METHOD OF STRUCTURAL ADAPTATION OF NETWORK INFORMATION SYSTEMS BASED ON GENERALIZED PARAMETER

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Abstract

The present research is devoted to developing a method of structural adaptation of network information systems (NIS) in conditions of high unstable input flow and the influence of destabilizing factors (interference) based on the current values of the generalized parameter of evaluating the effectiveness of information exchange (information efficiency) in the basic and reserve structures. Applying the abovementioned method allows determining the boundary value of the input traffic for implementing structural adaptation, as well as forming an unambiguous condition for the transitions between the basic and reserve topologies of the system. The method can significantly increase the efficiency of information transfer and significantly expand the bandwidth of the NIS. Simulation and analytical models for evaluating the effectiveness of information exchange in NIS using the obtained method of structural adaptation were developed. During the simulation, the

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feasibility of the developed method and the reliability of the results obtained on its basis were confirmed, as well as recommendations were given on its practical application as algorithmic software for the monitoring controller of the system.

**Keywords:** Algorithmic adaptation, information efficiency, information loss, adaptation criteria, adaptation procedures, lane transmission.

I. **Introduction**

To ensure effective NIS information exchange under the conditions of a changing high input information flow and the influence of various destabilizing factors (interference), a complex application of adaptation methods, algorithms and models at the network functioning level with the rational use of channel and physical resources is required. An analysis of the works that solve the adaptation problem shows that in modern digital transmission systems adaptation is multi-circuit in nature, while there are three basic adaptive control curves: parametric, algorithmic and structural. The simplest type of adaptation – parametric adaptation – is based on local indicators and performance criteria of individual elements of the NIS: switching nodes (SN) and communication channels (CC). It is most widely studied and used in practice; however, it has limited opportunities to improve the NIS functioning at the physical and channel levels of the system. Therefore, in NIS information exchange, especially as the input traffic increases and because of the interference, a transition is made to the algorithmic adaptation curve, which is implemented on the basis of generalized parameters and characteristics of information exchange efficiency. The work of the latter is to ensure the functioning of the NIS with the required quality without changing the structural design of the system with the help of the formation of algorithms and procedures for the quasi-optimal distribution of network and channel resources. Nevertheless, the conditions of information exchange can become so complex that to ensure the acceptable functioning of the NIS, reconfiguration of the system structure is required, which has completely exhausted the network and channel capabilities for increasing information efficiency. Thus, the limited range of the mechanisms of parametric and algorithmic adaptation necessitates the use of a higher curve – structural adaptation of the NIS. Figure 1 (which displays the functions of the NIS information efficiency in the form of dependences of the efficiency coefficient of information transfer taking into account the effects of interference from the input information stream illustrates the processes and operation intervals for each adaptive control curve (контур)).
Figure 1: Ranges of action of the NIS adaptation curves

Figure 1 shows that parametric adaptation is not able to solve the problem of outputting the NIS into the field of effective information functioning, which is determined by the threshold value of efficiency $\eta_{\text{thrsh}}$ which acts as an adaptation criterion. The range of its actions in the input information flow $\Delta \eta_{\text{input}} \, \text{Par. ad.}$ is strictly limited (the extreme left characteristic marked by a solid line) and ends with the beginning of the linear portion of the function $\eta_{\text{lin}}$ corresponding to the transition of the NIS into the ‘loaded state’ of the under-stress mode of information exchange according to the classification of NIS states and modes presented in. The capabilities of the parametric curve for adjusting the parameters of individual SN devices and channel characteristics of the CC (including measures aimed at increasing the immunity of information exchange to interferences) make it possible to change the slope of the efficiency function $\eta_{\text{int}}(\gamma_{\text{input}})$ at its initial section, that is, to increase the slope of the characteristic (Figure 1, arrows at the small dashed line), expressed in increment of the efficiency of information transmission by $\Delta \eta_{\text{Par. ad.}}$. However, for the NIS to function in the field of the required informational efficiency (by $\eta_{\text{thrsh}}$), the parametric mechanisms are not enough, especially in conditions of a high and sharply changing input information flow, as well as the influence of destabilizing factors.

Therefore, the contour of algorithmic adaptation comes into play, which implements the NIS with the basic structure in the bandwidth and maintains the efficiency of information exchange within $\Pi_{\text{Alg. ad.}}(\eta_{\text{thrsh}})$. Algorithmic adaptation, acting mainly at the channel and network levels of the NIS, intersects in the field of action and uses the
results of the parametric curve\(^1\), organizing the control of the parameters of individual elements of the system: SN and CC. Analysis of the simulation results and Figure 1 show that the algorithmic curve increases the NIS information efficiency in a wider range of changes in information transfer efficiency, even if the maximum values of the efficiency function \(\Delta \eta_{\text{Alg.adf.}} = (\eta_{\text{max}1}, \eta_{\text{max}4})\) are considered. Moreover, implementing adaptation by the criterion \(\eta'_{\text{ini}} \rightarrow \text{max}\) forms a transition from the boundary of the initial NIS operation mode \(\eta_{\text{dirsh}}\) (upward arrow in Figure 1) to the maximum value of the efficiency function of the transition mode \(\eta_{\text{max}}\). The maximum range of algorithmic adaptation can be achieved if it is implemented according to the criterion \(II_{\text{ran}} (\eta_{\text{dirsh}}) \rightarrow \text{max}\) (transition from the boundary of the initial SIS operation mode with the level \(\eta_{\text{dirsh}}\) to the efficiency function of the ‘new’ mode without changing the level of information transfer efficiency (point with a square frame in Figure 1). In this case, the ability of the algorithmic curve to increase efficiency and expand the NIS bandwidth is quite limited, since even a quasi-optimal combination of system parameters (in terms of delay \(T_{\text{delay}}\), pack \(L_{\text{pack}}\) and chan \(C_{\text{chan}}\)), adaptive procedures \((\gamma_{\text{input}}, \Delta \gamma_{\text{input}})\) and algorithms \((V_{\text{route}})\) for the basic structure are limited by its technical capabilities under conditions of increasing information flows and due to the influence of destabilizing factors. The range of algorithmic adaptation can be even narrower, due to the applied criterion for the transition to the structural curve (second transition zone in Figure 1). Here, the transition to the NIS reserve structure by the criterion of comparing the current efficiency values of transmitting information of the basic and reserve structures is given. The analysis clearly shows that using adjustments, algorithms and procedures only for the parametric and algorithmic curves is not enough to ensure and maintain high NIS information efficiency in a wide range of changes in the input information flow. For a NIS of a basic structure with limited technical and informational resources, the situation is further complicated by the high intensity of information flows and the influence of destabilizing factors. This objectively determines the need to use the structural contour of adaptation to ensure the required efficiency of the NIS functioning in terms of information exchange.

The transition to the information efficiency function of the first and subsequent NIS reserve structures (dash-dotted lines in Figure 1) is carried out after the algorithmic adaptation procedures of the basic topology have exhausted their capabilities at the current value \(\gamma_{\text{input}}\). The system operates in a ‘state of information overload’ of an overstressed operation mode which is accompanied by large information losses. Using structural adaptation allows transition to the under-stressed mode towards ‘the state of maximum permissible load (high information efficiency)’. Therefore, the work of the structural adaptation circuit provides a significant NIS bandwidth
expansion by the value $\Pi_{\gamma_{\text{lower}}}^{\text{Str.ad}} (\eta_{\text{thresh}})$ (Figure 1). In addition, structural adaptation provides the maximum (of all the curves) increase in the information transfer efficiency from the highest value during algorithmic adaptation to the absolute maximum for the NIS technical capabilities as a whole $\Delta \eta_{\text{Str.ad.}} = (\eta_{\text{max}}; \eta_{\text{max}}^{\text{NIS}})$.

When the conditions of information exchange become extreme (with even the NIS reserve topology with the maximum structural redundancy unable to provide the required information efficiency in accordance with $\eta_{\text{thresh}}$) the connection of the algorithmic and parametric adaptation curve procedures (third transition zone in Figure 1) is carried out to return the system into the bandwidth $\Pi_{\gamma_{\text{lower}}}^{\text{Str.ad}} (\eta_{\text{thresh}})$. In general, with the integrated approach to adaptation, the algorithmic and parametric curve procedures are constantly used for each variant of the NIS reserve structure, therefore the overall range of the complex multi-curve adaptation is very wide and is limited to the extreme points of the efficiency functions of the base and of the extreme reserve topology.

Thus, the implementation of the NIS structural adaptation to the changing information exchange conditions and to the influence of destabilizing factors is crucial to ensure high information efficiency of the system and, together with adaptations of the lower curves, provides the maximum effect of adaptive control.

The present research aims to develop a method of NIS structural adaptation based on the use (for decision-making on changing the structure) of the system of current values of the generalized parameter – the efficiency of information transfer taking into account the effects of interference.

II. Materials and Methods

Based on the analysis of the functions of each adaptive control curve (presented in the study of complex multi-curve adaptation architecture in and based on the need to use the structural curve, the NIS structural adaptation is seen as the ability of the system to best adapt to changing operating conditions, on the basis of adaptive changes in the NIS structural redundancy through successive transitions between the basic and reserve structures. To implement the basic procedures of adaptation structural contour in an integrated form, the method of NIS structural adaptation based on the current values of the generalized parameter was developed.

The technical result of the proposed method is to maintain the required efficiency of the system’s information exchange in accordance with the specified criterion (threshold level of information transfer efficiency $\eta_{\text{thresh}}$) in the extended interval of change of the input information flow (in the bandwidth $\Pi_{\gamma_{\text{lower}}}^{\text{Str.ad}} (\eta_{\text{thresh}})$) by determining

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the boundary of the NIS structural adaptation and the conditions of transition from the basic to the reserve structure and vice versa.

The specified technical result is achieved due to the fact that for the basic NIS structure in the interval of its effective operation, determined by the threshold value of the efficiency of transferring information of the system \( \eta^\text{basic}_i \), a reserve structure (from the generated database (GD) of reserve topologies of the NIS controller, based on the mathematical apparatus of the spectral graph theory and on NIS tensor analysis methodology), satisfying the condition of overlapping the interval of effective work with the basic structure. Then, after a specified period of time \( \Delta t_{\text{spe}} \), the current efficiency values of transmitting information of the basic \( \eta^\text{basic}_i \) and reserve \( \eta^\text{reserve}_i \) structures are measured and calculated, compared with each other. According to the results of comparison, by measuring the values of the input information flow, the values \( \gamma^\text{input trans}_1 \), \( \gamma^\text{input trans}_2 \) are found according to which the interval of transition \( \Delta \gamma^\text{input trans} \) from the basic to the reserve NIS structure and vice versa is calculated. Then, continuing sequential measurements and calculations through \( \Delta t_{\text{spe}} \), the only value of the input information flow \( \gamma^\text{input trans}_0 \) is determined – the boundary of the NIS structural adaptation (change of structures).

When describing the implementation of the proposed method, the NIS model is used where the system is represented as a combination of four main blocks reflecting the main processes of information exchange: a block of information input devices, a block of storage devices, a block of information transfer devices, and a block of information output devices. The essence of the developed method of NIS structural adaptation is that by measurements in the four blocks, the intervals of effective system operation are simultaneously determined (Figure 2) on the basic \( [\gamma^\text{input trans}_{\text{thrsh}}^1, \gamma^\text{input trans}_{\text{thrsh}}^2] \) and on the reserve \( [\gamma^\text{input trans}_{\text{thrsh}}^1, \gamma^\text{input trans}_{\text{thrsh}}^2] \) structures in accordance with the known methods for assessing NIS information effectiveness.

Then the following condition is checked:

\[
\gamma^\text{input trans}_1 \leq \gamma^\text{input trans}_2, \quad (1)
\]

If Condition (1) is not fulfilled, a new reserve system structure is selected from the database of reserve topologies of the controller of the SIS monitoring and control system.

Otherwise, in the interval of effective operation of the system on the basic structure \( [\gamma^\text{input trans}_{\text{thrsh}}^1, \gamma^\text{input trans}_{\text{thrsh}}^2] \) after a specified period of time \( \Delta t_{\text{spe}} \), the current efficiency values of transmitting information of the basic \( \eta^\text{basic}_i \) and reserve \( \eta^\text{reserve}_i \) NIS structures are measured and calculated, compared with each other. According to the results of comparison, by measuring the values of the input information flow, the values \( \gamma^\text{input trans}_1 \), \( \gamma^\text{input trans}_2 \) are found according to which the interval of transition \( \Delta \gamma^\text{input trans} \) from the basic to the reserve NIS structure and vice versa is calculated. Then, continuing sequential measurements and calculations through \( \Delta t_{\text{spe}} \), the only value of the input information flow \( \gamma^\text{input trans}_0 \) is determined – the boundary of the NIS structural adaptation (change of structures).
structures are determined, which are compared. If the following inequality is fulfilled, work continues on the basic structure of the system.

\[ \eta_i^{\text{basic}} \geq \eta_i^{\text{reserve}}, \]  

(2)

Otherwise, the value of the input information flow \( \gamma_{\text{input trans}} \) is stored in the ‘information’ database of the controller, and a ‘direct’ transition to the reserve NIS structure is performed. Measurements of the current values of the input information flow in the interval of effective operation of the system on the reserve structure continue through \( \Delta t \), are compared with \( \gamma_{\text{input trans}} \), and if

\[ \gamma_{\text{input}} > \gamma_{\text{input trans}}, \]  

(3)

work continues on the NIS reserve structure.

If Condition (3) is not fulfilled and condition (2) is simultaneously fulfilled, then a ‘reverse’ transition to the basic structure of the system is performed. In this case, the value of the input flow \( \gamma_{\text{input trans}} \) is stored in the information database of the controller, and the value of the transition interval is calculated

\[ \Delta \gamma_{\text{input trans}} = \gamma_{\text{input trans}} - \gamma_{\text{input trans}}. \]  

(4)

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Further, measurements of the current values of the input information flow through $\Delta t_{\text{spes}}$ continue in the interval of the NIS effective operation on the basic structure $[\gamma_{\text{input \ thresh 1}}, \gamma_{\text{input \ thresh 2}}]$ and are compared with $\gamma_{\text{input \ trans 2}}$. If

$$\gamma_{\text{input}} < \gamma_{\text{input \ trans 2}},$$

work continues on the basic structure of the system.

Otherwise, if Condition (2) is not fulfilled at the same time, a transition is made to the reserve NIS structure (second ‘direct’ transition). Measurements and calculations continue until the condition is fulfilled

$$\Delta \gamma_{\text{input trans}} = 0,$$

in this case, the only value of the input information flow $\gamma_{\text{input trans 0}}$ is determined and stored (in the controller information database), being the boundary of the NIS structural adaptation.

Further, in the interval $\Pi_{\gamma_{\text{input \ (thres) basic}}}^{\text{str. ad}} = [\gamma_{\text{input \ thresh 1}}, \gamma_{\text{input \ thresh 2}}]$ through $\Delta t_{\text{spes}}$, measurements of the values of the input information flow are continued, and the following condition is checked

$$\gamma_{\text{input}} < \gamma_{\text{input \ trans 0}},$$

during which the NIS runs on the reserve structure, otherwise on the basic topology. Figure 3 is the structural diagram explaining the work of the proposed method.

Thus, the essence of the developed method is explained as follows. As a result of a series of successive measurements of the current values of the input information flow and of the efficiency of transmitting information of the basic and reserve structures with the changing $\gamma_{\text{input}}$ in the interval of the NIS effective operation, the bandwidth

$$\Pi_{\gamma_{\text{input \ (thres) basic}}}^{\text{str. ad}} = [\gamma_{\text{input \ thresh 1}}, \gamma_{\text{input \ thresh 2}}]$$

in which the system functions efficiently (in the sense of information exchange) based on a given threshold level of information transfer efficiency $\eta_{\text{thresh}}$. This is achieved by determining the boundaries of the NIS structural adaptation $\gamma_{\text{input trans 0}}$ and the adaptation Condition (7), in the form of a rule of transition from the basic to the reserve structure and vice versa, which provides the technical result indicated in the method.

The difference of the proposed method from the known analogues is that it ensures the maintenance of the given efficiency of the NIS information exchange with changes in the input information flow and the effects of destabilizing factors by expanding the interval of effective operation (bandwidth)$\Pi_{\gamma_{\text{input \ (thres) basic}}}^{\text{str. ad}} = [\gamma_{\text{input \ thresh 1}}, \gamma_{\text{input \ thresh 2}}]$ of the system formed by the merging of the intervals of the NIS effective operation of the basic and reserve structures (Figure 2, Copyright reserved © J. Mech. Cont. & Math. Sci. Aleksander M. Mezhuev et al.)
the dashed line of the envelope of the graphs). In this case, the specific value of the input information flow is determined – the boundary of the structural adaptation at which the basic and reserve NIS structures are changed, as well as the condition for the transition from the basic to the reserve structure and vice versa.

Fig. 3: Structural diagram of implementing the method of NIS structural adaptation based on the current values of the generalized indicator

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The developed method can be practically implemented using the NIS structural adaptation device based on high-speed microcontrollers. The proof of the technical feasibility of the obtained method is that its implementation requires standard elements of microelectronics, existing means of measuring and computing equipment, such as data bus, counters, memory and subtracting devices, controlled switch and keys, comparison schemes, delay lines, as well as typical software for performing basic mathematical operations.

III. Results and Discussion

In the course of the research, imitation (in LiteIDE X environment) and analytical (in Delphi 7 environment) models for assessing the NIS information efficiency (using structural adaptation based on adaptive management of channel and channel-node redundancy) were developed. A tree topology with the minimum redundancy of eight SN was used as the NIS basic structure, and for reserve options for implementing the adaptation, the following were selected (increased structural redundancy): cellular, mixed, and fully connected structures. Figure 4 shows the simulation results which clearly demonstrate the effect of applying structural adaptation, expressed in the correction of the information efficiency function \( \eta_{\text{int}}(\gamma_{\text{input}}) \) of the NIS basic structure and providing a significant expansion of the bandwidth for the input information flow with an increase in information transfer efficiency. Figure 4a presents the results of the NIS model operation using the structural adaptation method based on current efficiency values \( \eta_{\text{int,i}} \), with adaptive control of the channel redundancy of the NIS structure, and Fig. 4b presents the results of the NIS model operation using joint adaptation of the channel-node redundancy of the NIS structure.

An analysis of the results shows that for the basic tree structure in the interval of the input information flow \( \gamma_{\text{input}} \approx 500-4000 \) packs/s, the application of the first approach based on adaptive control of channel redundancy (Figure 4a) allows increasing the information transfer efficiency by 17.4% (from 32.6 to 50%, the gain is shown by the maximum values of the efficiency of the basic and reserve structures) and extending the effective operation interval (bandwidth) of the NIS 2.5 times. The additional use of nodal redundancy (Figure 4b), although it does not allow increasing the efficiency more than the achieved value using channel redundancy, yet it extends the NIS bandwidth \( \tilde{\eta}_{\text{int,i}}(\eta_{\text{int,i}}) \) 3.8 times. The resulting function of the NIS effectiveness is formed as an envelope of functions for the individual components: the basic and reserve structures. It can be seen that the function is quite even with smooth transitions between individual graphs (without significant outliers, especially with an additional change in nodal redundancy). Moreover, the boundary values and transition rules between the basic and reserve topologies are determined in accordance with the developed method of NIS structural adaptation based on the current values of the generalized parameter \( \eta_{\text{int,i}} \). The maximum increase in efficiency is achieved during the transition to a fully connected structure and a given

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(for the basic structure) number of SN, because with a subsequent increase in nodal redundancy, the values of maximum efficiency slightly decrease (≈ 7.2% for $N_{SN} + 2$), and the efficiency function becomes more stable against sharp changes in the input information flow. The resulting bandwidth is determined by the extreme values of the bandwidths for the base tree and fully connected structures, respectively. For example, when using adaptive control of channel redundancy $\Pi_{\text{Str.ad.}}(\eta_{\text{loc}})$ lies within

$$[\gamma_{input_{\min}} = \gamma_{\text{basic}}^{input_{\text{thresh1}}} = 1\text{Mbps}, \gamma_{input_{\max}} = \gamma_{\text{fullyconn}}^{input_{\text{thresh2}}} = 18.5\text{Mbps}],$$

while joint adaptation for channel-node redundancy provides

$$\Pi_{\text{Str.ad.}}(\eta_{\text{loc}}) = [\gamma_{input_{\min}} = \gamma_{\text{basic}}^{input_{\text{thresh1}}} = 1\text{Mbps}, \gamma_{input_{\max}} = \gamma_{\text{fullyconn} + 2\text{SN}}^{input_{\text{thresh2}}} = 27.85\text{Mbps}].$$

This indicates the maintenance of NIS high information efficiency in a wide range of input traffic changes by combining (merging) the intervals of effective operation of individual (basic and reserve) structures in accordance with a specified criterion.
The simulation results were repeatedly verified using classical NIS models based on the theory of queuing systems in GPSS / PC and AnyLogic environments. Moreover, the discrepancies in the obtained efficiency estimates did not exceed 3%, and the value of the input information flow (when determining the NIS bandwidths) was no more than 0.2 Mbps, which confirms the efficiency of the obtained method of structural adaptation and the model built on its basis, as well as the reliability of the research results. Moreover, in comparison with the known ones, the developed model is universal with respect to NIS structural transformations and provides real-time control of algorithms (procedures) and system parameters.

IV. Conclusion

Thus, the analysis (which showed the limited range of action of the lower curves of the parametric and algorithmic adaptation of the NIS) substantiated the need to use a higher curve of structural adaptation in the most adverse conditions of high unstable input traffic and the influence of destabilizing factors. A method for the NIS structural adaptation was developed based on the assessment of the current values of the generalized parameter—the efficiency of information transfer taking into account the interference for the basic and reserve topologies. The obtained method of structural adaptation allows determining the specific value of the adaptation boundary according to the input traffic and the unambiguous condition for the change of structures (transitions between the basic and reserve system topologies). Based on the developed method, simulation and analytical models of NIS information exchange using structural adaptation were built. The results confirm the effectiveness of the developed method in real time. Improved NIS information efficiency (expressed in increasing the value of information transfer efficiency) and the system maintained at
the required level in accordance with the specified criteria (confirmed by the expansion of the bandwidth for input traffic) are the main results of applying the NIS structural adaptation. The developed method and models are recommended for implementation as algorithmic software for the controller of the NIS monitoring and control system in conditions of high input information flow and the influence of destabilizing factors.

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