Proceedings of the 4th International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/2026.34954

Symbol Synchronization and Throughput Optimization in OFDM Systems

Shuzhe Qin

School of Advanced Technology, Xi'an Jiaotong-Liverpool University, Suzhou, China
qsz050712@icloud.com

Abstract. Orthogonal frequency division multiplexing (OFDM) is widely used in modern wireless communication systems, but its performance is strongly affected by symbol synchronization errors and link adaptation decisions. In many existing studies, synchronization and throughput scheduling are treated as separate problems, which makes it difficult to connect physical-layer uncertainty with system-level throughput. This paper proposes a joint symbol synchronization and throughput optimization framework for OFDM systems. At the receiver, cyclic-prefix autocorrelation is first used for coarse timing acquisition and coarse carrier-frequency-offset estimation. Pilot cross-correlation is then applied in a local search window for fine timing alignment and residual frequency-offset refinement. Based on the CP correlation peak, pilot main-to-side-lobe ratio, and estimation stability, a synchronization confidence metric is defined and used as an input to adaptive modulation and coding (AMC). In multi-user scenarios, this confidence metric is further combined with channel-state information for subcarrier and power allocation. MATLAB simulation results show that the proposed closed-loop design can reduce aggressive MCS selection under unreliable synchronization, improve effective throughput stability, and maintain reasonable user fairness.

Keywords: OFDM, symbol synchronization, synchronization confidence, adaptive modulation and coding, resource allocation

1. Introduction

Orthogonal frequency division multiplexing (OFDM) has become a core physical-layer waveform in 4G, 5G, and candidate 6G communication systems. Its main advantage is that a high-speed bitstream is divided into several low-rate parallel subcarriers. Since these subcarriers are orthogonal in the frequency domain, OFDM can improve spectral efficiency and resist multipath fading within a limited bandwidth.

In practical systems, however, this orthogonality is sensitive to timing offset, sampling-clock mismatch, and carrier frequency offset (CFO). If the FFT window is misplaced or if the residual CFO is large, inter-symbol interference (ISI) and inter-carrier interference (ICI) appear. These effects increase the error rate and reduce the effective throughput after retransmission and coding overhead are considered.

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.34954

Another important issue is that symbol synchronization and throughput optimization are often designed as separated modules. A receiver may estimate the symbol boundary first, while the link adaptation and scheduler may only use signal-to-noise ratio (SNR) or channel-state information (CSI) later. This separation can lead to overly aggressive modulation and coding scheme (MCS) decisions when the channel seems strong but the synchronization result is not reliable. Therefore, a more useful system design should connect synchronization reliability with AMC and resource allocation.

The main contributions of this paper are summarized as follows:

• A hybrid synchronization strategy is designed by combining CP-based coarse acquisition and pilot-based fine tracking for OFDM systems under noisy and multipath channels.

• A synchronization confidence metric is constructed from CP correlation, pilot correlation, and estimation stability. This metric makes synchronization reliability more explainable and usable by higher-layer decisions.

• A joint throughput optimization framework is developed by coupling synchronization confidence, AMC selection, subcarrier allocation, and power control. Both single-user effective throughput and multi-user fairness are evaluated.

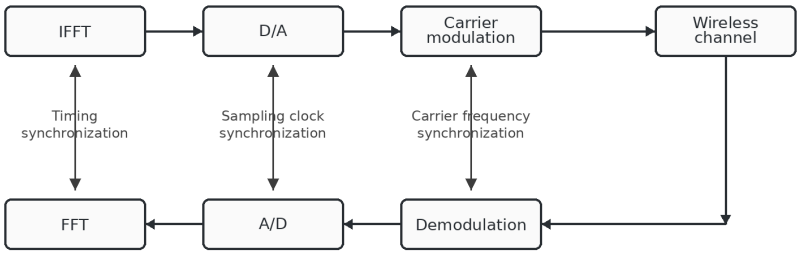

Figure 1. Synchronization positions in an OFDM transceiver chain

Figure 1 shows the main synchronization positions in a typical OFDM transceiver. The transmitter performs IFFT, D/A conversion, carrier modulation, and wireless transmission. The receiver performs demodulation, A/D conversion, and FFT. A clear synchronization error in any of these stages can shift the FFT window or break subcarrier orthogonality, which finally causes ICI, ISI, and throughput loss.

2. Related work

2.1. OFDM symbol synchronization

Recent OFDM and 5G NR synchronization studies usually follow a hierarchical process, including coarse timing acquisition, fine timing correction, and residual frequency-offset compensation. ETSI/3GPP TS 38.211 defines the physical channels, modulation schemes, and synchronization signal structures used in 5G NR [1]. Wang et al. proposed a simplified two-stage time synchronization method for 5G NR under high-frequency-offset conditions [2]. Qing et al. developed a lightweight cascaded 1-D CNN timing synchronization method and showed that conventional synchronization methods can suffer from complexity, delay, and performance loss in

DOI: 10.54254/2755-2721/2026.34954

complex wireless channels [3]. Liu et al. applied an extreme learning machine to fine timing and frequency synchronization in MIMO-OFDM systems [4].

Existing synchronization methods can be divided into three common groups. The first group uses known synchronization signals or pilots and detects the symbol boundary by cross-correlation. The second group uses the repeated structure between the cyclic prefix and the end of an OFDM symbol. This method has low overhead but may produce broad correlation peaks under low SNR or severe multipath. The third group introduces machine learning into the receiver to improve timing or frequency-offset estimation. These methods are promising, but a purely data-driven receiver may be harder to explain and may require more training data.

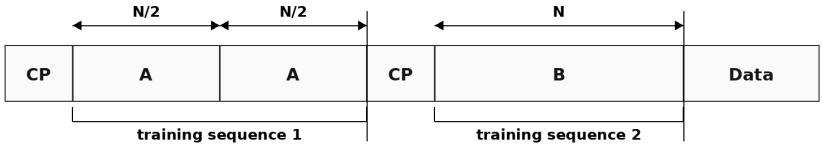

Figure 2. Repetitive training sequence structure for OFDM timing synchronization

Figure 2 illustrates a repeated training structure. The first training symbol contains a CP and two repeated A blocks, so the receiver can calculate autocorrelation between the two repeated parts for coarse timing and coarse CFO estimation. The second training symbol contains a CP and a known B block, which can be used for fine timing, channel estimation, or residual CFO correction. The main idea is to use a known and repeated structure to obtain a more reliable synchronization decision.

2.2. Throughput optimization and resource allocation

Throughput is affected not only by channel capacity, but also by MCS selection, coding rate, block error rate (BLER), retransmission, resource-block allocation, and synchronization errors. In 5G NR, TS 38.214 defines procedures related to CQI, MCS, transport block size, and link adaptation [5]. When the channel quality is poor, a conservative MCS should be selected to reduce BLER. When the channel is strong and synchronization is stable, higher-order modulation can be used to improve spectral efficiency.

Kamal et al. reviewed spectrum, power, user, and slicing resource allocation schemes in 5G networks [6]. Their work is useful for understanding scheduling-layer optimization, but it mainly assumes that link-quality information is already available. In contrast, this paper focuses on adding synchronization reliability as an additional input to AMC and scheduling decisions. Model-driven deep learning and learning-based OFDM receiver studies also show that combining communication knowledge with learning models can improve estimation and detection under complex channels [7, 8]. Nevertheless, many existing studies still treat synchronization, link adaptation, and resource allocation as independent modules.

$$\eta_i = \log_2(1+\gamma_i) \tag{1}$$

where γ_i is the SNR of the i-th subcarrier and η_i represents the theoretical spectral efficiency per hertz.

$$C_{sum} = \sum_u \sum_i a_{u,i} \log_2\left(1+\frac{p_{u,i}|H_{u,i}|^2}{N_0}\right) \tag{2}$$

DOI: 10.54254/2755-2721/2026.34954

where $a_{u,i}$ is the subcarrier allocation indicator and $p_{u,i}$ is the power assigned to user u on subcarrier i.

3. Proposed framework

3.1. System model

This paper builds a MATLAB-based OFDM simulation system with 64 subcarriers. The input bits are mapped to QPSK, 16QAM, or 64QAM symbols according to the selected MCS. The frequency-domain data are then converted to time-domain OFDM symbols by an N-point IFFT. A cyclic prefix of length 16, equal to N/4 in this simulation, is inserted to reduce ISI caused by multipath propagation.

$$x[n] = \frac{1}{\sqrt{N}} \sum_m X[m] \exp\left(j \frac{2\pi mn}{N}\right), \quad 0 \le n < N \tag{3}$$

where X[m] is the m-th frequency-domain symbol and x[n] is the generated time-domain OFDM sample.

Two channel models are considered. The first one is the AWGN channel, which is used as a baseline model. The second one is a multipath Rayleigh fading channel, which includes delay spread and possible Doppler or CFO effects. The received signal can be expressed as

$$r[n] = (h * x)[n - \tau] \cdot \exp\left(j \frac{2\pi \epsilon n}{N}\right) + w[n] \tag{4}$$

where τ is the timing offset, ϵ is the normalized CFO, h is the channel impulse response, and w[n] is additive noise.

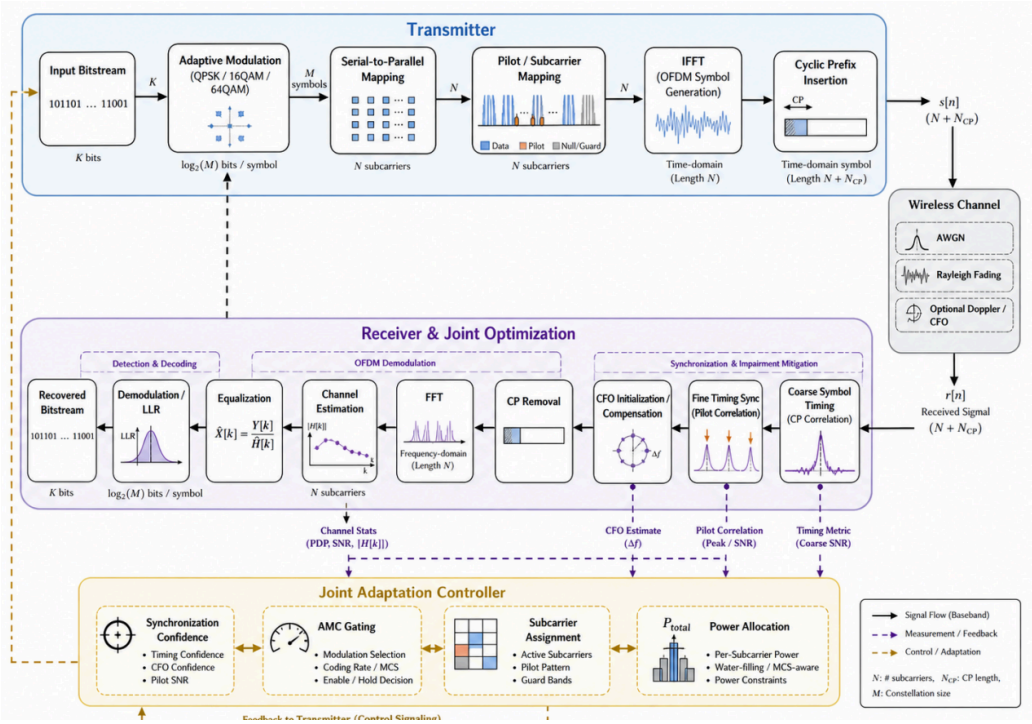

Figure 3. Overall flowchart of the proposed synchronization-throughput optimization framework

DOI: 10.54254/2755-2721/2026.34954

Figure 3 summarizes the whole simulation framework. The upper part is the transmitter, including bit generation, adaptive modulation, serial-to-parallel mapping, pilot or subcarrier mapping, IFFT, CP insertion, and channel transmission. The lower part is the receiver and joint optimization part, including synchronization estimation, CFO compensation, CP removal, FFT, channel estimation, equalization, demodulation, AMC gating, subcarrier assignment, and power allocation. The key point is that the synchronization result is not stopped at the receiver front-end. Instead, it is passed to the AMC and resource allocation modules as a decision input.

3.2. Hybrid symbol synchronization

The proposed receiver uses a two-stage synchronization strategy. In the first stage, CP autocorrelation is used for coarse synchronization. Because the CP repeats the end of the OFDM symbol, the receiver can search for a strong autocorrelation metric to estimate the approximate symbol boundary. The phase of the correlation result can also provide a coarse CFO estimate. This stage has low complexity and can reduce the following search range from the whole received block to a small local window.

In the second stage, pilot cross-correlation is applied near the coarse timing position. The known pilot sequence is correlated with the received samples in the local window. The strongest and most stable peak gives a more accurate symbol-start estimate. The pilot phase slope across subcarriers is also used to refine the residual CFO. This coarse-to-fine design combines the speed of the CP method and the accuracy of pilot correlation.

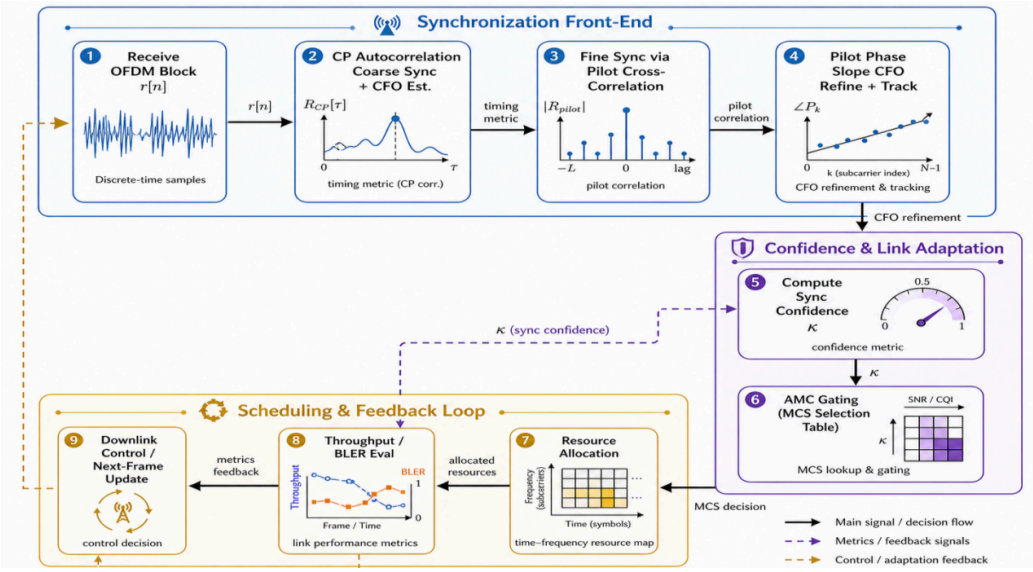

Figure 4. Two-stage synchronization and link-adaptation algorithm flowchart

Figure 4 describes the two-stage synchronization and link-adaptation process. The receiver first estimates coarse timing and initial CFO by CP autocorrelation. It then performs pilot cross-correlation and pilot phase-slope processing to obtain fine timing and residual CFO estimation. The correlation peak strength, pilot peak-to-side-lobe ratio, and estimation stability are combined into the synchronization confidence metric k. Finally, SNR, CSI, and k are jointly used for AMC selection and resource allocation.

DOI: 10.54254/2755-2721/2026.34954

3.3. Synchronization confidence metric

A key part of the proposed method is the synchronization confidence metric k. This metric is designed to describe how reliable the current synchronization decision is. It is not only based on the estimated SNR. Instead, it combines three explainable terms: the CP autocorrelation peak quality, the pilot main-to-side-lobe ratio, and the stability of the timing/CFO estimates over adjacent OFDM symbols.

$$k = \text{clip}\left(w_1 P_{CP} + w_2 R_{pilot} + w_3 S_{est}, 0, 1\right) \tag{5}$$

where P_{CP} denotes the normalized CP correlation peak, R_{pilot} denotes the pilot main-to-side-lobe ratio, S_{est} denotes the estimation stability, and w_1, w_2, and w_3 are weighting factors. A low value of k means that the synchronization result is unreliable, even if the SNR is not very low.

3.4. AMC and resource allocation

The AMC module selects the modulation order and coding rate according to both channel quality and synchronization confidence. If the SNR is low or k is small, the receiver selects a robust MCS such as QPSK with a lower coding rate. If the SNR is high and k is also high, the receiver can select 16QAM or 64QAM with a higher coding rate. Therefore, the proposed AMC strategy avoids making aggressive MCS decisions when synchronization is unstable.

$$T_{eff} = R_{MCS}\left(\gamma, k\right) \cdot \left(1 - \text{BLER}\right) \tag{6}$$

where T_{eff} is the effective throughput per OFDM symbol and $R_{MCS}(\gamma, k)$ is the selected coded data rate under the current SNR and synchronization confidence.

For multi-user OFDM, subcarriers are dynamically assigned to users with better channel gains on each frequency position. Uniform power allocation and approximate water-filling allocation are both evaluated. Uniform allocation is simple and robust under imperfect CSI, while water filling can improve the sum rate by allocating more power to stronger subcarriers. In the proposed framework, k is used as a constraint input to avoid over-optimistic scheduling under uncertain synchronization.

4. Simulation setup and evaluation metrics

4.1. Simulation environment

The simulation platform is implemented in MATLAB R2024b on a laptop with a 13th Gen Intel Core i9-13900H CPU and an NVIDIA GeForce RTX 4060 Laptop GPU under Windows 11. The simulation covers baseband signal generation, AWGN and multipath fading channels, timing and frequency offset, receiver synchronization, channel estimation, equalization, demodulation, and throughput calculation. Monte Carlo simulations are used to evaluate the proposed method under different SNR values and channel conditions.

4.2. Evaluation metrics

• Single-user effective throughput: the number of successfully delivered information bits per OFDM symbol after AMC, coding overhead, and BLER are considered.

DOI: 10.54254/2755-2721/2026.34954

• Synchronization confidence k: a normalized indicator that reflects synchronization reliability based on CP correlation, pilot correlation, and estimation stability.

• Multi-user sum rate: the total throughput achieved by all users after subcarrier and power allocation.

• Jain fairness index: a fairness metric used to evaluate whether resources are balanced among users.

$$J = \frac{(R_1+R_2+\cdots+R_U)^2}{U(R_1^2+R_2^2+\cdots+R_U^2)} \tag{7}$$

where R_u is the throughput of user u and U is the number of users. A value closer to 1 means better fairness.

5. Results and discussion

5.1. Comparison with existing research directions

To show the position of this work, two representative research directions are compared. Qing represents learning-aided OFDM timing synchronization, while Kamal represents 5G resource allocation and throughput optimization. This comparison evaluates the proposed work from three aspects: single-user effective throughput, synchronization confidence, and multi-user throughput/fairness. The detailed comparison is summarized in Table 1.

Table 1. Comparison between existing works and this paper

Compared work	Single-user effective throughput	Synchronization confidence k	Multi-user throughput and fairness
Qing	Improves OFDM timing accuracy, but does not directly optimize effective throughput.	Does not define k; reliability mainly depends on CNN-based timing decision.	Mainly focuses on receiver-side synchronization, without multi-user allocation or Jain fairness.
Kamal	Focuses on resource allocation and assumes link-quality information is available.	Does not use timing offset, residual CFO, or peak reliability for MCS selection.	Covers resource allocation and QoS, but does not couple OFDM synchronization with scheduling.
This paper	Uses effective throughput as the core metric by considering AMC, BLER, and synchronization quality.	Defines k using CP peak quality, pilot correlation, and estimation stability.	Uses k for AMC and resource allocation, and evaluates both sum rate and Jain fairness.

Compared with Qing, this paper does not simply increase neural-network model complexity. It adopts an explainable CP coarse synchronization and pilot fine synchronization procedure, which is easier to implement and explain in an undergraduate-level MATLAB simulation. Compared with Kamal, this paper does not only discuss how resources are allocated. It introduces physical-layer synchronization uncertainty as a key input, so the scheduler is less likely to rely only on SNR and select an overly aggressive MCS.

DOI: 10.54254/2755-2721/2026.34954

5.2. Simulation results

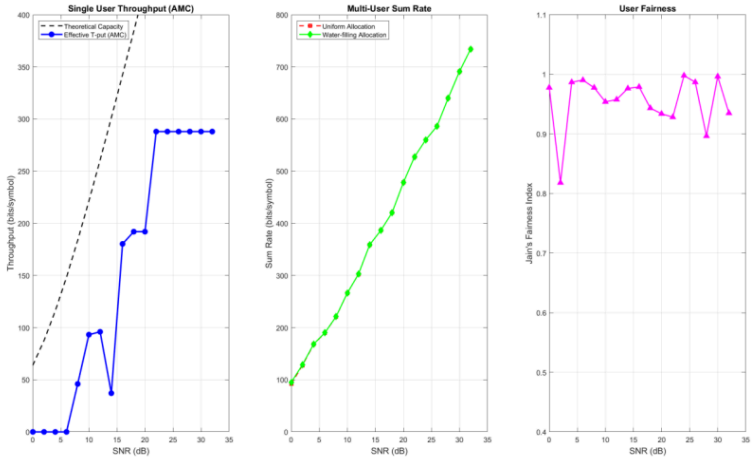

Figure 5. Simulation results of throughput and user fairness under different SNR conditions

Figure 5(a) shows the single-user throughput versus SNR. The dashed curve represents the theoretical capacity trend, while the solid curve represents the effective throughput after AMC and packet errors are considered. The effective throughput increases in a step-like manner and finally reaches a plateau at high SNR. This means that MCS limits, coding overhead, and retransmission can prevent the practical throughput from increasing indefinitely.

Figure 5(b) shows the multi-user sum rate under uniform allocation and approximate water-filling allocation. The water-filling method normally achieves a higher sum rate in the medium and high SNR regions because it allocates more power or resources to stronger subcarriers and users. Figure 5(c) shows Jain fairness index. The curve remains in a relatively high range, indicating that the system can still maintain acceptable fairness while improving the total throughput.

These results support the main idea of this paper: increasing SNR alone is not enough to guarantee effective throughput. When synchronization is unreliable, BLER and MCS mismatch can cause early throughput saturation. By using k as an AMC and scheduling input, the system can choose conservative transmission when synchronization quality is poor and use higher-order modulation and more aggressive resource allocation only when synchronization is reliable.

6. Conclusion and future work

This paper proposed a joint symbol synchronization and throughput optimization framework for OFDM systems. The proposed receiver combines CP autocorrelation-based coarse synchronization with pilot cross-correlation-based fine synchronization. A synchronization confidence metric k is then constructed from CP correlation, pilot correlation, and estimation stability. This metric is used to guide AMC and resource allocation, so that synchronization reliability becomes part of the throughput decision process.

The simulation results show that the proposed framework can reduce aggressive MCS selection under unreliable synchronization, improve effective throughput stability, and maintain reasonable fairness in multi-user scenarios. The key contribution is not only a synchronization module, but a closed-loop mechanism that connects synchronization, AMC, and resource allocation.

Several limitations remain. First, the current results are mainly based on MATLAB simulation and need further verification with real channel data or a hardware testbed. Second, the weight

DOI: 10.54254/2755-2721/2026.34954

selection in the synchronization confidence metric can be optimized more systematically. Third, future work can extend the framework to massive MIMO, millimeter-wave OFDM, and 6G ultra-reliable low-latency scenarios. Model-driven deep learning, lightweight CNNs, and online channel prediction may also be integrated into the receiver, but their complexity and real-time implementation cost must be carefully controlled [9, 10].

References

[1] ETSI. (2024). 5G; NR; Physical channels and modulation (3GPP TS 38.211 version 18.4.0 Release 18). ETSI TS 138 211 V18.4.0.
[2] Wang, X., Li, Z., Zhao, X., Gan, J., Zhang, B., & Liu, H. (2023). Simplified time synchronization method for 5G NR system in high-frequency offset environment. In Proceedings of the 2023 5th International Conference on Information Technology and Computer Communications (pp. 17-23). https: //doi.org/10.1145/3606843.3606847
[3] Qing, C., Yang, N., Tang, S., Chen, J., & Wang, J. (2024). CNN-aided timing synchronization in OFDM systems by exploiting lightweight cascaded mode. ICT Express, 10(1), 9-14. https: //doi.org/10.1016/j.icte.2023.03.003
[4] Liu, J., Mei, K., Zhang, X., McLernon, D., Ma, D., Wei, J., & Zaidi, S. A. R. (2021). Fine timing and frequency synchronization for MIMO-OFDM: An extreme learning approach. IEEE Transactions on Cognitive Communications and Networking. https: //doi.org/10.1109/TCCN.2021.3118465
[5] ETSI. (2024). 5G; NR; Physical layer procedures for data (3GPP TS 38.214 version 18.4.0 Release 18). ETSI TS 138 214 V18.4.0.
[6] Kamal, M. A., Raza, H. W., Alam, M. M., Su'ud, M. M., & Sajak, A. B. A. B. (2021). Resource allocation schemes for 5G network: A systematic review. Sensors, 21(19), 6588. https: //doi.org/10.3390/s21196588
[7] He, H., Jin, S., Wen, C.-K., Gao, F., Li, G. Y., & Xu, Z. (2019). Model-driven deep learning for physical layer communications. IEEE Wireless Communications, 26(5), 77-83. https: //doi.org/10.1109/MWC.2019.1800447
[8] Shammaa, M., Mashaly, M., & El-Mahdy, A. (2024). The use of deep learning techniques in OFDM receivers for 5G NR: A survey. Procedia Computer Science, 231, 32-39. https: //doi.org/10.1016/j.procs.2023.12.154
[9] Zhang, W., Gao, F., Jin, S., & Lin, H. (2018). Frequency synchronization for uplink massive MIMO systems. IEEE Transactions on Wireless Communications, 17(1), 235-249.
[10] Dai, L., Jiao, R., Adachi, F., Poor, H. V., & Hanzo, L. (2020). Deep learning for wireless communications: An emerging interdisciplinary paradigm. IEEE Wireless Communications, 27(4), 133-139. https: //doi.org/10.1109/MWC.001.1900491