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The development of multicarrier transmission and multiple access methods

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Abstract. This paper presents an overview of development of multicarrier transmission and multiple access methods over the past decades. Focus shifts towards optimizing communication methods for a more expeditious, reliable, and efficient system. Several communicational techniques, including TDMA, CDMA, OFDMA, and GFDMA are discussed. With the growing trend of artificial intelligence, it can be predicted that artificial intelligence will be of great use in improving multicarrier transmission and multiple access methods.

Keywords: Multicarrier, Multiple Access, Communicational Techniques, Artificial Intelligence

1. Introduction

Communication has been a constant demand for people since civilization begins, which stands as a vital and foundational element of human life, acting as a fundamental basis for interactions within society, collaborative efforts, and the sharing of thoughts and concepts. From beacon tower and lighthouse to envelop and telephone, people are constantly communicating with each other, but as technology and economy is advancing in a fast rate, past communication methods gradually become outdated because they cannot fulfil people’s demand for a more expeditious and convenient method to communicate with each other.

In the 1840s, F. B. Morse invented telegram, which represents the beginning of telecommunication [1]. Since then, simple wired telegraph communication has occurred. In 1870s, James Clerk Maxwell published the famous Electromagnetic Wave Theory [2]. Telephone was invented, as a simple telephone communication method with metal wires as the transmission line appeared. At the end of the nineteenth century, Marconi invented a simple radio transmitting and receiving device, opening a new era for radio communication [3]. At the beginning of the 20th century, telegraph and telephone communications had been developing rapidly. Electronic tubes and other devices appeared one after another, representing a higher level of wired and radio communication [4]. After the 1950s, engineers and scientists conducted in-depth theoretical research on the problems encountered in communication practice, and they had made huge progress.

In terms of communication theory, modulation and demodulation, encoding and decoding and multiplexing and demultiplexing have been successively formed in a more systematic way. In terms of communication system, the development of optical fiber communication, satellite communication, digital microwave communication and millimeter wave communication had greatly accelerated communication efficiency. In terms of communication transmission mode, the old concept of communication between people has been replaced by communication between humans and machines or even between machines. Over the past few decades, with the continuous development of human society, people's demand for electronic communication technology significantly increased. Driven by new technology, the public are constantly pursuing faster and more efficient communication methods, and multicarrier modulation has emerged as required. As population is growing rapidly, multiple access technique also emerged to share one communication channel since the spectrum is limited.

In this paper, several main multicarrier transmission and multiple access methods are mainly summarized. During the research process, based on our knowledge and some states of art, we have obtained some information to understand different communication methods by summarizing the application methods of different multicarrier modulations and multiple access methods, and to predict their future development trends and to combine them with Artificial Intelligence.

2. Methodology

In order to let multiple users access the allotted and limited spectrum in the most efficient way, engineers have been working to create the better way of multiple access. A cellular communication networks divides an assigned area into cells, allowing mobile devices in each cell to occupy certain bandwidth to connect with the base station. The total bandwidth is, however, often limited, so the primary goal of designing new communication system is to enhance the capacity of each communication cell, which involves efficiently accommodating numerous calls within a specific bandwidth while maintaining an acceptable level of quality. Multicarrier modulation allows multiple users to utilize a single communication channel, which refers to a system resources designated for a specific mobile user, enabling them to communicate with other network users.

2.1. TDMA

In the 2G era, the most common multicarrier modulation is Time Division Multiple Access (TDMA). In TDMA, the frequency spectrum is divided into time frames, and each time frame is further divided into multiple time slots. Each user's data will exclusively have its assigned time slots to transmit over the spectrum so that various user can transmit at the same frequency band at different times. The time slots are synchronized so that the receiver knows when to expect transmissions from specific users, allowing multiple users to share same frequency channel without causing interference. There are several advantages that TDMA can bring to communication system. Above all, it can adapt an efficient integration of voice and data transmission easily. Fantacci and Nannicini conducted a performance evaluation of random reservation TDMA protocol in a fading channel environment with nonindependent errors, and the results showed that the quality of voice transmission in nearly unaffected by the data traffic, and each data transmission can utilize all available slots to send its information [5]. Under heavy data load, TDMA will also show high performance and stability. Additionally, by sharing a single carrier frequency with multiple users, TDMA can avoid interference from simultaneous transmission. As the requirement for data rate and data quality increases, TDMA gradually lost its bellwether position. To use TDMA, to achieve reliable communication, high synchronization overhead is required, which often causes task delay at the receiver's side. Additionally, in TDMA, each user is assigned for its individual time slot, as a preplanned schedule for every user. Given the circumstance that one user roams from one cell to another cell, it's original cell occupancy will be vacant, as a scheduled opening for this time slot. In this case, this cell will likely to be disengaged. When the user goes back from roaming, its original time slot has been withdrawn and occupied by other clients, so that the user will not be able to use the service as before. Additionally, since all time slots are predefined, when the user roaming to another cell, it is likely that the next cell is already occupied, and the user will also be disconnected from the service. TDMA also has concerning data quality. The phenomenon of multipath distortion significantly impacts signal propagation. When a signal is transmitted from the tower to the mobile devices, it encounters multiple possible paths it can take due to reflections, diffraction, and scattering by the surrounding buildings, so that the signal will be ricocheted off several distance structures before arriving, which can cause interference. Additionally, when the signal bandwidth is greater than the channel bandwidth, after the signal is propagated through the wireless channel, signals at certain frequencies can pass, while signals at other frequencies will be severely attenuated, making the overall signal distorted. To solve this problem, 2G system employs narrowband signal, whose bandwidth is 200 KHz. Still, with limited signal bandwidth, the data rate is limited.

2.2. CDMA

To improve data rate and data quality, Code Division Multiple Access (CDMA) is used in the 3G era. Unlike TDMA with allocated time slot, CDMA, as a single carrier system, allows users to transmit and receive data simultaneously using the same frequency spectrum. Each user's data is encoded with a unique spreading code before transmission. Generally, it takes the digitalized analog signal from the collector, spreads it out over a wider bandwidth with a lower power level, and encodes with the designated spreading code. The codes are carefully designed to be orthogonal with low cross-correlation with each other, avoiding causing severe interference. At the receiver side, since the received signal is correlated with the spreading code of one specific user, other user's signal will appear as noise and can be filtered out, leaving the recovery of intended user's data. Additionally, CDMA introduces soft handoff in connection between cells. Soft handoff enables a mobile device to communicate with multiple cells simultaneously during a handoff transition, enhancing call quality and system reliability. CDMA proved to be a dependable choice for wireless sensor networks. Benkic proposed to employ CDMA technique in wireless sensor networks for its low latency, high fault tolerance, and no primary collision [6]. From the cellular service providers prospective, engineers at AT&T Bell Laboratories also proposed several advantages of using CDMA cellular system, including adaptive traffic load shedding, dynamic power control, jamming resistance and privacy protection [7]. The utilization of CDMA offers a diverse range of operational benefits compared to TDMA, some of which led directly to immediate operating cost savings, from the prospective of a larger corporation. However, as relatively small, or individual wireless operators, due to the fact that CDMA technology was independently developed by Qualcomm, which owns the most core CDMA patent, the continued use of CDMA will enable them to pay high royalties to Qualcomm, which is a significant factor for them to take into account as well as selecting among other digital cellular alternatives. Additionally, CDMA also requires time synchronization and does not offer international roaming, so it gradually falls back from the main current of multiple access techniques.

2.3. OFDMA

As the need for higher data rates, enhanced spectral efficiency, and dependable performance significantly increase over the past decades, various modulation techniques emerge to solve the problem. As a single-user modulation method, Orthogonal Frequency Division Multiplexing (OFDM) stands out as a dominant modulation scheme that addresses many of these challenges. OFDM divides a high-speed data spectrum into multiple low speed substreams, each transmitted over orthogonal subcarriers. It is accomplished by utilizing the Inverse Fast Fourier Transform, which converts the digital data symbols into the time domain. The spacing of between the subcarriers is orthogonal to each other to avoid interference. The resulting time-domain signals are transmitted simultaneously over orthogonal subcarriers. At the receiver, the signals are transformed back into the frequency domain using Fast Fourier Transform, and the original data symbols are recovered. Orthogonal Frequency Division

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Multiple Access (OFDMA) is the latest implementation of utilizing OFDM as multiple-user scenarios. It takes channels of OFDM and subdivides into smaller section, as known as resources units (RUs). Through channel segmentation, it becomes feasible to conduct simultaneous transmission between multiple users. Within an OFDMA channel, the subcarriers within each designated resource unit maintain adjacency and continuity.

OFDMA's subcarrier-based transmission enables low latency communication, as well as CDMA but better. in this case, data frames are divided into small subframes, allowing for quicker transmission and reception. This attribute is critical for real-time applications such as video conferencing, online gaming, or even autonomous vehicles, where minimizing communication delay is essential [8]. Another salient feature of OFDMA is its ability to enhance spectral efficiency. Through division of accessible frequency spectrum into orthogonal subcarriers, OFDMA facilitates concurrent data transmission and reception for multiple users within a shared bandwidth [9]. This effective utilization of spectrum contributes to increased capacity and throughput, satisfying the demand of users for data-intensive applications. OFDMA also enables flexible allocation of subcarriers to different users based on their varying communication needs. This flexibility allows for efficient utilization of available bandwidth, ensuring that users with high data rate demands receive more subcarriers while users with low requirements receive fewer subcarriers [10]. The result is an equitable distribution of resources, which improves overall network efficiency. In recent years, there were several algorithms proposed to improve the flexibility of subcarrier allocation even further. Jing and his fellow engineers introduced an Iterative Subchannel and Power Allocation algorithm (ISP) for resource allocation, which handles subchannel and power allocation in an iterative manner [11]. Through simulation outcomes, the ISP algorithm exhibits the distinct benefits and adaptability when contrasted with the existing approaches in terms of energy efficiency and spectral efficiency enhancement. Compared to TDMA, OFDMA's multicarrier structure effectively mitigates the effects of multipath fading [12]. In multipath environments, subcarriers experience different fading conditions due to their distinct propagation paths. As a result, even if some subcarriers experience deep fading, others remain relatively unaffected, leading to improved overall system performance, as verified to be a promising scheme. Additionally, OFDMA's ability to accommodate power control and adaptive modulation further enhances its resistance to channel impairments.

On the other hand, there are still several challenges regarding OFDMA to be overcome. Similar with TDMA and CDMA, OFDMA also requires precise synchronization in frequency among users. Variations in carrier frequency and timing offsets can result in interference between subcarriers, causing degradation, leading to decreased overall system performance [13]. Achieving accurate synchronization across multiple users and the receiver can be very challenging. With that being said, it is also hard to design a perfect receiver. While OFDMA's transmitter structure is relatively straightforward, its receiver design can be much complex due to the addition of synchronization, channel estimation, and equalization. Accurate channel estimation is critical for coherent demodulation of subcarriers, and managing synchronization errors and channel impairments demands sophisticated algorithms and processing resources [14]. Additionally, OFDMA signals are susceptible to high Peak-to-Average Power Ratio (PAPR), which can lead to inefficient power amplifier utilization. High PAPR requires power amplifiers to operate with significant headroom to avoid distortion, resulting in power inefficiency and reduced battery life in mobile devices. Various techniques, such as signal clipping and coding, are employed to mitigate this issue, but they introduce additional complexity [15].

2.4. GFDMA

With those challenging issues concerning OFDM, engineers have developed Generalized Frequency Division Multiple Access (GFDM), a novel modulation scheme that reimagines traditional communication approaches, and implementing further for multiple access as Generalized frequency division multiple access (GFDMA). Unlike OFDM, where subcarriers are orthogonal, GFDM employs non-orthogonal subcarriers and possesses a more flexible waveform structure. This inherent adaptability forms the basis for several advantages that GFDMA offers in comparison to other multiple access techniques. Similar to OFDMA, GFDMA have the features of flexibility in subcarrier allocation and enhanced spectral efficiency. Besides, GFDMA offers a potential advantage in terms of lower PAPR compared to conventional OFDMA [16]. This characteristic simplifies power amplifier design and contributes to more energy-efficient communication systems. Additionally, GFDMA's waveform flexibility makes it well-suited for the requirements of 5G and future wireless communication systems. The ability to tailor the waveform to specific deployment scenarios, including dense urban environments and massive machine-type communications, makes GFDM as a promising candidate for next-generation networks [17].

3. Future Work

In a rapidly evolving world driven by data and technology, artificial intelligence has emerged as a driving force behind innovation and progress. It has the ability to analyze massive amounts of data at unprecedented speeds, providing insights that can guide informed decision-making, which well-suits the demand for a more expeditious and convenient communication method. Artificial intelligence can be applied to various aspects of multi-carrier modulation systems to enhance the performance of wireless communication systems, which includes channel estimation, signal detection, modulation classification, and resource allocation.

3.1. Channel Estimation

Channel estimation estimates the Channel State Information (CSI) from the received signal, which is essential for coherent detection and equalization. However, traditional channel estimation techniques rely on mathematical models that may not accurately capture the characteristics of the actual channel, especially in complex environments such as 5G and 6G systems. Artificial intelligence can provide a data-driven approach to learn channel characteristics from received signals without relying on predefined models [18]. This research introduced an innovative channel estimation approach for OFDM systems, utilizing profound learning principles. Specifically, it investigated the application of a Generative Adversarial Network (GAN) in the context of Channel Super-Resolution (SR) for comprehensive CSI estimation. By incorporating a discriminator to enhance channel detail reconstruction, the resulting estimated channel aligns more closely with the characteristics of the actual channel. This strategy demonstrated superior performance compared to alternative SR-focused channel estimation techniques and achieved a performance level comparable to that of Linear Minimum Mean Square Error (LMMSE) estimation.

3.2. Signal Detection

Signal detection is recovering transmitted data from the received signal after channel estimation and equalization. However, traditional signal detection techniques face high computational complexity or suboptimal performance challenges, especially in multi-carrier systems with high bandwidth and modulation orders. Artificial intelligence can offer a low-complexity and high-performance approach by learning optimal detection functions from training data without the need to estimate channel parameters and perform matrix inversions, or iterative algorithms, thereby reducing estimation errors and bit error rates [19-22].

A deep learning-oriented technique was introduced for detecting time-varying channel signals in the context of OFDM. By treating the OFDM receiver as an opaque entity, the architecture of the OFDM system was streamlined [19]. It preserved the attributes of the wireless time-varying channel, leading to improved precision and resilience in signal retrieval outcomes. Similarly, another research proposed a deep neural network (DNN) model for estimating the OFDM channel and detecting signals [20]. This model presented an efficient strategy for augmenting accuracy while minimizing complexity. The deep learning simulation exhibited superior performance in comparative simulations over the Least Squares (LS) simulation.

3.3. Modulation Classification

Modulation classification involves identifying the modulation type of received signals, which is helpful for spectrum sensing, interference mitigation, and adaptive transmission. Traditional modulation classification techniques require prior knowledge of features that are not robust enough to withstand noise or fading. Artificial intelligence can provide a feature learning approach to extract relevant features such as signal-to-noise ratio from received signals, enabling automatic modulation classification and playing a crucial role in promptly identifying suspicious and unwanted signal activities. This approach does not require precise data or manual design and can simplify the entire modulation recognition process while ensuring classification accuracy [23-26].

An intelligent Automatic Modulation Classification (AMC) system based on Universal Software Radio Peripheral (USRP) was developed for real-time detection and classification of various digital modulation schemes, enhancing accuracy and performance [23]. The model proposed in aims to combine shallow and deep features, enabling multi-level feature extraction to obtain global receptive fields and positional information simultaneously without transforming the original data [25]. A new approach was proposed to utilize Signal-to-Noise Ratio (SNR) as weights in training, rather than an indicator of system robustness, to leverage limited data fully. This approach improved the performance of communication networks.

3.4. Resource Allocation

Resource allocation involves optimizing the distribution of resources such as power, bandwidth, and subcarriers among multiple users or applications, aiming to enhance system efficiency and fairness in multi-carrier systems. However, traditional resource allocation techniques might require centralized control or global information exchange, which can be infeasible or non-scalable in large-scale multi-carrier systems. Artificial intelligence can provide a distributed and adaptive approach to learning optimal resource allocation strategies from local observations and feedback without centralized coordination or global information exchange. These methods can achieve high prediction accuracy, reduce computational time, enhance spectrum efficiency, and contribute to green energy goals [27-30].

The research studied intelligent resource allocation for Enhanced OFDM systems using intelligent reconfigurable surfaces [28]. The goal was to maximize system capacity and throughput by jointly optimizing subcarrier allocation, base station beamforming, and intelligent reflecting surface (IRS) phase shift. An intelligent resource allocation scheme combining Deep Q-Network (DQN) and Deep Deterministic Policy Gradient (DDPG) was proposed to tackle challenging non-convex problems. Furthermore, a Deep Neural Network (DNN) approach was proposed to approximate resource allocation algorithms, significantly reducing computation time while maintaining high prediction accuracy [29]. Simulation results demonstrated the impact of Doppler frequency shift on DNN’s SE performance and computation time.

4. Conclusion

In this paper, several multicarrier transmission and multiple access methods are presented. As technology continues to advance, the focus shifts towards optimizing communication methods that fulfill the increasing need for more expeditious, reliable, and efficient system. The transition from 2G to 3G and beyond reflects this trend, with multicarrier transmission and multiple access methods evolving to accommodate the growing number of users and their diverse communication requirements. TDMA and CDMA played their roles in earlier generation, but the demand for higher data rates and enhanced efficiency led to the rise of OFDMA. OFDMA has demonstrated remarkable advantages over its predecessors, including low latency, enhanced spectral efficiency, flexibility to allocate resources and mitigation to multipath distortion. Moreover, the emergence of GFDMA introduced a new dimension to communication, which offers improved PAPR compared to traditional OFDM. This makes GFDMA an competitive option for next-generation networks, particularly in scenarios like massive machine-type communications. Additionally, artificial intelligence brings a new dimension to the evolution of communication systems. Its data-driven approach to channel estimation, signal detection, modulation classification, and resource allocation holds the promise of more accurate, efficient, and adaptive communication systems. By leveraging AI's capabilities, researchers aim to overcome traditional limitations and create communication systems that are capable of adapting to complex environments and user needs.

The journey of communication technology has been characterized by constant innovation, adaptation, and the pursuit of efficiency. From the humble beginnings of beacons and telegrams to the sophisticated OFDMA and GFDMA techniques of today, the evolution of communication reflects humanity's quest to stay connected in a rapidly changing world. As people continue to explore the intersections of communication and artificial intelligence, more transformative advancements that will shape the way people interact, collaborate, and exchange ideas, are still yet to come in the future.

References

[1] L. Coe, in The telegraph: A history of Morse's invention and its predecessors in the United States, Jefferson, NC: McFarland & Company, 2003, pp. 26–37.

[2] J. C. Maxwell, in A dynamical theory of the electromagnetic field, London: The Society, 1865, pp. 459–512.

[3] P. K. Bondyopadhyay, "Guglielmo Marconi - the father of Long Distance Radio Communication - An Engineer's tribute," 25th European Microwave Conference, 1995, 1995. doi:10.1109/euma.1995.337090.

[4] G. S. Vernam, "Cipher Printing Telegraph Systems: For secret wire and Radio T elegraphic Communications," Journal of the A.I.E.E., vol. 45, no. 2, pp. 109–115, 1926. doi:10.1109/jaiee.1926.6534724.

[5] R. Fantacci and S. Nannicini, "Performance evaluation of a reservation TDMA protocol for voice/data transmission in personal communication networks with Nonindependent Channel Errors," IEEE Journal on Selected Areas in Communications, vol. 18, no. 9, pp. 1636–1646, 2000. doi:10.1109/49.872952.

[6] K. Benkic, "Proposed use of a CDMA technique in wireless sensor networks," 2007 14th International Workshop on Systems, Signals and Image Processing and 6th EURASIP Conference focused on Speech and Image Processing, Multimedia Communications and Services, 2007. doi:10.1109/iwssip.2007.4381112.

[7] C. K. Kwabi et al., "Operational advantages of the AT&T CDMA cellular system," [1992 Proceedings] Vehicular Technology Society 42nd VTS Conference - Frontiers of Technology. Denver, CO, USA, 1992, pp. 233-235 vol.1, doi: 10.1109/VETEC.1992.245433.

[8] J. G. Andrews et al., "What Will 5G Be?," in IEEE Journal on Selected Areas in Communications, vol. 32, no. 6, pp. 1065-1082, June 2014, doi: 10.1109/JSAC.2014.2328098.

[9] S. Sesia, I. Toufik, and M. Baker, "Orthogonal Frequency Division Multiple Access (OFDMA)," in LTE - the UMTS long term evolution: From theory to practice, Hoboken, New Jersey: John Wiley & Sons, 2015, pp. 113–134.

[10] E. Dahlman, S. Parkvall, and J. Sköld, "Overall Transmission Structure," in 5G nr: The next generation wireless access technology, London: Elsevier, Academic Press, 2021, pp. 115–145.

[11] W. Jing, Z. Lu, X. Wen, Z. Hu, and S. Yang, "Flexible resource allocation for joint optimization of energy and spectral efficiency in OFDMA Multi-Cell Networks," IEEE Communications Letters, vol. 19, no. 3, pp. 451–454, 2015. doi:10.1109/lcomm.2015.2392113.

[12] J. Fu and Y. Karasawa, "Fundamental analysis on throughput characteristics of orthogonal frequency division multiple access (OFDMA) in multipath propagation environments," Proceedings IEEE 56th Vehicular Technology Conference, 2002. doi:10.1109/vetecf.2002.1040802.

[13] M. Konstantinos, A. Adamis, and P. Constantinou, "SNR degradation due to timing and frequency synchronization errors for OFDMA systems with Subband Carrier Allocation," 2008 14th European Wireless Conference, 2008. doi:10.1109/ew.2008.4623899.

[14] M. Morelli, C.-C. J. Kuo, and M.-O. Pun, "Synchronization techniques for orthogonal frequency division multiple access (OFDMA): A Tutorial Review," Proceedings of the IEEE, vol. 95, no. 7, pp. 1394–1427, 2007. doi:10.1109/jproc.2007.897979.
[15] L. Cimini, "Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing," IEEE Transactions on Communications, vol. 33, no. 7, pp. 665–675, 1985. doi:10.1109/tcom.1985.1096357.
[16] I. Jagenneevas and P. Dananjayan, "Performance analysis of GFDMA and SC-FDMA in Rayleigh and Gaussian Fading Channel," 2015 IEEE 9th International Conference on Intelligent Systems and Control (ISCO), 2015. doi:10.1109/isco.2015.7282342.
[17] M. Shafi et al., "5G: A tutorial overview of standards, trials, challenges, deployment, and Practice," IEEE Journal on Selected Areas in Communications, vol. 35, no. 6, pp. 1201–1221, 2017. doi:10.1109/jsac.2017.2692307.
[18] S. Zhao, Y. Fang and L. Qiu, "Deep Learning-Based channel estimation with SRGAN in OFDM Systems," 2021 IEEE Wireless Communications and Networking Conference (WCNC), Nanjing, China, 2021, pp. 1-6, doi: 10.1109/WCNC49053.2021.9417242.
[19] R. Yao, S. Wang, X. Zuo, J. Xu and N. Qi, "Deep Learning Aided Signal Detection in OFDM Systems with Time-Varying Channels," 2019 IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM), Victoria, BC, Canada, 2019, pp. 1-5, doi: 10.1109/PACRIM47961.2019.8985060.
[20] T. Fathi, S. Ashraf and A. A. Rhebi, "Deep Learning For Channel Estimation And Signal Detection," 2022 International Conference on Engineering & MIS (ICEMIS), Istanbul, Turkey, 2022, pp. 1-6, doi: 10.1109/ICEMIS56295.2022.9914039.
[21] J. Ruseckas, G. Molis, A. Mackutė-Varoneckienė and T. KrilaviČius, "Multi-carrier Signal Detection using Convolutional Neural Networks," 2019 International SoC Design Conference (ISOCC), Jeju, Korea (South), 2019, pp. 190-191, doi: 10.1109/ISOCC47750.2019.9078534.
[22] J. Cao, C. Liu and Y. Lu, "Performance analysis of AI aided embedded OFDM receiver based on RK3399 platform," 2021 International Conference on Wireless Communications and Smart Grid (ICWCSG), Hangzhou, China, 2021, pp. 64-69, doi: 10.1109/ICWCSG53609.2021.00020.
[23] Z. Kaleem, M. Ali, I. Ahmad, W. Khalid, A. Alkhayyat and A. Jamalipour, "Artificial Intelligence-Driven Real-Time Automatic Modulation Classification Scheme for Next-Generation Cellular Networks," in IEEE Access, vol. 9, pp. 155584-155597, 2021, doi: 10.1109/ACCESS.2021.3128508.
[24] T. Huynh-The et al., "Automatic Modulation Classification: A Deep Architecture Survey," in IEEE Access, vol. 9, pp. 142950-142971, 2021, doi: 10.1109/ACCESS.2021.3120419.
[25] J. Nie, Y. Zhang, Z. He, S. Chen, S. Gong and W. Zhang, "Deep Hierarchical Network for Automatic Modulation Classification," in IEEE Access, vol. 7, pp. 94604-94613, 2019, doi: 10.1109/ACCESS.2019.2928463.
[26] T. Huynh-The, C. -H. Hua, Q. -V. Pham and D. -S. Kim, "MCNet: An Efficient CNN Architecture for Robust Automatic Modulation Classification," in IEEE Communications Letters, vol. 24, no. 4, pp. 811-815, April 2020, doi: 10.1109/LCOMM.2020.2968030.
[27] P. Yu, F. Zhou, X. Zhang, X. Qiu, M. Kadoch and M. Cheriet, "Deep Learning-Based Resource Allocation for 5G Broadband TV Service," in IEEE Transactions on Broadcasting, vol. 66, no. 4, pp. 800-813, Dec. 2020, doi: 10.1109/TBC.2020.2968730.
[28] W. Wu, F. Yang, F. Zhou, Q. Wu and R. Q. Hu, "Intelligent Resource Allocation for IRS-Enhanced OFDM Communication Systems: A Hybrid Deep Reinforcement Learning Approach," in IEEE Transactions on Wireless Communications, vol. 22, no. 6, pp. 4028-4042, June 2023, doi: 10.1109/TWC.2022.3222864.
[29] Y. Guo, F. -C. Zheng, J. Luo and X. Wang, "Optimal Resource Allocation via Machine Learning in Coordinated Downlink Multi-Cell OFDM Networks under High Mobility," 2021 IEEE 93rd

Vehicular Technology Conference (VTC2021-Spring), Helsinki, Finland, 2021, pp. 1-7, doi: 10.1109/VTC2021-Spring51267.2021.9448996.
[30] Y. Guo, F. -C. Zheng, J. Luo and X. Wang, "Optimal Resource Allocation via Machine Learning in Coordinated Downlink Multi-Cell OFDM Networks under Imperfect CSI," 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), Antwerp, Belgium, 2020, pp. 1-6, doi: 10.1109/VTC2020-Spring48590.2020.9128768.