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Comprehensive Study of Least Squares Estimation in Fast Fading MIMO-OFDM Systems

Pragya Choudhary[1],*, Sandeep Shukla[2]

Abstract

MIMO-OFDM technology is now the foundation for modern wireless communication systems, allowing dramatic improvements in spectral efficiency, power efficiency, and transmission rate. On the other hand, the least accurate channel estimation is still a critical task, especially when they are in fast-fading environments. This study gives a comprehensive survey of LSE-based approaches and their applications on different fast-fading channel models for MIMO-OFDM systems. Techniques like Pilot Assisted Channel Estimation (PACE), Decision Directed Channel Estimation (DDCE), and Data Aided Channel Estimation (DACE) are examined, their advantages and disadvantages, and to what extent these techniques can be suited for application in dynamic environments. Deep learning-based approaches, including Fully Connected Deep Neural Networks (FDNN) and Convolutional Neural Networks Auto Encoder (CNNAE), offer a transformative approach in raising estimation accuracy. Additionally, emerging trends like compressive sensing for sparse millimeter-wave channels and 6G technologies are explored. This study aims to bridge existing research gaps, offering a roadmap for future innovations in channel estimation techniques and their applications in next-generation wireless networks. The significance of Least Squares (LS) estimate in the context of MIMO-OFDM systems, particularly in fast-fading scenarios, is outlined in this study along with its goal of analyzing and contrasting LS estimation methods. An overview of MIMO-OFDM Systems provided a quick explanation of the technologies of MIMO and OFDM as well as their combined importance in contemporary systems for wireless communication. The impact of fast-fading pathways on signal reliability and the significance of precise channel estimates are discussed in it. Least Squares Estimation's function is to present LS estimation as a basic channel estimation method and highlight its applicability in preventing fast fading.

Keywords: MIMO-OFDM, channel estimation, least squares estimation (LSE), deep learning, fast-fading channels, 5G and 6G wireless networks

INTRODUCTION

MIMO-OFDM technology is a very high leap that optimizes time, frequency, and spatial dimensions, which increases substantial improvements in spectral efficiency, power efficiency, and transmission rate in communication systems. The technology plays a great role in wireless broadband communication systems. Precise channel state information (CSI) is very fundamental in employing the MIMO-OFDM fully and may be achieved through channel estimation [1]. The important question, regardless of the method used for channel estimation, is how to improve the accuracy of channel estimation based on a fixed number of pilots in MIMO-OFDM

***Author for Correspondence**
Pragya Choudhary
E-mail: pragyakumari0311@gmail.com

[1]M.Tech Scholar, Department of Digital Communications, Technocrats Institute of Technology, Bhopal, Madhya Pradesh, India
[2]Assistant Professor, Department of Electronics and Communication Engineering, Technocrats Institute of Technology, Bhopal, Madhya Pradesh, India

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systems. To address this, several studies have been carried out and it has been established that the data-aided channel estimation techniques give better performances for the system. In these techniques, data carriers that are less affected by the wireless channel are reliably detected and used as virtual pilots. The addition of reliable data carriers with pilots enhances the spectral efficiency of MIMO-OFDM systems [2]. Conventional MIMO-OFDM is also infamous for its poor performance in terms of out-of-band radiation power leakage, which reduces the system's multipath propagation and spectral efficiency. Therefore, a filtered OFDM with MIMO system is suggested to get around the drawbacks of the traditional approach. MIMO F-OFDM can correct out-of-band radiation power loss and decrease spectrum efficiency [3].

Cognitive radio networks are now more significant to the effective management of available spectrum resources, with reduced interference between neighboring users, according to the IEEE 802.22 standard. Other users may be able to use the available communication resources because CR has the power to modify its specifications.

However, one of the features that SDR offers as a novel architecture idea is CR [4]. Simply said, OFDM is an MCM technique that divides a high-rate data stream into streams with lower rates. They all need a lot less bandwidth than the channel's coherence bandwidth. Because of this, data in OFDM is naturally resistant to frequency-selective fading.

Furthermore, fourth generation (4G) and fifth generation (5G) mobile networks will likewise primarily rely on OFDM to provide end users with high-speed data access because to the minimal complexity of OFDM systems. In 4G, OFDM-based LTE wireless systems have been deployed, offering balanced Quality of Service (QoS), fair scheduling, and several traffic kinds. Good QoS delivery is provided by LTE for specific traffic classes.

The use of QoS balancing scheduling rules in an LTE downlink has also been suggested to deliver high-quality QoS for various traffic classes [5]. Natural language processing (NLP) has recently brought DL into wireless communication because of its successful uses in computer vision (CV). The DL-based approaches are capable of learning time-varying CSI patterns in data-driven ways without assuming anything about the channel models. Numerous effective prediction techniques have been developed when channel prediction is seen as a time series problem [6].

OVERVIEW OF FAST FADING CHANNEL MODELS

The section identifies the basic characteristics of MU-MIMO technology, building on its structure and application in wireless communication systems. Multiuser MIMO allows for simultaneous communication between multiple transmitters and receivers, enhancing the system capacity and spectral efficiency of the network. Figure 1 describes the architecture of MU-MIMO technology in two key scenarios:

1. *Uplink:* Multiple user devices send signals to the central base station with an array of antennas. Spatial multiplexing and advanced signal processing are used to separate signals from one user. End.
2. *Downlink:* A base station equipped with multiple antennas sends information to many different user devices in parallel. Beam forming techniques are utilized to steer the signal energy to the target users while minimizing interference.

Figure 1 also illustrates the bidirectional characteristic of MU-MIMO, stressing the dynamic nature of interactions between the DoAs at the receiving end and DoDs at the transmitting end. These properties, combined with spatially selective characteristics of frequency-selective channels, are a basis for models and optimal designs of the MU-MIMO system. The finite scatterers and the clustering of MPCs in delay as well as in space add further complexity and relevance to the system. In addition, the ability of the technology to adapt to various types of diverse network demands makes it the cornerstone of modern communication systems, especially in 5G and beyond [7].

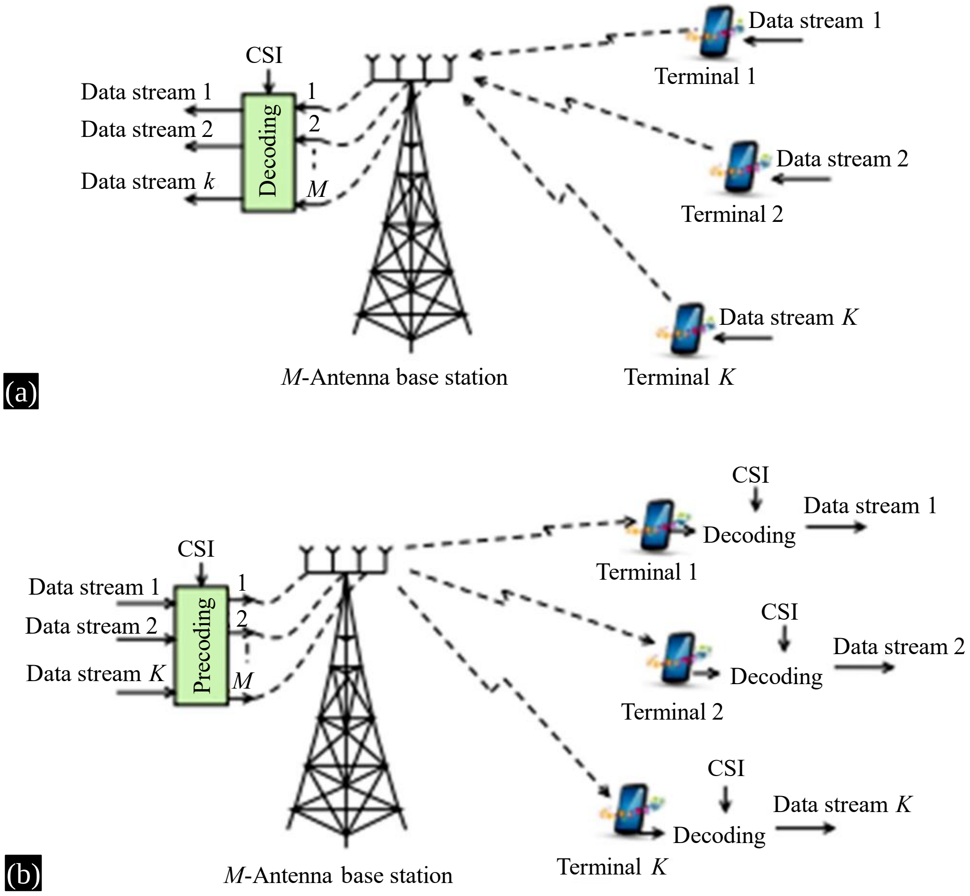

Figure 1. Illustration of multiuser MIMO technology: (a) uplink and (b) downlink [7].

CHANNEL ESTIMATION IN MIMO–OFDM SYSTEMS

In any wireless network, channel estimate is a crucial and common operation that is necessary for performance, dependability, and security assurance. For example, decoding, beam shaping, signal detection, interference reduction, security and privacy improvements, and many more uses in a BackCom network require the reader's channel state information (CSI). Pilot-based, blind, or semi-blind CSI estimators can satisfy these requirements [8].

Pilot Assisted

PACE, often referred to as the training-based channel estimation technique, multiplexes the sent data symbols at a predefined position with the receiver's known data prior to transmission. The PACE approaches provide improved performance in terms of the system's spectrum efficiency by using an optimal space between the pilot and data symbols [2].

Decision Directed

One type of blind channel estimating technique is called decision directed channel estimation (DDCE), which tracks the time-varying channel using an iterative algorithm after using the preamble signal to obtain the initialized channel estimation. DDCE has a higher bandwidth usage than the pilot-based channel estimate approach because it does not require additional bandwidth, except for the preamble signal, which is insignificant when compared to the entire amount of broadcast information [9].

Data Aided

To get over the drawbacks of PACE methods, data-aided channel estimating schemes have been created. Comparative Table of PACE, DDCE, DACE has been shown in Table 1. Because PACE schemes only use pilot symbols, the wireless systems' spectrum efficiency is decreased. On the other hand, DACE

Table 1. Comparative table of PACE, DDCE, DACE.

Technique	Description	Advantages	Limitations
Pilot Assisted Channel Estimation (PACE)	Known data (pilots) are multiplexed with transmitted symbols; optimized spacing improves spectral efficiency.	Improved spectral efficiency with optimized pilot placement.	Relies solely on pilot symbols, reducing spectral efficiency.
Decision Directed Channel Estimation (DDCE)	Uses preamble signal for initial estimation and iterative algorithms for tracking; requires negligible extra bandwidth.	Higher bandwidth utilization; no extra bandwidth except negligible preamble signal.	Initial estimation depends on preamble signal accuracy.
Data Aided Channel Estimation (DACE)	Utilizes both pilot and decoded data symbols for adaptive refinement; achieves better accuracy and spectral efficiency.	More robust in dynamic environments; better MSE and BER performance.	Higher complexity due to adaptive refinement processes.

methods maintain higher spectrum efficiency while improving channel estimation accuracy by using both pilots and decoded data symbols. Because they use information from decoded data to adaptively refine channel estimations, they are more resilient in dynamic settings. Better bit-error rate (BER) and MSE performance results from this [10].

CHANNEL ESTIMATION BASED ON DEEP LEARNING

Coherent detection in wireless communications systems necessitates an understanding of the propagation channels between the transmitter and the receiver, which can be estimated using standard estimation methods.

Fully Connected Deep Neural Network-Based Channel Estimation

Figure 2 shows the structure of the suggested FDNN-based channel estimate. The input layer, hidden layers, and output layer are among the layers that make up the suggested FDNN structure, as seen in this Figure 2. Keep in mind that an FDNN may contain many hidden levels. The suggested FDNN structure, on the other hand, is made with three hidden layers that contain several neurons for the MIMO-OFDM system under consideration. Specifically, the following computation is carried out by a neuron, a processing unit:

$$0 = \mathrm{f}(\mathrm{z}) = \mathrm{f}\left(\sum_{\mathrm{i}=1}^{\mathrm{M}} \mathrm{w}_{\mathrm{i}} \mathrm{x}_{\mathrm{i}} + \mathrm{b}\right) \tag{1}$$

Where, M is the number of inputs to the neuron for which x_i is the i-th input (i=1, …, M); wi is the i-th weight corresponding to the i-th input; b is a bias; and o is the output of this neuron.

$$f(z) = \frac{e^{z}-e^{-z}}{e^{z}+e^{-z}}, \tag{2}$$

Where Euler's number is denoted by e. The FDNN-based channel estimation is utilized to learn the actual channel information supplied by the channel estimations derived from the LS estimation as the input to minimize the mean square error [11].

Convolutional Neural Network Auto Encoder (CNNAE) Channel Estimation

The CNNAE estimator is seen as a perfect substitute for solving channel estimate issues in the wireless communication systems depicted in Figure 3. In particular, the CNNAE estimator can be considered a suitable model for the channel estimation of interference-corrupted and inappropriate systems due to its effective learning properties and applicability [12].

VARIOUS FADING CHANNELS

Quadrature Phase Shift Keying (QPSK)

The QPSK method modulates two bits at the same time, selectively shifting a carrier to one of four possible planes (0, 90, 180, 270°). Signals carrying QPSK information use the same bandwidth as traditional PSK signals. Video transmissions over satellites, cable modems, videoconferences, cellular phones and other digital communication over radio waves are all done in QPSK. In comparison with

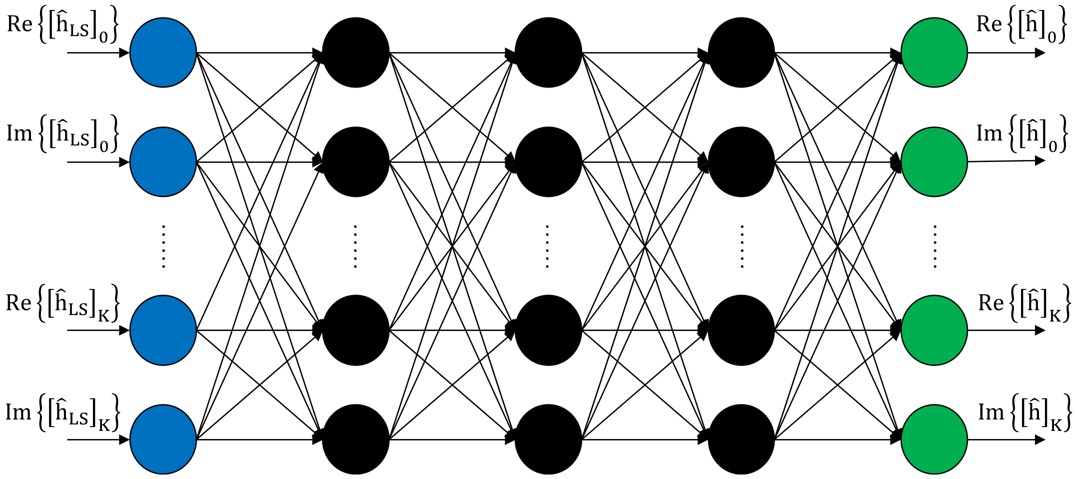

Figure 2. FDNN-based channel estimation [11].

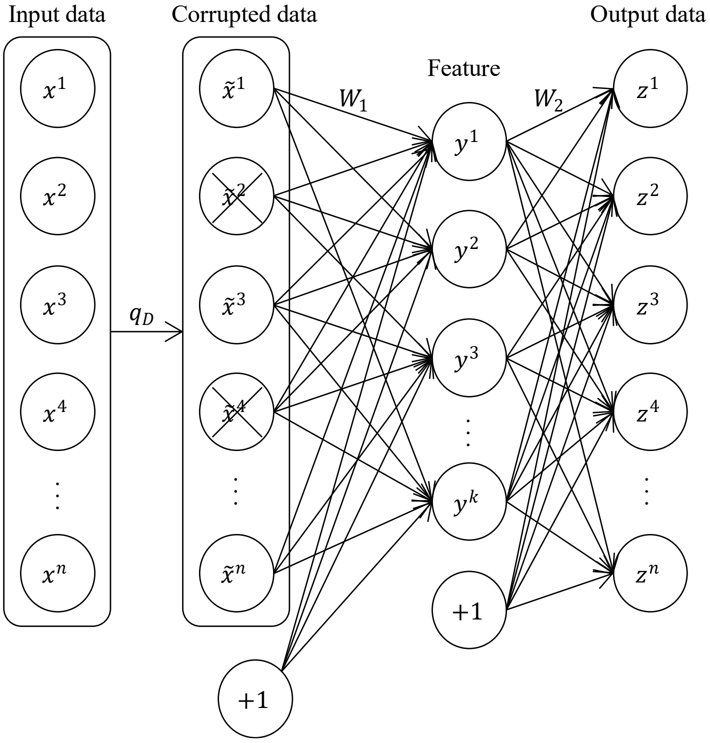

Figure 3. Illustration of a single-layer CNNAE [12].

BPSK modulation, this modulation scheme doubles the data rate while maintaining the same bandwidth. BPSK has the advantage of being simple, while QPSK requires the use of more complicated transmitters and receivers. Figure 4 shows 1-channel and q-channel data. QPSK is defined by the equation:

$$S_k(t) = \sqrt{\frac{2e_b}{T_b}} \cos\left[2\pi f_c t + \frac{(2k-1)\pi}{4}\right]; k = 0,1,2,3 \quad (3)$$

Quadrature Amplitude Modulation (QAM)

In QAM, two amplitude modulated carriers are in phase with one another at a 90° angle. Phase changes combined with amplitude adjustments increase information transmission efficiency. It can transport larger data rates than traditional time/amplitude modulated methods. The number of locations at which the signal can rest roughly during transmission is known as the N point constellation, as the modulation format shows [13].

MIMO-OFDM SYSTEMS

For wireless frameworks, MIMO has been developed for a long time. In the 1980s, Bell Laboratories' Jack Winters and Jack Saltz made some of the first advancements in MIMO technology for wireless communications. They attempted to use several receiving wires on both the transmitter and the beneficiary to send data from various customers on a comparable recurrence/time channel. Since then, a few academicians and engineers have also accomplished outstanding work in the field of MIMO. The prospective uses of MIMO technology for digital TV, wireless LANs, metro organizations, and mobile communications have currently attracted attention.

The MIMO system employs numerous antennas, as depicted in Figure 5, in both the transmitter and the receiver to enhance communication system performance through multiplexing and other technologies. More spectrum potency, increased responsibility, weakening reduction, and excellent interference resistance are all provided by the MIMO system [14].

In wireless broadband systems, orthogonal frequency division multiplexing, or OFDM, has been widely utilized. For coherent OFDM systems, channel estimation is essential and has been studied in great detail. The subcarriers carrying pilot signals are multiplexed with the data subcarriers in systems that employ pilot-aided channel estimation. Least-squares (LS) estimation is frequently used to acquire initial channel estimates at pilot subcarriers. Then, interpolation procedures are utilized to generate the channel responses at data subcarriers. Although there are other interpolation techniques available, the minimum mean-square error (MMSE) interpolation method is very popular because of its exceptional performance [15].

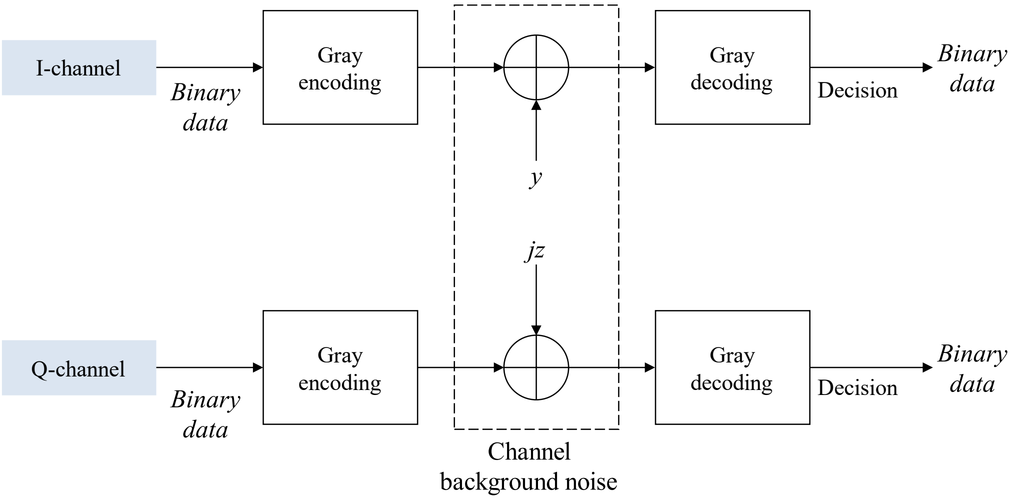

Figure 4. QPSK system model [13].

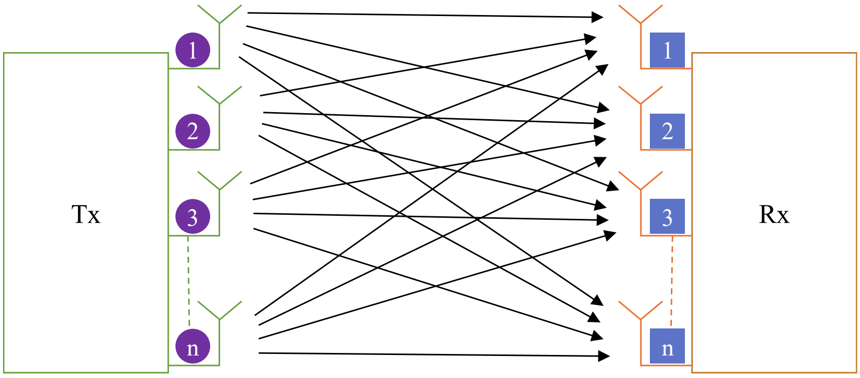

Figure 5. Structure of MIMO System [14].

MILLIMETER WAVE AND TERAHERTZ COMMUNICATIONS

6G mobile communications will make it possible to make significant progress in a variety of scientific fields, including brain-computer connections and emotions. The ability to see, identify, and think will enable intelligent agents to completely replace conventional intelligent equipment. Human-like interactions with emotions and mutual understanding will replace the current user-tool relationship between humans and intelligent agents. Through conversations and facial expressions, these intelligent agents will be able to discern users' psychological and emotional situations and assist them in reducing health risks. Mind-controllable devices that facilitate lossless brain information transfer will be made available to assist people with disabilities in overcoming physical challenges in their daily lives and at work, as well as in rapidly gaining knowledge and skills.

6G will provide ultrahigh data rates by utilizing all spectrum up to THz or even visible light. Additional spectrum resources are needed to support ultra-immersive applications like holographic communication and immersive XR, which demand extremely high data rates (up to tens of Tbps). In order to enable exceptional data-hungry and delay-sensitive services and applications that demand high-resolution sensing, new spectra of up to THz and optical bands would be thoroughly investigated and utilized in addition to sub-6 GHz and millimeter Wave [16].

For 5G and beyond 5G communication systems, the millimeter wave (mm Wave) bands with multiple-input multiple-output (MIMO) transmission are a potential option. Large antenna arrays at both ends of the link can be used to make up for the significant free-space route loss, which limits the transmission distance. Compared to small-scale MIMO systems with fewer uncertain channel coefficients, this in turn creates difficulties for the channel estimation (CE). The wireless channels at millimeter Wave frequencies are confirmed to have less dispersion than the sub-6 GHz bands. As a result, there are fewer pathways that can be resolved between the mobile station (MS) and base station (BS).

As a result, the mmWave MIMO channel is usually intrinsically sparse, meaning that there are significantly less identifiable pathways in the angular domain than there are transmit and receive antennas. Point-to-point (P2P) mmWave MIMO channel (parameter) estimation has made extensive use of efficient yet effective compressive sensing (CS) approaches that exploit the sparsity [17].

WIRELESS COMMUNICATION TECHNOLOGIES

Wireless Communication Technologies have evolved in several directions based on context and applications. WC networks and technologies can be classified as follows.

Cellular Network

Over time, cellular networks have seen tremendous change, evolving through several generations to satisfy the increasing needs for dependability, speed, and connectivity. New uses, frequency usage, and technological developments were brought about by each generation. Table 2 presents a concise comparison of the 3G, 4G, and 5G cellular networks, emphasizing their respective year of launch, frequency ranges, data rates, technology, benefits, and common uses [18].

Ad-hoc Network

The term “MANET” refers to “Mobile Ad hoc Network”, a kind of wireless network based on multihop packets that is made up of several mobile nodes that may communicate and move autonomously. One type of ad hoc network that can quickly move and change its own configurations is a mobile ad hoc network (MANET). Wireless connections are necessary for mobile ad hoc networks (MANETs) to connect to other networks. Although it can also apply to other transmission systems such as satellite or cellular, the word “Wi-Fi” refers to any wireless network connection [19]. Figure 6 depicts how MANET structure is decentralized. It shows nodes which are configured to directly communicate with one another without the use of fixed infrastructure. That is, it is a flexible dynamic network configuration. This kind of configuration supports rapid deployment in diverse scenarios such as disaster recovery and defense operations.

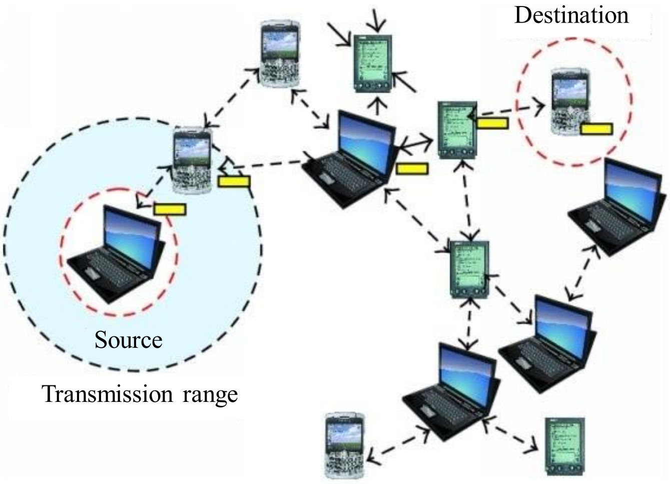

Figure 6. Mobile Ad-Hoc Network [16].

Table 2. Comparative table of Cellular network.

Generation	3G	4G	5G
Year of Introduction	2001	2009	2018
Frequency	1.6–2.0 GHz	2–8 GHz	3–30 GHz
Data Rate	2 Mbps	20 Mbps	150 Mbps
Technology	WCDMA, UTMS	OFDM, LTE	OFDM, MIMO
Advantages	International roaming, high security	High-speed handoff, global mobility	Extremely high speed, low latency
Applications	Mobile TV, Video conferencing, GPS	High-speed applications, wearable devices	IoT, Medical procedures, HD video

CONCLUSION

This review highlights the critical role of channel estimation in enhancing the performance of MIMO-OFDM systems under fast-fading conditions. Least Squares Estimation-based methods, complemented by advanced techniques like DACE and DDCE, provide effective solutions for improving estimation accuracy and spectral efficiency. The integration of deep learning methodologies, such as FDNN and CNNAE, marks a paradigm shift, enabling adaptive and robust channel modelling even in highly dynamic environments. Emerging technologies like millimeter-wave communications and compressive sensing further address challenges in high-frequency sparse channels, paving the way for ultra-reliable low-latency communications in 5G and 6G systems. However, challenges such as computational complexity and real-world scalability remain open for future research. By synthesizing existing methodologies and outlining potential advancements, this study provides a solid foundation for researchers and practitioners to innovate and enhance wireless communication systems.

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