# Artificial Intelligence for 3-D Satellite Networks: A Comprehensive Overview

# Artificial Intelligence for 3-D Satellite Networks: A Comprehensive Overview

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***Abstract*—Day-by-day, wireless devices and diverse radio services require extended spectrum. Additionally, sixth generation (6G) mobile communication systems that are introducing new challenging use cases, need deep focus on latencies, number of connections, and so on. Hence, the combination of advanced design and working methodologies leads to enhance the necessary infrastructure, that in some cases can incorporate satellite networks as well. Artificial intelligence (AI) technique has been applied for various electromagnetic devices aiming to accelerate their overall design and analysis. In recent years, this paradigm has brightened the way of their application for space applications as well. In this framework, the present paper discusses a review on machine learning techniques employed toward design of 3-D satellite networks where it provides the use cases, requirements and enablers for these networks. Most importantly, the AI technology is employed for estimating the dynamic radio channel, signal detection and demodulation, network security, predicting the microwave signal attenuation, recognizing appropriate beam hopping patterns, and also for increasing efficiency in the places with the dust and sand storms. By preparing this paper, the authors has targeted to clarified that developing state-of-the-art methods including AI techniques would be a fundamental step towards the development of high-dimensional satellite network systems.**

***Index Terms*—Artificial intelligence (AI), deep neural network (DNN), machine learning (ML), satellite network (SN).**

## I. Introduction

Due to the exponential demand in the telecommunication systems, wide bandwidth (BW) with higher data rate are critically necessary. These requirements can be met by the next generation networks. Antennas are one of the most important devices in the fifth generation (5G) and sixth generation (6G) technologies that are employed in the communication systems [1], [2]. It is expected to have superior performance in 6G networks in comparison with 5G counterpart because of a large-dimensional and autonomous network [3], [4]. Suitable BW with the low-profile geometry are important specifications leading to improved performances in the wireless systems [5]. Satellite systems are wireless arrangements with the specificity that the distance is greater (up to the satellite back down to earth) with respect to the terrestrial counterparts. These space-networks are a candidate for providing a true global connectivity in next-generation networks.

With the help of satellite networks (SNs), computing, following, and navigating for various applications would be straightforward leading to communicate and interact with smart terminals. These kinds of networks need efficient design methods that are quick and dynamic enough for dealing with various specifications. Unlike the conventional techniques, artificial intelligence (AI) offers intelligent-based optimization leading to solve highly adaptable and technology aware problems. The theory of AI technique is based on learning from non-linear behaviors results in determining the necessary system configurations. Hence, AI can be useful enough for interacting with radio environment for providing a satisfied quality-of-service (QoS). Figure 2 presents the summary of practical use of AI including deep neural network (DNN) for detecting the target signals [6].

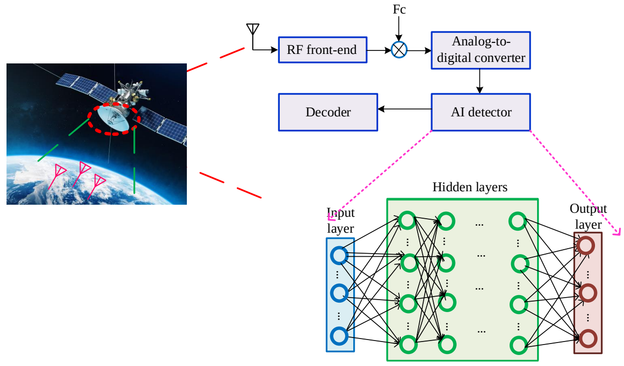


Fig. 1. Signal detection for a satellite link through deep neural networks.

The main contribution of this paper is on presenting various uses of AI for satellite systems leading to realize robust next generation satellite networks. Firstly, a brief description regarding the importance of AI with the general structure is explained and afterwards the various unique features, details, state-of-the-art AI methods used for SNs are presented. Any author by reading this work would get a general view regarding the importance of AI in SNs and would get views/ideas regarding the future implementation of this strong technique for future studies.

The following part of this work is structured as above: Sec. II presents the general view around the AI. Section III summarizes the recently published works related to the implementation of AI in SN. Finally, Sec. IV concludes this paper.

## II. General Overview around AI

In the AI, the Bayesian optimization (BO) is a common employed method for optimizing single or multi-objective functions. The general overview about the AI is presented in Fig. 2 where the input data is presented as $(x)$ and the output specification is defined as $(f(x))$ leading to predict the outcomes. This method builds the surrogate for the objectives through Gaussian process (GP) regression. The BO method solves the problem of (max/min $f(x)$) and the GP suggests a Bayesian posterior probability distribution of the input parameters.

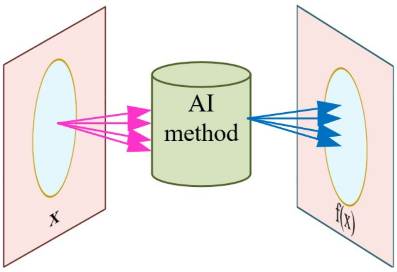


Fig. 2. Flowchart of AI methods.

The machine learning (ML) and Deep learning (DL) are the subsets of AI [7] in which, ML includes three subsets namely as: supervised learning, unsupervised learning, and reinforcement learning (see Fig. 3 and Fig. 4). Each of these subsets can be employed for specific applications [8].

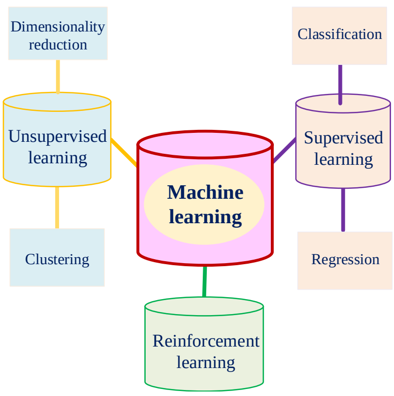


Fig. 3. Various sections of ML.

As previously discussed, DNNs are the subset of AI in which the overall structure includes input layer, hidden layers, and output layers as reported in Fig. 5. For any specific application, the various layers can be defined leading to predict the output specifications for any given input data.

## III. Use of AI in SNs

Figure 6 shows the general structure of a single satellite. It includes the satellite body, solar panel and deployable antenna system. A SN consists of tens/hundreds of single satellites, that can communicate one withe the other(s). Hence for these complex structures, advanced solutions and optimizations are required considerably. Typically, AI provides a pathway to follow the process such as: orbital speed, and inter-satellite links among others. Additionally, these methods facilitate the analysis of various created behavior with modeling the effects on the networks. This section devotes to present a comprehensive overview around the various up-to-date literature that introduce the use of AI in satellite systems and network.

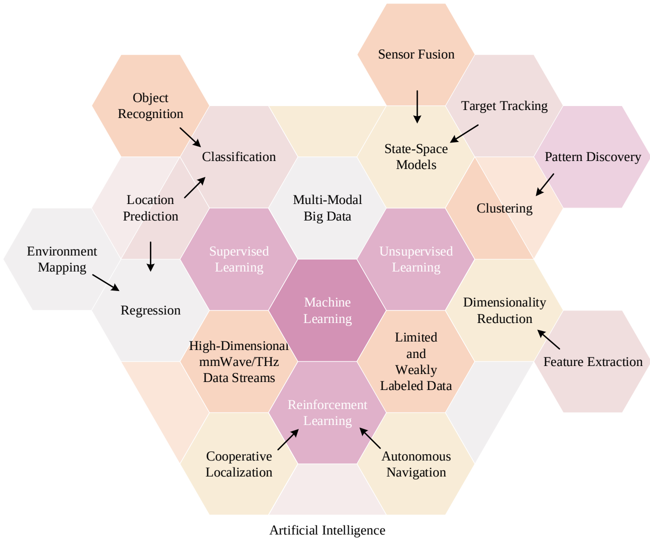


Fig. 4. AI-based methods used for the localization and sensing solutions [9].

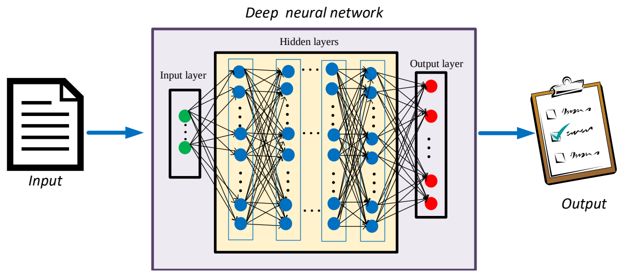


Fig. 5. Structure of DNN.

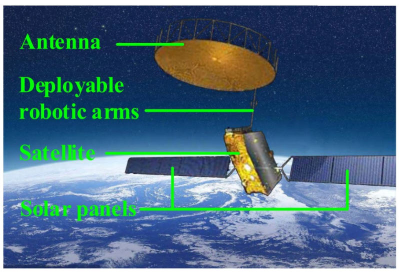


Fig. 6. A summary of the spacecraft includes various structures [10].

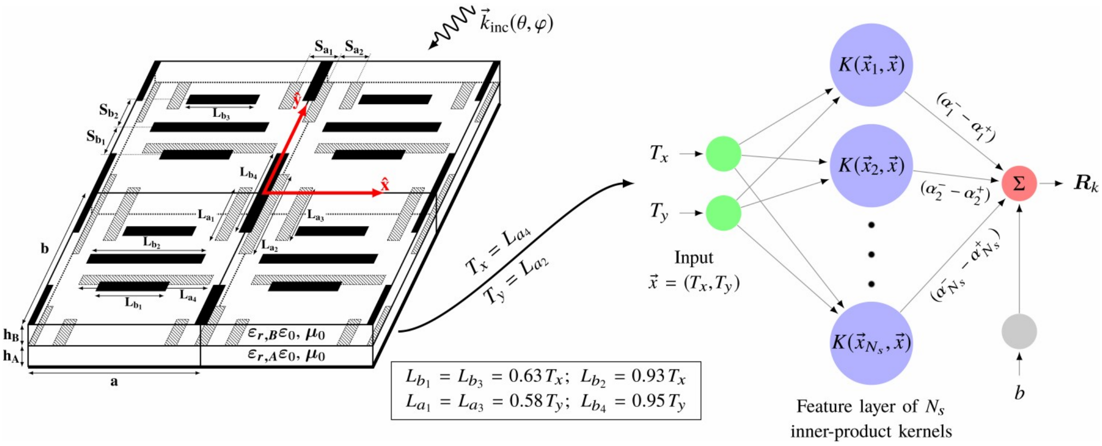


Fig. 7. Representation of the reflectarray unit cell; Tx and Ty are the lengths of the dipoles [11].

In [6], the AI technique is employed for realizing next generation massive low earth orbit (LEO) satellite networks [12]. The AI can be used for predicting the highly dynamic radio channel, spectrum sensing and classification, signal detection and demodulation, inter-satellite link and satellite access network optimization, and network security. In another study as [13], the role of ML in rate-splitting multiple access (RSMA) is studied consistentely in which RSMA plays an important role in next generation communication systems. In this work, the ML technique is used at the transmitter of RSMA for optimizing the resource allocation, power allocation, task offloading, and beamforming design.

Figure 7 presents the general structure of a reflectarray unit cell with the support vector machines (SVMs) leading to predict the electromagnetic response of the unit cell as the output specification. Also, in [14] the SVMs are used for designing and optimizing of reflectarray antennas that the presented methodology leads to accelerate the computing time. This acceleration factor is function of the required resolution of the far field response.

In [15], a channel model which is a data-driven one is presented leading to predict the channel attenuation at any specific time. The accuracy of the model is calculated by the cumulative density function. In summary, the channel model for atmospheric information estimation is executed.

Beam hopping (BH) is another important aspect in future multi-beam satellite systems that is dealing with the time-varying traffic requests. In [16], the combination of ML with the optimization is employed for providing the optimal solution leading to accelerate the process of identifying suitable BH patterns. Figure 8 presents the procedure of data generation with the satellite system parameters as the input data.

A two-stage ML technique is used in [17] that is the combination of self-supervised learning and deep reinforcement learning to be used in high-throughput satellite communication systems. In the first phase, the traffic demand matching through demand awareness is executed, and afterwards the

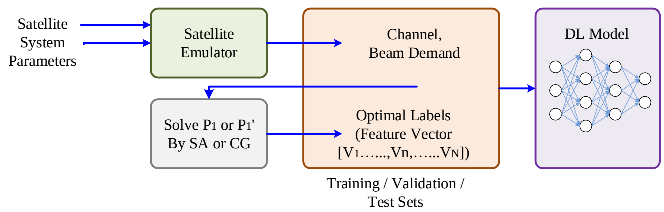


Fig. 8. A general flowchart for data generation to be used in ML technique [16].

system capacity via interference coordination is enhanced. By the presented method, spectrum efficiency and demand satisfaction is improved.

The ML method is also proved its efficiency in the places with the dust and sand storms. These environmental concepts can make a fundamental drawback for signal attenuation. For this case, a study as one in [18] presents the application of ML for estimating the microwave signal attenuation. In [19], an adaptive design is presented that can be beneficial in various applications such as Terahertz communication, and space-air-ground integrated networks where ML technique is estimating and making decision for the near-instantaneously adaptive mode of operation.

## IV. Conclusion

This short paper presents a review on the ML method used in combination with satellite systems and discusses the incorporation of AI and ML methodologies in the process of developing satellite networks for 6G communications. The manuscript starts with a brief overview on the general structure of AI, focusing on the definitions and visions of ML method. Next, the use cases of ML for the 3-D satellite systems and networks are presented in detail that are reported in the very recently published papers. By reviewing recent works, it can be observed that one of the most important steps towards achieving high-dimensional autonomous networks, that can sustain worldwide connectivity, is the integration of ML techniques into satellite networks. This strategy is in line with the direction that research in telecommunications is currently taking, which is towards using intelligent systems for optimization, decision-making, and handling the complexity that comes with next-generation networks. Reader by considering this review can identify links to recent works written in the subject of satellite and AI. Hence, various employed methodologies for SNs can be accessed faster and will facilitate the future work studies in this domain.

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