Massive MIMO System using Channel Estimation and Machine Learning Technique: A Review

Sunil Kumar[1], Prof. Suresh S. Gawande[2]
M. Tech. Scholar, Department of Electronics and Communication, Bhabha Engineering Research Institute, Bhopal[1]
Guide, Department of Electronics and Communication, Bhabha Engineering Research Institute, Bhopal[2]

Abstract: - Next-generation smart air interface solution for wireless local area network is mixture of MIMO-OFDM (Multiple-input multiple-output) with (Orthogonal frequency division multiplexing). To discuss and predict the use of machine learning and deep learning based on MIMO communications, channel estimation, signal detection and selection in OFDM systems. Massive Multiple-Input Multiple-Output (MIMO) technology is a fundamental enabler of next-generation wireless networks, offering significant improvements in spectral efficiency, energy efficiency, and network capacity. However, accurate channel estimation remains a critical challenge due to the large number of antennas and dynamic wireless environments. Traditional channel estimation techniques, such as Least Squares (LS) and Minimum Mean Square Error (MMSE), often suffer from high computational complexity and performance degradation in low-SNR conditions. To address these limitations, machine learning (ML)-based approaches have emerged as a promising solution, leveraging data-driven models to enhance channel estimation accuracy and adaptability.

Keywords: - MIMO, OFDM, Machine Learning (ML)

I. INTRODUCTION

In recent years, Internet usage has increased in leaps and bounds and has billions of users. Internet usages like VOD-Video on Demand, E-Mail, Browsing, Contacts etc. Demand high speed Internet that leads to a need for broadband adoption. At the same time, cellular systems have made it possible for people to stay connected with the world from almost anywhere, resulting in a concept while On The Move. With the increase in users and their demands, the broadband market continues to grow, which in turn leads to development of new technologies like Wimax [1], LTE, LTE-advanced for broadband wireless. These technologies provide usage flexibility, high throughput and more coverage. Wireless channel [2] is the main barrier for these new technologies. It causes impairments like noise addition, interference, multipath fading effects etc. in the transmitted signal. This demands very complex algorithms in the wireless receiver to overcome these impairments. Previous technologies like GSM [3] use FDM (Frequency Division Multiplexing), while CDMA uses orthogonal codes and spread spectrum to overcome channel impairments. These systems have their own limitations. For example, FDM requires guard band for separation to overcome interference between two consecutive users. Similarly, CDMA [4] needs to generate orthogonal sequences with zero correlation which is difficult to achieve if the number of users increases indefinitely. This leads to OFDM [5] (Orthogonal Frequency Division Multiplexing). The concept is equivalent to dividing the channel frequency response into smaller orthogonal sub-bands. Since each adjacent frequency is orthogonal to each other, it eliminates the need of guard band for separation. Simultaneously, OFDM divides high data rate signal into multiple small data rate signals. Moreover, it can be implemented by simple FFT/IFFT techniques, leading to ease in implementation.

First-Generation Systems (1G):- In 1970, 1G (First generation) was introduced for voice communication. 1G was an analog system with frequency modulation technique for radio transmission using Frequency Division Multiple Access (FDMA). 1G system was Advanced Mobile Phone System (AMPS), Total Access Communication Systems (TACS) and Nordic Mobile Telephone (NMT). In North America, two 25 MHz bands were allocated to AMPS, one for downlink transmission from the base station to the mobile unit (869- 894 MHz) and the other for uplink transmission from the mobile to the base station (824-849 MHz) [5].
In 1985, the Federal Communications Commission (FCC) enabled the commercial development of wireless LANs (WLAN) by authorizing the public use of the Industrial, Scientific, and Medical (ISM) frequency bands for wireless LAN products.

Second Generation Systems (2G):- The 2nd generation system was accomplished in 1990's. The 2G mobile communication system is a digital system. Today in different parts of the world, it is used for voice communication and other services such as SMS and e-mail. In this generation Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) are used with frequency band 850-1900 MHz. Also in this age, GSM technology uses eight channels per carrier with a gross data rate of 22.8 kbps (a net rate of 13 kbps) in full rate channel and a frame of 4.6 milliseconds (ms) duration. The 2.5G and 2.75G are enhancement of this generation. 2G standards are GPRS, Enhanced Data Services for GSM Evolution (EDGE), Interim Standard (IS) as IS-54 and IS-136 systems currently provide data rates of 40-60 Kbps. The IS-95 systems support higher data using a time-division technique called High Data Rate (HDR) [6].

Third Generation Systems (3G):- Third generation (3G) services combine high speed mobile access with Internet Protocol (IP)-based services. The 3G technology supports both for packet and circuit switched data transmission which is compatible to 2G. The 3G technology includes the services such as wireless web base access, email, video conferencing and multimedia services. The 3G devices may share the same wireless network and be connected to internet anytime, anywhere. 3G provides different data rates from 384 kbps for pedestrian use, 144 kbps for vehicular use and 2 Mbps for indoor office use depending on mobility and environment. The frequency band is 1.8 - 2.5 GHz [7]. Different versions of wireless LAN (WLAN) standards exist in the 2.4 GHz and 5 GHz bands [8].

Fourth Generation Systems (4G):- 4G is an enhanced version of 2G and 3G. Recently 3GPP (third Generation Project Partner) has introduced LTE Advanced version as 4G standard. A 4G system provides a comprehensive and secure IP based services. 4G gives the facilities such as voice, streamed multimedia and data to users at anytime, anywhere with much higher data rates than earlier generations. 4G can provide larger demanding requirements in terms of QoS. 4G applications are wireless broadband access, video chat, Multimedia Messaging Service (MMS), mobile TV, HDTV and Digital Video Broadcasting (DVB) etc. The 4G wireless system is for Global and seamless roaming between different wireless systems, hot spots and pedestrian environments data rate 100M~1Gbps, vehicular environments rate up to 100 Mbps and high spectrum efficiency. MIMO technology is used in 4G to get high data rate and reliability [9].

Fifth Generation System (5G)

5G networks are digital cellular networks, in which the service area covered by providers is divided into small geographical areas called *cells*. Analog signals representing sounds and images are digitized in the phone, converted by an analog to digital converter and transmitted as a stream of bits. All the 5G wireless devices in a cell communicate by radio waves with a local antenna array and low power automated transceiver (transmitter and receiver) in the cell, over frequency channels assigned by the transceiver from a pool of frequencies which are reused in other cells. The local antennas are connected with the telephone network and the Internet by a high bandwidth optical fiber or wireless backhaul connection. As in other cell networks, a mobile device crossing from one cell to another is automatically "handed off" seamlessly to the new cell [10].

There are plans to use millimeter waves for 5G. Millimeter waves have shorter range than microwaves, therefore the cells are limited to smaller size; The waves also have trouble passing through building walls. Millimeter wave antennas are smaller than the large antennas used in previous cellular networks. They are only a few inches (several centimeters) long. Another technique used for increasing the data rate is massive MIMO (multiple-input multiple-output). Each cell will have multiple antennas communicating with the wireless device, received by multiple antennas in the device, thus multiple bit streams of data will be transmitted simultaneously, in parallel. In a technique called beamforming the base station computer will continuously calculate the best route for radio waves to reach each wireless device, and will organize multiple antennas to work together as phased arrays to create beams of millimeter waves to reach the device.

The new 5G wireless devices also have 4G LTE capability, as the new networks use 4G for initially establishing the connection with the cell, as well as in locations where 5G access is not available [11].

II. MIMO TECHNOLOGY

The framework which has one antenna at input and single antenna at destination may be supposed as SISO framework in the arena of communication. This endures a few issues of capacity, as a result of technologist Shannon Nyquist rule. The current day telecommunication framework requirements enhanced quality, more prominent system and higher data rate. Keeping in mind to achieve exceptional demand, its data transfer capacity and power of transfer should be expanded. Advancements In current day technology demonstrate that utilization of MIMO framework in inaccessible communication enhance the capacity without increase in bandwidth and transfer power. To improve the capacity of framework signal with multiple paths is employed. Now in wireless communication, MIMO has become an essential element and includes:

1) Long Term Evolution (4G)
2) WIMAX (4G)
3) HSPA+ (3G)
4) IEEE 802.11ac

Digital communication utilizing numerous input output antennas has been viewed as a standout amongst the foremost specialized breakthrough current communications. Before the explaining of ―Why MIMO System‖, it is important to quickly deliberate the meaning of MIMO. MIMO stances for multiple inputs and multiple output system. A method where signals are transmitted by means of numerous antennas rather than just one antenna as in FDM. Like several different communication systems, MIMO-OFDM system has

numerous elements of antennas at the input and destination.
Mathematically MIMO system can be represented as:

$$Y(t) = X(t) * H(t) + n(t) \quad (1)$$

In this equation
Y (t) =signal at the destination
H (t) =matrix of channel
X (t) = signal at the input signal
n (t)=noise

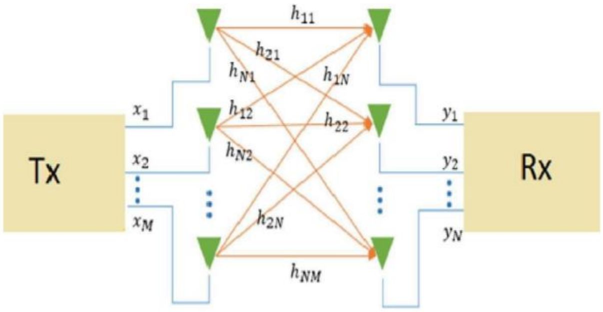

Figure 1: General Concept of MIMO

III. LITERATURE REVIEW

Han Jin Park et al. [1], in order to achieve a high error correcting capability with a fast convergence speed of the iterative JDD process using a low-complexity detection, we design a multi-user massive MIMO system with LDPC coding. Low-complexity linear detection algorithms include Minimum MMSE-PIC and its variants. We formulate updating rules for messages flowing in the JDD process and provide a factor graph representation of an LDPC coded multi-user massive MIMO system using the JDD algorithm with MMSE-PIC detection. We suggest a useful and effective tool for examining the eEXIT properties of messages sent back and forth between the detector and the decoder. This tool serves as the foundation for the joint design of LDPC codes and JDD strategy, which produces a low BER and a quick convergence speed of the JDD mechanism. It is found that the suggested analysis tool's predicted JDD convergence behavior and error correcting capability closely match the simulations' actual results. Additionally, it is noted that a multi-user massive MIMO system with LDPC codes and a JDD strategy optimally designed by the suggested EXIT analysis tool achieves a lower BER with a faster rate of convergence.

B. Cheng et al. [2], in this letter, the minimum mean-square error parallel interference cancellation (MMSE-PIC) algorithm is proposed for an iterative multiple-input multiple-output (MIMO) receiver for polar-coded systems. In order to lower the computational complexity of MMSE-PIC without sacrificing performance, we also suggest a novel type of tree-structured Gray codes. According to simulation results, the iterative detection and decoding (IDD) scheme with various decoding algorithms performs better than the separate detection and decoding (SDD) scheme for a 64 × 4 MIMO system by 0.35 ~ 0.58 dB at a frame error rate (FER) of 10−3 when there are four iterations.

Y. Chi et al. [3], the primary focus of traditional multi-user multiple-input multiple-output (MU-MIMO) was on independent and identically distributed (IID) channels, Gaussian signaling, and a small user count. The diverse needs of next-generation wireless communications, including diverse transmission data, complex communication scenarios, and previously unheard-of levels of user access, will be difficult to handle. The generalized MU-MIMO (GMU-MIMO) system is thus studied in this paper under more general and practical constraints, such as non-Gaussian signaling, practical channel coding, right-unitarily-invariant channels (including Rayleigh fading channel matrices, some ill-conditioned and correlated channel matrices, etc.), massive users, and antennas. These broad presumptions present fresh theoretical and practical difficulties. For instance, GMU-MIMO lacks an accurate constrained capacity region analysis. Furthermore, it is unclear how to combine practical complexity with constrained-capacity-optimal performance. In order to overcome these difficulties, a unified framework that takes into account encoding, modulation, detection, and decoding simultaneously is proposed in order to determine the constrained capacity region of GMU-MIMO and design a constrained-capacity-optimal transceiver. In order to group users based on their rates, group asymmetry is created, which trades off implementation complexity and user rate allocation. In particular, the relationship between mutual information and MMSE, as well as the minimum mean-square error (MMSE) optimality of orthogonal/vector approximate message passing (OAMP/VAMP), are used to characterize the constrained capacity region of group-asymmetric GMU-MIMO.

Q. Liu et al. [4], a high dimensional multiple input multiple output (MIMO) scheme with partial mapping for high order modulation that is non-binary LDPC coded is proposed in this work. When M-ary QAM is used in the suggested scheme, partial mapping is done using a non-binary LDPC code built over a Galois field of order M−−√, where M−−√ is an integer. A detection algorithm based on real-valued expectation propagation (REP) is employed at the receiver end. Additionally, the concatenated non-binary LDPC code is optimized using an iterative optimization algorithm based on the symbol-wise extrinsic information transfer (SEXIT) chart. A streamlined approach that can eliminate a significant number of simulations is suggested for calculating the massive MIMO detector's component EXIT chart. Results from numerical simulations show that the aforementioned concept is valid.

T. V. Nguyen et al. [5], due to the numerous high-resolution, power-hungry analog-to-digital converters (ADCs) at the receiver side, large-scale multiple-input multiple-output (LS-MIMO), a promising technology for future wireless networks to increase the network capacity, inevitably faces hardware cost and power consumption issues. It has recently been demonstrated that low-resolution ADCs are a useful way to reduce system costs. The purpose of this paper is to examine LS-MIMO communication systems that use three-level ADCs, also known as Ternary ADCs (T-ADCs), to improve energy efficiency in specific LS-MIMO configurations. The uniform scalar quantizer of the T-ADCs has a truncation limit that is optimized to minimize quantization distortion on the LS-MIMO received signal. As a result, its performance is comparable to that of the well-known Lloyd-Max algorithm, but it has better robustness and less complexity.

Giordani M. et al. [6], reliable data connectivity is vital for the ever increasingly intelligent, automated, and ubiquitous digital world. Mobile networks are the data highways and, in a fully connected, intelligent digital world, will need to connect everything, including people to vehicles, sensors, data, cloud resources, and even robotic agents. Fifth generation (5G) wireless networks, which are currently being deployed, offer significant advances beyond LTE, but may be unable to meet the full connectivity demands of the future digital society. Therefore, this article discusses technologies that will evolve wireless networks toward a sixth generation (6G) and which we consider as enablers for several potential 6G use cases. We provide a fullstack, system-level perspective on 6G scenarios and requirements, and select 6G technologies that can satisfy them either by improving the 5G design or by introducing completely new communication paradigms.

Malik et al. [7], device to Device and Cooperative communication are the two new emerging technologies in the new era of communication technology which differ from the existing cellular technology. In review article we have enlisted different technologies which play a very important role in third Generation Partnership Project (3GPP). In this paper we have studied the various techniques of resource allocation, Mode selection for underlay communications in terms of device to device and cooperative communication techniques in terms of Long Term Evolution and Long Term Evolution-Advanced platform. A new technique LTE-Advanced Pro has also been introduced by 3GPP. Various simulators including Vienna LTE-Advanced have also been discussed. Better utilization of the spectrum is also depicts which is done on the basis of analysis if proper resource allocation whether it is power, frequency or time and mode selection is done in the programmed manner which would result in the reduction of interference and it will also lead to the secure system.

C. Chen et al. [8], beamforming with antenna arrays has been considered as an enabling technology in future wireless communication systems. To conduct beamforming, one has to know the angle-of-departure (AoD) or angle-of-arrival (AoA). For data detection, the receiver also has to know channel response. In this paper, we propose a new joint AoD, AoA, and channel estimation scheme for pilot-assisted multiple-input-multiple-output-orthogonal-frequency-division-multiplexing (MIMO-OFDM) systems. First, a compressive-sensing technique is employed to estimate the channel impulse response, exploiting the sparsity property of wireless channels. Then, AoA and AoD are jointly estimated for each detected path by the maximum likelihood method. The Cramér-Rao lower bound (CRLB) is also derived and a transmit beamforming scheme is proposed accordingly. In the scenario of available prior information, a maximum a posteriori estimation is proposed. The Bayesian CRLB (BCRLB) for the problem is also derived and a transmit beamforming scheme is further proposed. It turns out that only two training OFDM symbols are required for the estimation. Simulation results show that the proposed methods can approach the CRLB/BCRLB in both scenarios and achieve the same spectral efficiency as that obtained with the ideal channel in millimeter-wave communications.

Chakraborty R. et al. [9], the benefits and advantages of using millimeter wave (mm wave) draws its attention towards the 5G, cellular and other wireless communication applications. In this case, the carrier arise from the potential for larger bandwidths as compared to lower carrier frequency beam forming and equalization. The wireless networks are recommended as a complement for mobile network because of their scalability and implementation ease as like creating the hotspot on the basis of MIMO antennas. the 5G mobile communication network is used for the presentation of distribution on network architecture. This paper gives us a brief review on the mm waves of mobile networks as well as its implications on 5G. The high directivity and prone to noise makes mm waves best suitable for 5G and other wireless communication techniques. Further, the generation of these waves along with the hardware designs are less complex and reliable as compared with micro waves communication.

Supraja Eduru et al. [10], in gigantic Multiple Input Multiple Output (MIMO) frameworks, spatial connection is one of the components, which essentially influences the bit mistake rate (BER) execution. Along these lines, in this paper, direct discovery is utilized with various deterioration procedures to improve the exhibition. At a BER of 10-3, with Zero Forcing (ZF) utilizing Singular Value Decomposition (SVD), the channel gain is multiplied by multiplying the request for the MIMO framework when contrasted with Cholesky and QR decay. Further, the BER stays unaltered for Minimum Mean Square Error (MMSE) discovery independent of the sort of deterioration systems utilized. In any case, it is additionally seen that for 32×32 MIMO framework, at a BER of 10-3, MMSE gives about 10 dB to 15 dB channel gain when contrasted with ZF.

IV. MACHINE LEARNING

Uproarious information is available in the heap of substance that will be identified through the anomaly strategies. The information can be spatial or can be a transient method spatial connected with the geological conditions and worldly connected with the time perspectives [14, 15]. The principle point of exception identification is to deal with the loud information that is introduced in the heap of text. Different methods for recognizing abnormalities in Text are specified in below:

Learning

The main property of an ML is its capability to learn. Learning or preparing is a procedure by methods for which a neural system adjusts to a boost by making legitimate parameter modifications, bringing about the generation of wanted reaction. Learning in an ML is chiefly ordered into two classes as [16].

- Supervised learning
- Unsupervised learning

Supervised Learning

Regulated learning is two stage forms, in the initial step: a model is fabricated depicting a foreordained arrangement of information classes or ideas. The model developed by investigating database tuples portrayed by traits. Each tuple is expected to have a place with a predefined class, as dictated by one of the qualities, called to have a place with a reclassified class, as controlled by one of the traits called the class name characteristic. The information tuple are dissected to fabricate the model all things considered from the preparation dataset [17].

Unsupervised learning

It is the kind of learning in which the class mark of each preparation test isn't knows, and the number or set of classes to be scholarly may not be known ahead of time. The prerequisite for having a named reaction variable in preparing information from the administered learning system may not be fulfilled in a few circumstances.

Data mining field is a highly efficient techniques like association rule learning. Data mining performs the interesting machine-learning algorithms like inductive-rule learning with the construction of decision trees to development of large databases process. Data mining techniques are employed in large interesting organizations and data investigations. Many data mining approaches use classification related methods for identification of useful information from continuous data streams.

Nearest Neighbors Algorithm

The Nearest Neighbor (NN) rule differentiates the classification of unknown data point because of closest neighbor whose class is known. The nearest neighbor is calculated based on estimation of k that represents how many nearest neighbors are taken to characterize the data point class. It utilizes more than one closest neighbor to find out the class where the given data point belong termed as KNN. The data samples are required in memory at run time called as memory-based technique. The training points are allocated weights based on their distances from the sample data point. However, the computational complexity and memory requirements remained key issue. For addressing the memory utilization problem, size of data gets minimized. The repeated patterns without additional data are removed from the training data set [18].

Naive Bayes Classifier

Naive Bayes Classifier technique is functioned based on Bayesian theorem. The designed technique is used when dimensionality of input is high. Bayesian Classifier is used for computing the possible output depending on the input. It is feasible to add new raw data at runtime. A Naive Bayes classifier represents presence (or absence) of a feature (attribute) of class that is unrelated to presence (or absence) of any other feature when class variable is known. Naïve Bayesian Classification Algorithm was introduced by Shinde S.B and Amrit Priyadarshi (2015) that denotes statistical method and supervised learning method for classification. Naive Bayesian Algorithm is used to predict the heart disease. Raw hospital dataset is employed. After that, the data gets preprocessed and transformed. Finally by using the designed data mining algorithm, heart disease was predicted and accuracy was computed.

Support Vector Machine

SVM are used in many applications like medical, military for classification purpose. SVM are employed for classification, regression or ranking function. SVM depends on statistical learning theory and structural risk minimization principal. SVM determines the location of decision boundaries called hyper plane for optimal separation of classes as described in figure 3. Margin maximization through creating largest distance between separating hyper plane and instances on either side are employed to minimize upper bound on expected generalization error. Classification accuracy of SVM not depends on dimension of classified entities. The data analysis in SVM is based on convex quadratic programming. It is expensive as quadratic programming methods need large matrix operations and time consuming numerical computations.

V. CONCLUSION

Massive MIMO is a key technology for modern wireless communication systems, particularly in 5G and future 6G networks, due to its ability to enhance spectral and energy efficiency. However, accurate channel estimation remains a critical challenge due to factors such as pilot contamination, high computational complexity, and hardware constraints. Traditional channel estimation techniques, including Least Squares (LS) and Minimum Mean Square Error (MMSE), have been widely used but face limitations in complex and dynamic wireless environments.

Machine learning (ML)-based approaches have emerged as a promising solution to improve channel estimation by leveraging data-driven models that can adapt to varying channel conditions. This review analyzed different ML techniques, including deep learning, reinforcement learning, and hybrid methods, highlighting their advantages and challenges compared to conventional approaches. While ML-based estimation demonstrates significant performance gains in terms of accuracy and robustness, challenges such as training data availability, generalization across different scenarios, and hardware feasibility must be addressed.

Future research should focus on optimizing ML models for real-time deployment, reducing computational overhead, and integrating ML with emerging technologies like 6G, THz communications, and quantum computing. Additionally, explainable AI techniques could enhance the interpretability of ML-based channel estimation models, making them more practical for real-world applications.

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