

Issues of Adaptive Neuro-Fuzzy Modeling of Operational and Predictive Control Systems for Information Flows in Telecommunication Networks

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Abstract: This article discusses the issues of improving the efficiency of information flow management in telecommunication networks. In particular, scientific approaches to the development of operational and predictive control systems based on adaptive neuro-fuzzy modeling are analyzed. The proposed models make it possible to reduce computational load in traffic flow distribution, enhance real-time decision-making capabilities, and ensure stable network operation under various uncertainty conditions. Furthermore, the performance of neuro-fuzzy models of different orders is comparatively evaluated, and the mechanisms by which their application in military communication networks reduces information transmission losses and increases network throughput are revealed. The research findings are of significant scientific and practical importance for identifying priority directions in the development of communication systems of the Armed Forces.

Keywords: telecommunication networks, information flows, operational and predictive control, adaptive neuro-fuzzy model, Takagi–Sugeno mechanism, traffic distribution, military communication system.

INTRODUCTION

The rapid development of modern information and communication technologies, the expansion of digital services, and the continuous increase in the number of users have led to a significant growth in the volume of information flows transmitted through telecommunication networks. Traditional network management methods respond to changes in the network only after problems or overloads have already occurred. Consequently, they are unable to fully ensure the high speed, continuity, and reliability required by modern telecommunication networks[1].

In the process of command and control of military forces, a large number of communication network components are deployed to ensure the exchange of information flows and traffic of all types, as well as to support voice communications. These include channel-forming equipment, special terminal switching devices, remote control systems, and automation facilities, which are organizationally integrated into separate elements (communication centers, stations, and groups) according to their technical interconnection, communication type, information transmission method, and electrical characteristics. The continuous development of means and forms of combat operations imposes increasingly stringent requirements on the command and control system and, consequently, on the military communication system[2].

In the rapidly changing conditions of modern warfare, where troops are frequently redeployed and command posts are constantly relocated, evaluating the efficiency of communication networks is one of the key factors in ensuring effective command and control. Therefore, special attention is paid to the organization of modern communication systems at all levels of military headquarters.

At present, various methods, particularly those based on probability theory, are widely used to improve the efficiency of telecommunication network management systems within the Ministry of Defense. However, these methods are unable to adequately account for uncertainties arising within the network or require the analysis of a large volume of statistical data[3].

Under the conditions of modern combat operations, the reliable functioning of telecommunication networks is of critical importance for ensuring the effectiveness of the command and control system of the Armed Forces. The rapid growth of information flows, the increasing demand for new communication services, and the accelerated development of technological solutions require the continuous improvement of the telecommunication networks of the Ministry of Defense. The uninterrupted operation of communication systems ensures promptness and accuracy at all levels of troop command and control, which is an essential prerequisite for real-time decision-making and the timely transmission of commands to military units. Therefore, the development of operational and predictive information flow management systems for telecommunication networks and the application of an adaptive neuro-fuzzy modeling approach in such systems are considered important scientific and practical challenges[4].

Improving the efficiency of information flow management in telecommunication networks, ensuring the rational utilization of network resources, and maintaining Quality of Service (QoS) have become among the priority directions of scientific research in recent years. In particular, the rapid development of 5G and future 6G networks, the Internet of Things (IoT), cloud computing, Software-Defined Networking (SDN), and Artificial Intelligence technologies has significantly increased the volume and complexity of information flows transmitted through telecommunication networks. Consequently, this has created the need for developing new methods for real-time traffic forecasting, network load prediction, and intelligent support for management decision-making[5].

RESEARCH METHODOLOGY

The study employed systematic analysis, mathematical modeling, adaptive neuro-fuzzy modeling (ANFIS), the Takagi–Sugeno fuzzy inference mechanism, comparative analysis, and simulation modeling methods. Information flow management processes in telecommunication networks were modeled using first-, second-, and third-order neuro-fuzzy models, and their computational complexity, prediction accuracy, and convergence speed were comparatively evaluated. Based on the obtained results, network throughput, packet loss, transmission delay, and the efficiency of network resource utilization were assessed.

RESULTS AND DISCUSSION

The theoretical foundations of Artificial Intelligence-based management systems have been extensively studied by many researchers. L. Zadeh, the founder of fuzzy logic theory, demonstrated that decision-making processes under conditions of uncertainty and incomplete information can be mathematically represented. According to his studies, hybrid intelligent systems are of particular scientific importance in solving modern complex control problems, as they enable the integration of various intelligent methods within a unified modeling framework [6].

The theoretical and practical foundations of artificial neural networks were comprehensively investigated by S. Haykin, who demonstrated their high efficiency in identifying complex nonlinear relationships, learning from large-scale datasets, and solving forecasting problems [7].

This approach has been widely applied in telecommunication networks for traffic prediction and the modeling of dynamic processes.

The integration of fuzzy logic and artificial neural networks reached a new stage with the development of the Adaptive Neuro-Fuzzy Inference System (ANFIS) model proposed by S. R. Jang. This model combines self-learning neural networks with fuzzy inference mechanisms, enabling the high-accuracy modeling of complex and uncertain systems[8].

Issues related to traffic modeling and management in telecommunication networks have also been extensively studied in the scientific works of D. Bertsekas, R. Gallager, L. Kleinrock, and other researchers. Their studies established the theoretical foundations of packet-switched networks, queueing theory, routing algorithms, and network resource optimization. However, since most of these approaches are based on deterministic or statistical models, their ability to adequately represent the highly dynamic and uncertain processes occurring in telecommunication networks remains limited[9].

In recent years, studies devoted to the application of modern technologies in telecommunication networks have proposed effective methods for traffic prediction based on adaptive control, machine learning, and neuro-fuzzy models. Nevertheless, the existing research has not comprehensively addressed the issues of operational and predictive information flow management, real-time forecasting of network conditions, and the adaptive optimization of control parameters within an integrated framework[10].

As a result of the conducted research, a scientific approach based on adaptive neuro-fuzzy modeling was developed for the operational and predictive management of information flows in telecommunication networks. The scientific novelty of the research is as follows:

- A multilayer adaptive neuro-fuzzy architecture was developed to model the process of information flow distribution. This architecture makes it possible to reduce computational complexity and improve model execution speed by optimizing the number of inference rules.
- A modified adaptive neuro-fuzzy model based on the Takagi–Sugeno fuzzy inference mechanism was proposed. This model enables real-time prediction of traffic parameters and rapid generation of control decisions in telecommunication networks.
- Based on the modeling results, first-, second-, and third-order neuro-fuzzy models were comparatively analyzed, and their computational complexity, prediction accuracy, and convergence speed were evaluated. According to the analysis results, the model providing the optimal balance between prediction accuracy and computational efficiency was recommended.
- A new scientific approach to adaptive neuro-fuzzy modeling was developed to reduce uncertainties in predicting the volume and intensity of traffic flows in telecommunication networks, improve the stability of control decisions, and enhance the efficiency of network resource utilization[11].

The proposed adaptive neuro-fuzzy modeling approach can be applied in the telecommunication networks of the Ministry of Defense as well as in other information and communication systems requiring a high level of reliability. Its practical significance is manifested in the following aspects:

- Enhancing the throughput capacity of telecommunication networks and improving the efficiency of network resource utilization through intelligent real-time traffic management and dynamic traffic distribution.
- Improving the performance of transit routers and switching nodes by reducing packet loss, transmission delay, and network congestion.
- Ensuring the timely and reliable transmission of combat orders, service information, and control signals among military units through the optimization of control algorithms and routing processes.
- Increasing the efficiency of traffic management and queue optimization for various types of traffic flows by adapting the developed model to mass service systems, corporate data

transmission networks, Internet of Things (IoT) infrastructures, and other multi-flow telecommunication systems.

The traffic management system of the Ministry of Defense telecommunication networks is a complex dynamic system consisting of interconnected functional components. Each component performs specific functions, including the reception, processing, routing, transmission, and monitoring of information flows. In this study, based on the proposed adaptive neuro-fuzzy models, the main indicators characterizing the efficiency of information flow transmission in the telecommunication network of the Ministry of Defense—traffic intensity, network throughput, packet loss, transmission delay, queue length, and the level of network resource utilization—are comprehensively evaluated. Based on the obtained results, it becomes possible to improve the functional efficiency of the network, adaptively optimize control parameters, and develop effective mechanisms for the operational and predictive management of information flows.

Let us consider the development of operating algorithms for programmable logic controllers (PLCs) that perform the functions of controllers in operational and predictive information flow management systems for telecommunication networks. In such decision support systems, the distributed adaptive neuro-fuzzy architecture [1], [2] is represented as a six-layer neural structure, the architecture of which is shown in Fig. 1.

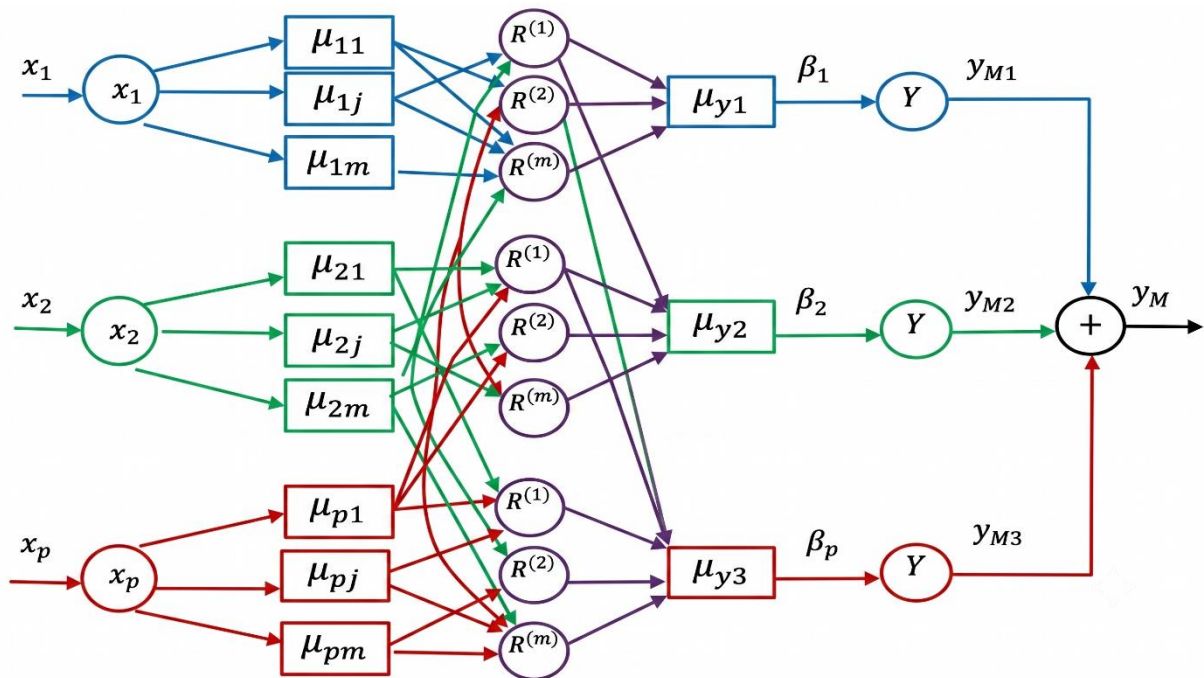


Fig. 1. Structure of the Distributed Neuro-Fuzzy Model for Information Flow Management in the Telecommunication Networks of the Ministry of Defense

In this approach, the input signals of the information flow management system in the telecommunication networks of the Ministry of Defense are distributed among separate neuro-fuzzy structures. A network of neuro-fuzzy structures is formed, where each structure performs the role of an individual submodel, while the aggregated (generalized or global) model consists of a set of these submodels.

The number of fuzzy production rules in the generalized model is significantly reduced compared with that of the original model. The number of fuzzy rules is determined by the corresponding expression. For the information flow management model considered in the telecommunication networks of the Ministry of Defense, we obtain:

$$N = m_1^{p_1} + m_2^{p_2} + \dots + m_q^{p_q} \quad (1)$$

The layers of the model that perform the controller functions in operational and predictive information flow management systems for telecommunication networks operate as follows:

Layer 1: The neurons at this layer receive the input signals and transmit them to the next stage.

Layer 2: At this layer, the fuzzification operation is performed for the operational and predictive management of information flows in telecommunication networks. This requires determining the type and number of the membership functions to be used. In this study, the Gaussian membership function described by Equation (1) is employed.

Layer 3: This layer serves as the generator of fuzzy production rules for information flow management in the telecommunication networks of the Ministry of Defense, where the fuzzy rules are formed.

Layer 4: The implication operation is performed.

Layer 5: The outputs of the individual submodels are generated according to the corresponding expressions, where n denotes the number of submodels used.

Layer 6: The output of the generalized model for the information flow management process in the telecommunication networks of the Ministry of

Defense is obtained as the aggregate of the outputs of the individual submodels.

The partially fuzzified neuro-fuzzy model of the input signals is represented as a five-layer structure based on the Takagi–Sugeno fuzzy inference mechanism. In this approach [3], some input signals are precise (non-fuzzy) (Fig. 2), but their actual values, weighted by the corresponding weighting coefficients, are directly fed into the third layer, namely, into the consequent part of the Takagi–Sugeno functions. The use of the Takagi–Sugeno fuzzy inference mechanism reduces the number of fuzzy rules involved in the process model as well as the number of parameters that must be determined during neural network training[12].

For example, in the model developed for information flow management in the telecommunication networks of the Ministry of Defense, there are four input variables, resulting in a total of nine fuzzy rules. The total number of parameters to be determined during the training process is 64. Furthermore, the structure of the proposed model is considered to be close to that of a linear model; therefore, it can be classified as a quasi-linear model.

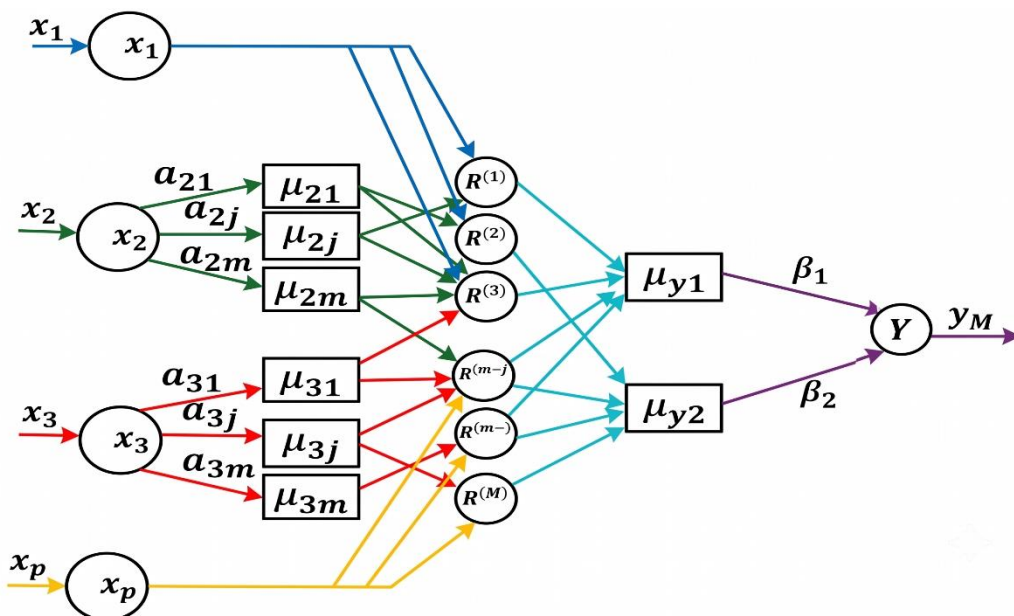


Fig. 2. Structure of the Partially Fuzzified Neuro-Fuzzy Model of Input Signals

Furthermore, in the process of optimizing decision-making for information flow distribution in the telecommunication networks of the Ministry of Defense, the proposed approach reduces the computational load and ensures the suitability of the model for real-time operation. The main challenge in applying the proposed model is determining which input signals should be fuzzified and which should be directly introduced into the consequent part of the fuzzy rules (Fig. 3). To

address this problem, three distributed neuro-fuzzy models—first-order, second-order, and third-order models—were investigated, and their efficiency and accuracy in the modeling process were evaluated. In this approach, the output values of the transmitted information flows in the telecommunication networks of the Ministry of Defense, together with the values of the control actions, are directly introduced into the consequent part of the second-order fuzzy model, which represents the inverse version of the first-order and third-order models, also referred to as the interdependence model that fuzzifies one control variable and one output signal of the system[13]. It should be noted that all three proposed models were developed under the assumption that the system contains four input variables, of which only two are fuzzified.

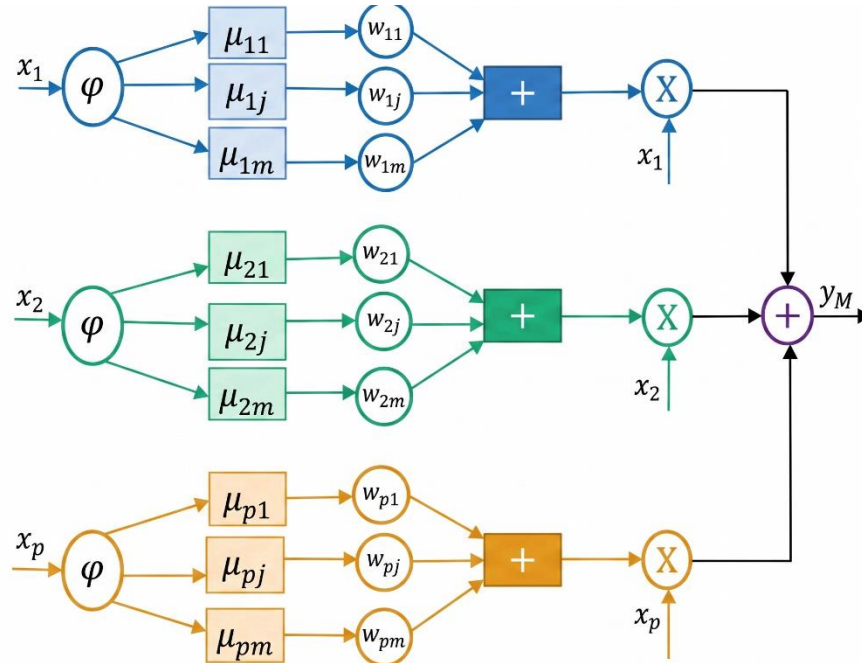


Fig. 3. Structure of the Modified Neuro-Fuzzy Model

Professor T. Yamakawa and his research group proposed a neuro-fuzzy neuron. In essence, it represents a radial basis function neural network with a zero-order Takagi–Sugeno fuzzy inference mechanism. Furthermore, the modified neuro-fuzzy model is implemented in a multivariable version using the structure presented in [4]. The results of our research show that, when using T. Yamakawa’s modified neuro-fuzzy model, it is necessary to minimize two instantaneous errors and, accordingly, update two weighting coefficients, $w_{ji}(k)$ and $v_{ji}(k)$, whereas there is no need to investigate the influence of the fuzzy set parameters[14-15].

Thus, based on the application of the method proposed in this paper, it is possible to significantly improve the efficiency of traffic dropping in transit routers of military communication networks under conditions where the transmission capacity of channels allocated for servicing different classes of traffic varies.

CONCLUSION

The main quality indicators of the efficiency of the military communication network management system, the principal factors influencing them, and the various processes occurring within these networks were identified and analyzed. Simulation experiments were conducted to determine the impact of traffic loss, channel transmission capacity, and other factors on network performance during data transmission.

The experimental results were aimed at developing management protocols for data transmission networks in military communication systems, including multimedia applications. The obtained

results can also be applied to other queuing and mass service systems to improve queue management efficiency.

The problem of information flow management in telecommunication networks is one of the most important factors in ensuring the reliability of the Armed Forces command and control system under the conditions of modern combat operations. In the telecommunication networks of the Ministry of Defense of the Republic of Uzbekistan, the continuous growth of traffic volume, the increasing demand for new services, and rapid technological advancements have created a growing need to introduce operational and predictive management methods to improve network management efficiency.

The proposed adaptive neuro-fuzzy modeling approach enables the efficient distribution of information flows, real-time decision-making, and stable system operation under various uncertainty conditions. The advantage of the developed neuro-fuzzy architecture lies in its ability to reduce the number of inference rules required for information flow regulation, optimize computational workload, and improve the accuracy of output results.

The results of the simulation experiments demonstrated that the proposed approach significantly improves channel throughput, reduces traffic loss, and enhances the efficiency of management protocols in military communication networks. Furthermore, adaptive neuro-fuzzy models increase the efficiency of transit routers in servicing different types of traffic flows.

Thus, adaptive neuro-fuzzy modeling of operational and predictive information flow management systems in telecommunication networks provides an important scientific and practical solution for ensuring the stability and efficiency of military communication systems. Its application enhances the capability of the Armed Forces leadership to make real-time decisions, guarantees uninterrupted command and control down to the smallest military units, and is of strategic importance for establishing a high-performance communication system that meets the requirements of modern combat operations.

The main directions for the development of the military communication system enable the leadership of the Armed Forces of the Republic of Uzbekistan to respond in real time to changes in the military-political and operational-strategic situation, ensure the timely delivery of operational decisions and commands during the employment of the Armed Forces, and consequently provide effective command and control of subordinate military units during combat operations.

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