BULLETIN of Cherkasy State Technological University

Journal homepage: https://bulletin-chstu.com.ua/en

Vol. 31 No. 3. 2026

UDC 621.391:004.8
DOI: 10.62660/bcstu/3.2026.68

Methods of adaptive control of iterative decoding of turbo codes

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Abstract. The rapid development of 5G and 6G wireless networks has put forward strict requirements for the delay of channel decoding, which has actualised the task of reducing the computational complexity of iterative turbo decoders without losing noise immunity. The purpose of the study was to systematise, classify, and compare methods of adaptive control of the number of iterations of the turbo decoder, in particular, the classical criteria for early stop and the neural network adaptive approach. Methods of comparative theoretical analysis, analytical classification of criteria by convergence indicator type, and assessment of computational complexity based on published results for codes compatible with the 4G standard were applied. Classification of criteria by the type of convergence indicator and by the type of implementation was proposed. It was found that classical criteria based on hard solutions, ratio and sign difference, cross-entropy, and average reliability of soft solutions reduced the average number of iterations by 30-55% with a slight degradation in the bit error rate. It was found that improvements in the efficiency of the criteria were accompanied by increased demands on memory and computing resources. It was shown that the neural network adaptive method integrated into the model-oriented decoder reduced the average number of iterations by 60-75% due to the fact that the stop threshold was trained together with the decoder weights and automatically adapted to channel conditions. Recommendations are formulated for choosing a criterion for resource-constrained hardware platforms, real-time systems with minimum latency priority, and systems with a wide dynamic range of signal-to-noise ratios. The results obtained can be used by developers of communication systems and designers of hardware turbo decoders for portable diagnostic and telecommunications devices

Keywords: BCJR algorithm; early stop criterion; external information; computational complexity; neural network decoder; decoding convergence

INTRODUCTION

5G and 6G wireless networks impose strict requirements on the latency and power consumption of channel decoding, especially in ultra-reliable low-latency communication applications where the processing budget

Article's History: Received: 11.04.2026; Revised: 21.08.2026; Accepted: 21.09.2026; Published: 07.10.2026

Suggested Citation:
Bodnarenko, B., Zvuzdetskyi, Ye., & Ivanov, Yu. (2026). Methods of adaptive control of iterative decoding of turbo codes. *Bulletin of Cherkasy State Technological University*, 31(3), 68-76. doi: 10.62660/bcstu/3.2026.68.

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of a single code block is limited to a few milliseconds. Turbo codes provide noise resilience close to the Shannon limit; however, their iterative decoding involves a fixed number of rounds of external information exchange between the two component decoders. With a high signal-to-noise ratio, decoder convergence occurs much earlier than the set iteration limit, so subsequent passes practically do not improve decoding quality, but increase latency and power consumption. Eliminating these redundant iterations without losing noise immunity is an urgent scientific and technical problem, which determines the suitability of turbo decoders for real-time systems and resource-limited platforms. In addition to increasing latency, redundant iterations unnecessarily waste energy, which is especially critical for portable and stand-alone devices with limited power supply, so finding methods for dynamic decoding completion is both an energy efficiency challenge and a challenge to ensure compatibility with the tight time budgets of modern protocols. Turbo codes remain a component of 3G and 4G standards and a number of satellite protocols, so improving the efficiency of their decoding remains practical even during the transition period to new-generation networks.

Contemporary research is actively looking for ways to reduce the complexity and delay of channel decoding. A.-M. Cuc *et al.* (2023) compared the noise immunity of turbo codes, low-density parity checks, and polar codes in the channel with additive white Gaussian noise in the presence of inter-character interference and concluded that turbo codes retain their advantage at medium block lengths, which confirms the feasibility of their further optimisation. L. Zhang *et al.* (2022) proposed a parallel turbo decoder based on a recurrent neural network and showed that the neural network implementation allows to significantly parallelising calculations without losing decoding quality. According to S. Miao *et al.* (2024), who analysed channel coding trends for 6G systems, reducing decoder latency will be a determining factor in development, and trained and hardware-oriented decoders will play an increasingly important role alongside classic turbo, LDPC, and polar codes. C. Yue *et al.* (2023) reviewed efficient short-block decoders for ultra-reliable communication systems with low latency and showed that the choice of decoder is determined by the balance between noise immunity and computational complexity. S. Murugan *et al.* (2025) implemented a reliability-oriented direct turbo decoder on a programmable logic integrated circuit and achieved approximately 3.8-fold delay reduction with low use of crystal resources, which demonstrates the practical significance of hardware-oriented methods for reducing calculations specifically for short blocks typical for real-time applications.

Despite a significant amount of research devoted to either classical stop criteria or neural network decoders separately, there is a lack of a comprehensive comparison of these two areas, including the suitability of the methods for hardware implementation, power consumption and a wide range of signal-to-noise ratios. The research was aimed at generalising and typologising approaches to adaptive control of the number of iterations of the turbo decoder, their comparison by the main technical characteristics, and determining appropriate selection criteria for communication systems with limited resources and high delay requirements. To achieve this objective, the objective was to consolidate disparate criteria into a single system of metrics, thereby enabling them to be directly compared in terms of complexity and efficiency, and to identify trade-offs between reducing latency, memory requirements, and maintaining noise immunity.

LITERATURE REVIEW

The theoretical foundations of iterative decoding were put forward by L. Bahl *et al.* (1974), who proposed an algorithm for calculating the posteriori probabilities of symbols, optimal by the criterion of the minimum probability of error per symbol. This result established the theoretical limit of optimality, with respect to which all practical decoding simplifications were further evaluated. On its basis, C. Berrou *et al.* (1993) introduced turbo codes, which, due to the parallel connection of two recursive systematic convolutional codes and iterative exchange of external information, achieve noise immunity close to the Shannon limit. P. Robertson *et al.* (1995) proposed logarithmic variants of the algorithm – Log-MAP and Max-Log-MAP, which retain the basic properties of optimal decoding with significantly lower computational complexity and are still used as the arithmetic core of both classical and neural network decoders. Reducing the computational complexity at this stage paved the way for further research into ways of reducing not the arithmetic involved in a single iteration, but the number of iterations themselves. J. Hagenauer *et al.* (1996) formalised the exchange of external information as an iterative concurrent process and proposed a cross-entropy (CE) criterion for detecting convergence. Thus, it was shown for the first time that the decoding process can not only be performed, but also quantified for completeness.

The first practical criteria for early stopping were proposed by R. Shao *et al.* (1999): the hard decision-based criterion (HDA), which stops decoding when the signs of the logarithmic likelihood ratio (LLR) stop changing, and the sign change ratio (SCR), which is a threshold version of the HDA and is less sensitive to single false sign changes. Y. Wu *et al.* (2000) introduced the sign difference criterion (SDR), which compares the signs of a priori and external information at the output of a component decoder and does not require storing the LLR of the previous iteration, which makes it attractive for hardware implementations. A. Taffin (2003) proposed a generalised criterion that combines the

detection of both convergence and failure of decoding in a single indicator. R. Mohamad *et al.* (2014) investigated the measurement of reliability (MOR) based on the average LLR module and showed its effectiveness at a low signal-to-noise ratio, where other criteria tend to perform maximum iterations. This showed that the effectiveness of the criterion is not a constant characteristic, but depends on the channel conditions under which it is applied. M. AlMahamdy & J. Dill (2017) proposed a method for identifying unsolvable blocks that separately tracks markers of "slow" and "frozen" convergence and demonstrates high efficiency in channels with an unknown or variable signal-to-noise ratio.

It is these classical papers that set the terminology and basic convergence indicators, which are systematised in further analysis. Together, they show a gradual movement from the simplest signs of decoding completion to more subtle and sensitive indicators that can consider not only the fact of convergence itself, but also the characteristics of the decoder's behaviour in different conditions. Therefore, a common feature of all the considered approaches remains the focus on a pre-set, empirically established threshold, which outlines the boundary of the classical approach to iteration management.

MATERIALS AND METHODS

The research was carried out using a comparative theoretical analysis of published results, combining analytical classification, an assessment of computational complexity, and an evaluation of the effectiveness of iteration control methods. The research material was published in peer-reviewed scientific sources quantitative characteristics of early stop criteria, and neural network decoders obtained for turbo codes compatible with the LTE standard (code speed R = 1/3, information block length K = 6,144 bits). The choice of these parameters was conditioned by their prevalence in the literature, which ensures comparability of numerical estimates of different researchers. Additional materials included structural descriptions of model-oriented decoders and their training parameters given in the relevant primary sources, and qualitative characteristics of hardware implementations.

The analytical classification method is used to organise criteria by two independent criteria: by the type of convergence indicator (hard solutions, soft solutions, statistical characteristics of LLR, neural network estimates) and by the type of implementation (fixed threshold, adaptive threshold, model-oriented, and fully end-to-end implementations). This method is chosen because it allows reducing heterogeneous criteria to a single coordinate system and identifying patterns between complexity and efficiency; in the absence of such ordering, a direct comparison of the criteria described by different researchers in different terms would be incorrect.

The method of estimating computational complexity involved determining three indicators for each criterion: the need to store LLR or intermediate values of the previous iteration; the number of arithmetic operations per iteration (addition, multiplication, comparison, module calculation); and the need for a preliminary assessment of the signal-to-noise ratio. Based on these indicators, a qualitative complexity scale with gradations "very low", "low", "medium" and "moderate" was formed, which was substantiated by the heterogeneity of the initial data and the impossibility of directly reducing the hardware costs of different researchers to a single metric. The qualitative scale was deliberately chosen instead of point estimates, since hardware costs depend on the manufacturing technology and architecture, and therefore, the exact numerical values would not be reproducible enough.

The method for evaluating efficiency was to determine the percentage of reduction in the average number of iterations compared to a fixed number, provided that the bit error rate remains at the level of basic decoding without stopping early. For the analysis of the neural network adaptive method, the structural decomposition method was additionally applied, in which the decoder was considered as a sequence of blocks of a deep neural network (DNN), and the threshold function – as a parameterised neural network value that is trained together with the decoder weights. The final step was the recommendation synthesis method, which compared the results of classification and evaluation for three typical operational scenarios; the study sequence included a transition from classification to quantification and ended with a synthesis of recommendations. A limitation of the applied approach was that numerical estimates of different researchers were obtained under slightly different modelling conditions; for a unified comparison, they were rounded to the nearest range with a width of 5%, which ensures the correctness of qualitative conclusions without losing practical significance.

RESULTS AND DISCUSSION

Systematisation of the considered methods allows distinguishing four classes of criteria by the type of convergence indicator. The first class includes HDA-based criteria that track the sign stabilisation of decoded bits between adjacent iterations and have minimal memory requirements. The second class is formed by criteria based on the statistics of soft solution signs – SCR and SDR, which replace binary verification of the complete absence of changes with a threshold estimate of the share of changed positions. The third class consists of criteria based on the statistical characteristics of LLR – CE and MOR, which quantify either the discrepancy between the posterior distributions between iterations or the average confidence of the decoder. The fourth class is formed by neural network adaptive estimates,

in which the convergence indicator and its trigger threshold are learned from data. According to the type of implementation, the criteria are divided into methods with a fixed threshold, methods with an adaptive threshold that depends on the block and channel parameters, model-oriented methods, and fully end-to-end neural network decoders.

A model-oriented neural network decoder naturally integrates adaptive control of the number of iterations: each block of a deep neural network corresponds to one iteration of classical decoding, and the weights of blocks are trained end-to-end. After each block, the normalised convergence rate is calculated – the norm of the difference between the external information vectors of two adjacent iterations:

$$\Delta_i = \frac{||L_e^i - L_e^{i-1}|\ \ |_2}{K}, \quad (1)$$

where *Le(i)* – external LLR vector after the i-th block of the neural network, *K* – length of the information block.

Decoding is completed ahead of schedule as soon as Δi falls below the adaptive threshold ε, which inversely depends on the current estimate of the signal-to-noise ratio. The fundamental difference between this approach and classical criteria is that the threshold is not set empirically for a specific code configuration, but is trained together with the decoder weights, so it automatically adapts to different block lengths, code speeds, and channel conditions without re-tuning. The sequence of calculations of the control subsystem is shown in Figure 1.

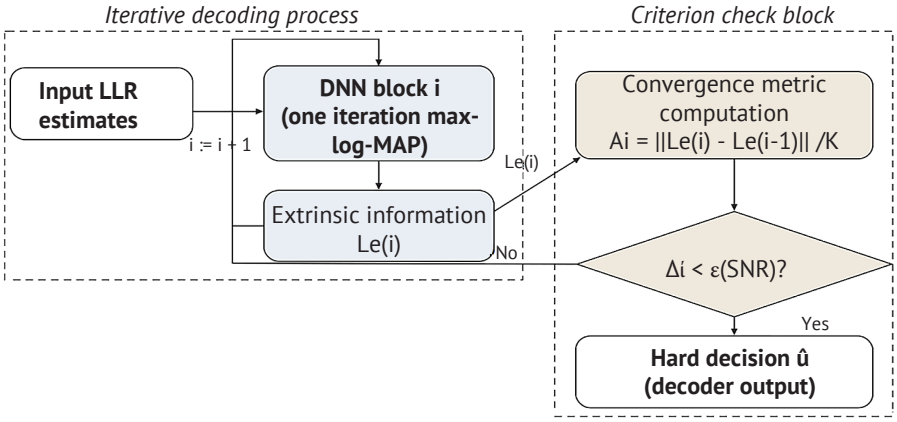


Figure 1. Structure of the adaptive management iterative decoding subsystem

Source: compiled by the authors

As can be seen from Figure 1, the architecture clearly distinguishes between the process of iterative decoding (establishment of external information by a neural network block) and the criterion verification block (calculation of the convergence indicator and comparison with the adaptive threshold). This structural organisationallows the stop check to be carried out in parallel with the main computational path and control to be returned to the next iteration only when necessary, thereby minimising the overhead associated with the control procedure itself. According to Y. He *et al.* (2020), the neural network criterion reduces the average number of iterations by 60-75% for a signal-to-noise ratio of more than 2 dB, which is equivalent to a 3-4-fold reduction in the average decoding delay compared to a fixed six iterations. The established properties of the adaptive criterion can be conveniently compared with the characteristics of the classical criteria summarised in Table 1.

Table 1. Comparative characteristics of iterative decoding early stop criteria

Criteria	Basis of the solution	Difficulty	Reduction of iterations	Notes
Fixed number of iterations	I = const	Very low	–	Base case, excess at high SNR
HDA (Shao *et al.*, 1999)	Hard decisions between iterations	Low	~30-40%	Does not require LLR storage
SCR (Shao *et al.*, 1999)	Share of LLR sign change	Low	~35-45%	HDA threshold version
SDR (Wu *et al.*, 2000)	Difference between a priori and external information signs	Low	~35-45%	Does not require LLR memory
CE (Hagenauer *et al.*, 1996)	Cross-entropy of LLR between iterations	Average	~35-50%	High accuracy, requires memory
MOR (Mohamad *et al.*, 2014)	Average reliability of soft decisions	Average	~40-55%	Effective at low SNR

Continued Table 1.

Criteria	Basis of the solution	Difficulty	Reduction of iterations	Notes
Sum-α / Max-log (Ouardi, 2021)	Sum of direct recursion values A	Low-average	~40-55%	Early solution to the LLR calculation
Generalised (Taffin, 2003)	Combined convergence / failure detection	Average	~60-75%	Considers unsolvable blocks
Identification of unsolvable blocks (AlMahamdy & Dill, 2017)	Frozen convergence markers	Low-average	~45-65%	Effective at variable SNR
Adaptive neural network (He *et al.*, 2020)	Δ external information between DNN blocks	Moderate	~60-75%	Integrated model-oriented decoder

Notes: SNR – signal-to-noise ratio
Source: compiled by the authors

A comparison of the criteria presented in Table 1 reveals a consistent trend: as the complexity of the convergence criterion increases, the reduction in the number of iterations becomes greater, albeit at the expense of higher memory and computational requirements. The rigid solution-based criterion forms the lower limit of complexity and remains appropriate for hardware implementations with severe resource constraints, while the cross-entropy criterion provides higher efficiency at the cost of storing the full LLR vector of the previous iteration. The generalised criterion and method for identifying unsolvable blocks extend the reduction range due to additional logic for detecting decoding failure. The neural network adaptive method occupies the top level of the hierarchy: with moderate overhead costs, it achieves maximum reduction due to the fact that the threshold adapts to the current channel conditions, and is not fixed at the system design stage.

The specification of computational complexity shows that the criteria of the first and second classes (HDA, SCR, SDR) require only sign comparison and counting operations and do not preserve the LLR vector of the previous iteration, so their complexity is estimated as low. The character difference criterion additionally differs in that it uses existing a priori and external information of the current iteration, avoiding memory accesses. The third class criteria require more resources: cross-entropy requires storing the full LLR vector of the previous iteration and calculating the sum of products, and the reliability criterion is the accumulation of LLR modules corresponding to the average level of complexity. The neural network method adds to the arithmetic calculation of the norm of difference of vectors of external information and comparison with the threshold, but these operations are insignificant relative to the calculations of the neural network block itself, so the overall control complexity is estimated as moderate. The need for a preliminary assessment of the signal-to-noise ratio occurs only for methods with an adaptive threshold, primarily for the neural network criterion.

Advanced performance analysis shows that classical criteria based on hard and soft solutions provide a reduction in the average number of iterations in the range of about 30-45%, criteria based on LLR statistics – about 35-55%, and methods with combined detection and neural network methods – about 60-75%. The behaviour of criteria with low signal-to-noise ratio is important: the criteria for cross-entropy and sign change in noisy channels tend to perform the maximum number of iterations, while the neural network criterion sets a lower threshold for a low signal-to-noise ratio, allowing more iterations to be performed and the potential for error correction to be exhausted. This asymmetric adaptation provides a compromise between latency and noise immunity for systems with a wide dynamic range of signal-to-noise ratios, while the reliability criterion remains the most appropriate for a permanently low signal-to-noise ratio.

Based on a comparison of complexity and efficiency, recommendations are formulated for three operating scenarios. For resource-constrained hardware platforms with stringent silicon area and power consumption requirements, hard decision- or sign difference-based criteria are preferable, as they do not require LLR storage and can be implemented with minimal hardware resources. For real-time systems with minimum latency priority, primarily ultra-reliable communication systems with low latency, the best balance of latency and noise immunity is provided by a neural network adaptive method integrated into a model-oriented decoder, provided that there is a computational resource for the neural network blocks. For systems with a wide dynamic range of signal-to-noise ratios, it is advisable to combine a reliability criterion that is effective at a low signal-to-noise ratio with an adaptive threshold that can be adjusted according to the current channel parameters. The recommendations provided should be regarded as indicative, in view of the numerical rounding procedure described in the Methods section.

It is advisable to compare the generalisations obtained in this paper with the results of contemporary research, which allows assessing their validity and place among current trends. T. Matsumine & H. Ochiai (2024), in a systematic review of deep learning methods for channel coding, concluded that model-oriented

approaches provide the best compromise between interpretability and computational complexity; this conclusion is fully consistent with the author's observation that it is the model-oriented neural network method that occupies the top level of the hierarchy in terms of iteration management efficiency, while maintaining structural compliance with classical decoding.

However, a number of studies have demonstrated the limits of applicability of purely neural network solutions. Y. Choukroun & L. Wolf (2022) proposed a decoder based on the transformer architecture, which achieves high performance for several code families. S.-J. Park *et al.* (2025) developed this area by introducing a multiple masking strategy to improve decoding of short blocks. Despite the high quality of such decoders, they require a complete rethinking of the reception path and are incompatible with existing standards, which limits their immediate implementation. This cautious assessment was supported by Y. Yuan *et al.* (2025), who, based on the results of critical mapping of neural network decoders, found that decoding according to ordered statistics can be superior to transformer decoders in the field of short and medium blocks. The researchers agreed with this caveat: it emphasises that the advantage of neural network methods is not universal, but is implemented primarily in combination with the classical decoding structure, as in the model-oriented approach under consideration.

Special attention should be paid to the hardware-energy dimension of the problem, which often remains outside the limits of purely algorithmic comparisons. M. Rowshan *et al.* (2024) noted that in 6G systems, turbo, LDPC, and polar codes will co-exist, and therefore, universal iteration management mechanisms independent of a particular code family will be of particular value. In contrast to the studies that optimise a particular type of decoder, the analysis shows that adaptive control of the number of iterations is such an end-to-end mechanism: it reduces latency and power consumption regardless of the chosen decoder and therefore complements both classical and neural network solutions well. It is this combination of universality and compatibility with standardised protocols that determines the practical significance of the methods systematised in the paper.

The area of delay reduction for ultra-reliable communication systems with low latency was investigated by A. Gautam *et al.* (2025), who analysed universal code-independent decoders for the 6G scenario and showed their competitiveness in relation to standardised solutions. The findings complement these studies: while the researchers mentioned focus on choosing the type of Decoder, the current study shows that an additional reserve for reducing latency is contained at the level of managing the number of iterations and can be combined with any of the decoders considered. A similar reserve at the early completion level was confirmed by M. Indoonundon & T.P. Fowdur (2025), who used machine learning to reduce the average number of iterations of the 5G LDPC decoder while maintaining noise immunity, while Z. Xu *et al.* (2021) proposed a common early stop criterion for cross-entropy-based source-channel decoding systems. The coincidence of trends for turbo and LDPC codes indicates the universality of the principle of adaptive iteration management.

The prevalence of this approach to other code families was confirmed by M. Meenalakshmi *et al.* (2024), who developed deep learning-based polar code decoders for 5G systems and demonstrated reduced latency compared to classical algorithms. This is consistent with the current finding that model-oriented stop threshold training is carried over between code families. A separate line consists of studies aimed at analytical criteria suitable for logarithmic decoders: A. Ouardi (2021) proposed a criterion based on the sum of direct recursion values that makes the completion decision even before calculating the LLR, and A. Ouardi & B.S. Bouazza (2025) moved this criterion to the logarithmic domain without loss of accuracy, ensuring compatibility with hardware implementations. These results confirm this pattern: the practical significance of the criterion is determined not only by theoretical efficiency, but also by the possibility of integration into already standardised protocols and hardware platforms. In general, the comparison showed that the obtained generalisations do not contradict contemporary research, but systematise them from the same positions of the convergence indicator and computational complexity, which is the main contribution of this study.

CONCLUSIONS

The paper systematised and compared methods for adaptive control of the number of iterations of the turbo decoder, which allow eliminating redundant iterations at a high signal-to-noise ratio and thereby reducing decoding latency and power consumption. The classification of early stop criteria based on two independent features – the type of convergence indicator and the type of implementation – was proposed, which reduced heterogeneous methods to a single coordinate system and facilitates their reasonable choice. It was found that classical criteria based on hard solutions, ratio and difference of signs, cross entropy, and average reliability of soft solutions provided a reduction in the average number of iterations by about 30-55% with a slight degradation in the frequency of bit errors, and an increase in efficiency was accompanied by an increase in memory and computing requirements.

It was shown that the neural network adaptive method integrated into the model-oriented decoder surpasses classical approaches, reducing the average number of iterations by 60-75%, since the stop threshold is trained together with the decoder weights and automatically adapts to channel conditions. It was revealed

that the choice of the optimal criterion is determined by the application scenario: under strict hardware constraints, criteria based on rigid solutions or sign differences are appropriate; for real-time systems with minimum delay priority, the neural network method provides the best balance; for a wide dynamic range of signal-to-noise ratio, a combination of reliability criterion with an adaptive threshold is appropriate. Promising areas of further research are the integration of adaptive stop criteria with suboptimal logarithmic decoding algorithms, joint training of a neural network decoder, and a stop criterion with a multi-purpose loss function that simultaneously considers the frequency of bit errors, the average number of iterations and power consumption, and the hardware implementation of a model-oriented decoder with an integrated stop criterion on a programmable logic integrated circuit for portable diagnostic devices.

ACKNOWLEDGEMENTS

The authors express their gratitude to the team of Research Project No. 32-D-413 at Vinnytsia National Technical University for their technical support and valuable comments, which contributed to the successful completion of this study.

FUNDING

This study was conducted based on the results of research project No. 32-D-413, funded from the State Budget of Ukraine, on the topic "Development and research of intelligent micro- and optoelectronic devices and systems for functional diagnostics in disaster medicine" (Order of the Ministry of Education and Science of Ukraine No. 22 of 9 January 2026).

CONFLICT OF INTEREST

None.

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Методи адаптивного керування ітеративним декодуванням турбо-кодів

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Анотація. Стрімкий розвиток бездротових мереж п'ятого та шостого поколінь висунув жорсткі вимоги до затримки канального декодування, що актуалізувало завдання зниження обчислювальної складності ітеративних турбо-декодерів без втрати завадостійкості. Метою дослідження було систематизувати, класифікувати та порівняти методи адаптивного керування кількістю ітерацій турбо-декодера, зокрема класичні критерії дострокової зупинки й нейромережевий адаптивний підхід. Застосовано методи порівняльного теоретичного аналізу, аналітичної класифікації критеріїв за типом показника збіжності та оцінювання обчислювальної складності за опублікованими результатами для кодів, сумісних зі стандартом четвертого покоління. Запропоновано класифікацію критеріїв за типом показника збіжності та за типом реалізації. Встановлено, що класичні критерії, які ґрунтуються на жорстких рішеннях, відношенні та різниці знаків, перехресній ентропії й середній надійності м'яких рішень, скорочували середню кількість ітерацій на 30-55 % за незначної деградації частоти бітових помилок. Виявлено, що зростання ефективності критеріїв супроводжувалося підвищенням вимог до пам'яті та обчислювальних ресурсів. Показано, що нейромережевий адаптивний метод, інтегрований у моделеорієнтований декодер, скорочував середню кількість ітерацій на 60-75 % завдяки тому, що поріг зупинки навчався разом із вагами декодера й автоматично адаптувався до умов каналу. Сформульовано рекомендації щодо вибору критерію для апаратно-обмежених платформ, систем реального часу з пріоритетом мінімальної затримки та систем широкого динамічного діапазону відношення сигнал/шум. Отримані результати можуть бути використані розробниками систем зв'язку та проєктувальниками апаратних турбо-декодерів для портативних діагностичних і телекомунікаційних пристроїв

Ключові слова: алгоритм BCJR; критерій дострокової зупинки; зовнішня інформація; обчислювальна складність; нейромережевий декодер; збіжність декодування