization and modelling, and network optimization and planning. The channel characterization and modelling. Modelling optical channel impairments and uncertainties using machine learning and deep learning. Optimising network architecture, transmission parameters, and resource allocation improves system performance and reliability. In order to decrease the complexity of networks, deep learning and machine learning methods use network optimization in order to reduce complexity. As a result of using these methods, it is possible to optimize the configuration of the network, minimize the energy consumption, and improve the efficiency and reliability of communications.

This article highlights the role of machine learning and deep learning in improving optical solutions. The design science approach and literature review conducted in this study provide valuable insights into the challenges and opportunities associated with utilizing these techniques. The successful implementation of machine learning and deep learning in optical solutions has the potential to revolutionize various industries, leading to improved efficiency, performance, and accuracy.

This article is organized as follows: the methodology is discussed in Section 2 whereas the conclusion and future works are offered in Section 3.

## 2. Methodology

This study used a mixed methodology to explain the role of machine learning and deep learning approaches in improving optical communications. The literature review [15] and design science methodology [16] are used in this study. Literature reviews are excellent methods for synthesizing research findings to demonstrate evidence on a meta-level and also to uncover areas that need further study, which is a critical component of the creation of theoretical frameworks and the development of conceptual models [15]. In design science research, a research paradigm focuses on solving problems through the application of design thinking. Increasingly, Information Systems (IS) researchers are adopting it as a legitimate research paradigm because of its ability to balance the importance of research and its rigor, which makes it a desirable paradigm for conducting research [17]. Therefore, the mixed methodologies aim to highlight the challenges and issues of optical communications, and the design science research aims to suggest solutions for the highlighted challenges and issues. **Figure 2** illustrates the mixed methodology. The methodology consists of two stages: literature review stage, and the design science research stage.



**Figure 2.** Adapted methodology.

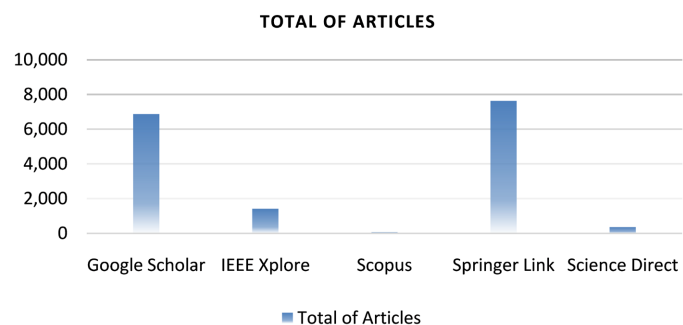
## 2.1. Literature Review Stage

This stage includes identifying the search controls, collecting data, and analysing data. Identifying search controls includes identifying keywords, identifying online databases, identifying searching language, and Identifying publication period. The identifying keywords include “Deep Learning”; “Machine Learning”; “Optical communication”. Five online databases are identified: Scopus, IEEE Xplore, Web of Science (WoS), Science Direct, and Google Scholar. The English language is identified as the main language for this study. The Identifying publication period is between 2015-2025. 6,870 articles from Google Scholar, 1,411 articles from IEEE Xplore, 62 articles from Scopus, 353 articles from Science Direct, and 7,633 from the Springer link. **Figure 3** displays the collected data from the identified common online databases. The total articles are 16,329 articles. These articles are complied with the including and excluding criteria. **The inclusion criteria are:**

- a) Articles published in related, peer-reviewed journals;
- b) Articles performed during the last five years;
- c) Articles examining deep learning, machine learning, and optical communication;
- d) Articles containing complete explanations of the data and optical communication models applied.

**The exclusion criteria are:**

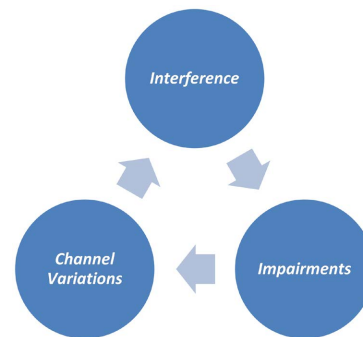
- a) Article not published in relevant, peer-reviewed journals;
- b) Article conducted more than five years ago;
- c) Article focusing on general optical communications models;
- d) Article providing only theoretical insights without any empirical evidence;
- e) Article lacking detailed descriptions of the data and AI models used.



**Figure 3.** Data collected from the common five online databases.

After collecting and filtering the collected data, the authors analyzed the relevant articles and highlights the following challenges and issues in the optical communications which illustrates in **Figure 4**.

- **Interference:** Optical signals are susceptible to interference from various sources, such as atmospheric turbulence, thermal noise, and crosstalk. Machine learning algorithms can be trained to identify and mitigate interference to enhance system performance.

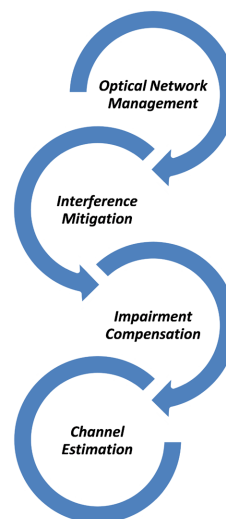


**Figure 4.** Challenges and issues of the optical communication.

- **Impairments:** Optical signals can experience impairments, such as distortion, absorption, and dispersion, which can degrade the signal quality. Deep learning techniques can be trained to analyse and compensate for these impairments in real-time, improving the overall performance of the communication system.
- **Channel Variations:** Optical channels can exhibit significant variations in parameters such as attenuation, dispersion, and polarization. Machine learning algorithms can be trained to estimate and adapt to these channel variations, ensuring a reliable and efficient data transfer.

## 2.2. Design Science Research Stage

The aim of this stage is to find the proper solutions for the above challenge and issues. The following machine learning and deep learning applications which displays in **Figure 5** are some of the solutions for the challenges of the optical communication.

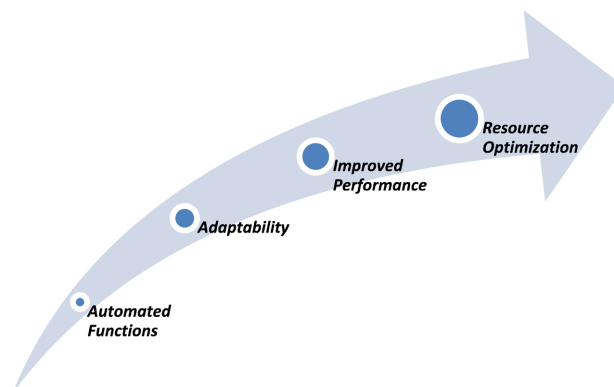


**Figure 5.** Some of the solutions for the challenges of the optical communication.

- **Optical Network Management:** Machine learning algorithms can be employed to automate and optimize network management tasks, such as resource allocation, link optimization, and fault detection. This can help enhance network efficiency and reduce manual intervention.
- **Interference Mitigation:** Deep learning models can be trained to detect and mitigate interference in optical communication systems, ensuring reliable and error-free data transmission.
- **Impairment Compensation:** Deep learning models can be trained to compensate for the impairments present in optical channels, improving signal quality and bandwidth efficiency.
- **Channel Estimation:** Machine learning algorithms can be trained to estimate channel parameters, such as attenuation, dispersion, and polarization, in real time. This helps in optimizing system parameters such as modulation format and bit rate.

Implementing machine learning and deep learning approaches in optical communication systems offers several benefits as shown in **Figure 6**, including:

- **Improved Performance:** By leveraging the power of machine learning and deep learning techniques, optical communication systems can achieve higher data rates, lower error rates, and improved link reliability.
- **Automated Functions:** Machine learning and deep learning algorithms automate various tasks, reducing human intervention and increasing the operational efficiency of optical communication systems.
- **Adaptability:** Machine learning and deep learning algorithms can adapt to changing conditions, such as channel variations and interference, ensuring robust and reliable communication.
- **Resource Optimization:** Machine learning algorithms can optimize system resource allocation, such as power allocation and resource allocation, maximizing system performance and minimizing energy consumption.



**Figure 6.** Benefits of implementing machine learning and deep learning approaches in optical communication systems.

Traditional optical communication systems play a significant role in data

communication and long-distance transmission. However, as technology advances, machine learning optimized systems provide an alternative approach that enhances system performance in challenging environments. Noise immunity, error correction, and bandwidth efficiency are some of the key performance advantages offered by machine learning optimized systems. The practical application effects, especially in high noise environments or non-ideal operating conditions, demonstrate the benefits of machine learning techniques in optical communication systems. Future research and development efforts should focus on exploring the integration of machine learning techniques into traditional optical communication systems to further improve their performance and reliability.

The latest standards and specifications play a crucial role in evaluating and validating the feasibility and reliability of machine learning optimization techniques in practical optical communication networks. These standards define the necessary frameworks and metrics for assessing the performance of optical communication systems, including HSE networks, DBA algorithms, signal impairments, and network intrusion detection and prevention systems.

### 3. Conclusion

Optical communication systems have revolutionized the way we transmit information in recent years. Through optical communication systems, fast and high-capacity data transmission is possible. Since demand for faster and higher-capacity networks is increasing, traditional optical communication systems are reaching their limits. The use of machine learning and deep learning approaches has given rise to powerful tools that can significantly boost optical communication systems' performance. This paper presents an overview of how machine learning (ML) and deep learning can be used to improve the performance of optical communication systems, including modulation techniques, channel modelling, equalization, and system optimization. According to the paper, these approaches offer advantages such as spectral efficiency improvements, reduced latency, and enhanced robustness to impairments, including spectrum degradation, in the channel. Furthermore, machine learning and deep learning are discussed in light of potential challenges and limitations. Moreover, their potential benefits are discussed. As a result of this paper, we gain an understanding and highlight the potential of these approaches to improve optical communication in the future.

### Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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