MULTI-LOOP ADAPTATION OF TELECOMMUNICATION NETWORK ON THE BASIS OF GENERALIZED INFORMATION EFFICIENCY INDICES

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Abstract

This paper discusses the multi-loop adaptation of a telecommunication network and shows how this problem can solved in the network's variable operation conditions by applying generalized indices of information exchange efficiency evaluation (information efficiency indices), tensor methodology, spectral theory of graphs, and coherent models and considering accepted assumptions. The model representation of multi-loop adaptation is structured by levels, proceeding from the commonality of the problems being solved. The elaborated generalized algorithm and tensor orthogonal and imitative models for the telecommunication network of various topologies allow deriving information efficiency functions and evaluate this efficiency on the basis of generalized indices, including information transmission performance coefficient, inflow bandwidth, and band efficiency angle tangent. The modeling results confirm the feasibility and functionality of the suggested methodological tools for organization adaptation on the basis of the integral approach and the system of generalized indices in the context of inflow changes and under destabilizing influences.

Keywords: Telecommunication network, multi-loop adaptation, integrated approach, information efficiency, performance coefficient, bandwidth

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I. Introduction

According to the analysis of approaches to organizing adaptation processes in case of destabilizing factors in a loaded and dynamically controlled telecommunication network (TCN), most of these approaches are intended for solving adaptive control problems at the physical and path-wide levels and ensure quasi-optimal (against a chosen criterion) regulation of parameters of TCN elements, including switching nodes (SN) and communication paths (CP), on the basis of local information exchange efficiency indicators. Thus, several studies, for example, 1—9, expose procedures for adaptively adjusting the capacity of SN in the TCN against MEI (Maximum extra interference), i.e., the level of maximal extra interference in the USW receiver, which are used as basic in forming procedures of MAC (Media Access Control) to maintain rapid information transmission at low energy costs. Work 10 suggests multi-criterial vector adaptation (optimization) techniques for building TCN for ATM and Next-Gen networks (NGNs). The techniques are based on SN and network models using the conventional approach from the queuing systems (QS) theory as well as the techniques of analyzing information processes for efficiency, designed for optimizing network capacity and evaluated against the particular probabilistic indicator called the probability of timely packet delivery \( P_{tmd}(r) \) for the \( r \) priority. Another approach to organizing adaptation in special-purpose wireless networks, when solving the scalability problem, is described in 11—19 and consists in applying distributed algorithms that ensure the adjustment of local parameters of the system’s elements to the current operational conditions. This approach allows having a large gain in the TCN performance specifications but may result in extra difficulties related to the increased complexity and lower configurational flexibility of the TCN. The composed function suggested in 20 for evaluating the efficiency and implementation of adaptation in TCN for automated decametric radio communication systems (ADMRCs) with a ported out relay point (PORP) is the risk of average material losses \( R_{AML} \) determined by the sum of particular indices and their relative importance. A multi-loop adaptation framework is suggested with the partition of functions among the parametric, the algorithmic, and the structural loop. The absence of the common physically significant generalized TCN information efficiency indicator and the integrated approach to solving adaptation problems, from a system’s element (SN or CP) and up to the operational algorithms and structural reconfiguration of the TCN, has made it necessary to do research for creating the integrated multi-loop adaptation to information exchange conditions and destabilizing factors.

This work is written to determine the basics of integrated multi-loop adaptation of TCN and the ways of implementing this adaptation by model representation (description) using the system of generalized information exchange efficiency indicators.

II. Materials and Methods

In this day and age the limited information resources of TCN (opportunities for utilizing and distributing them in an optimal manner) are inconsistent with the constantly growing demands for information exchange manifested in significantly intensified information flows

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under a heavy influence of destabilizing factors (Fig. 1). The scientific problem determined by the indicated inconsistency and the distinct kind of adaptation problems in specific loops in case of applying conventional approaches consist in the need for creating and implementing integrated multi-loop adaptation in TCN. The solution of this problem is aimed at improving the performance efficiency of the TCN (in terms of information exchange), which involves meeting the requirements on making the system structurally sustainable and information efficient. The implementation of adaptation in practice involves creating a set of engineering tools in the form of the TCN operation management and monitoring system. These tools must ensure the system’s acceptable performance against predefined criteria and the quasi-optimal utilization of the TCN’s information resources for the current conditions of operation in real-time mode. The TCN operation management and monitoring system must be based on new principles of organizing the operation of distributed systems and new analytical, procedural, and imitative models that would reflect as completely as possible the information exchange in the TCN.

In this respect, the tools suggested for adequately evaluating and meeting the requirements on TCN information efficiency include the tensor methodology for analyzing the TCN (similarly to G. Kron’s electric mains in

\[ \text{(21)} \] and the system’s enhanced orthogonal model, combining three main regions for network interaction, including the discrete static structural region of the TCN, and two dynamic regions of information and interference flows\[ \text{(22)}. \] To maintain the TCN structurally sustainable in real-time mode, it is proposed to utilize in analysis and synthesis topological TCN models with required structural characteristics derived using the spectral theory of graphs. This approach allows having a precise analytical description of the principal structural parameters of the TCN, forming criteria of structural synthesis of sustainable topologies, determining co-spectral structures to form a base of backup topologies, and elaborating algorithms to transform the TCN’s basic structures. The tensor approach used together with the system of generalized indicators and the spectral theory of graphs allows implementing the technique of forming structurally sustainable and information efficient TCN\[ \text{(23)}. \]
Fig. 1: Organizing integrated multi-loop adaptation of TCN

The common foundation for implementing the integrated multi-loop adaptation of TCN (on the basis of interaction among all of the adaptation loops) is the justification and formation of the system of generalized parameters and indicators of information efficiency evaluation that have all features of system-wide indicators and, at the same time, reflect specific physically intelligible characteristics of individual elements of the TCN (SN and CP). These indicators are TCN cybernetic capacity $P_{TCN}$, information transmission performance coefficient $\eta_{TCN\ i}$, performance coefficient $\eta_{inter\ i}$ taking into account the influence of interferences (destabilizing factors), threshold efficiency value $\eta_{\text{thresh}}$ as efficiency criterion, TCN bandwidths for information inflow $P_{\text{infr}}(\eta_{\text{thresh}})$ and intra-network information flow $P_{\lambda_{\text{infr}}}(\eta_{\text{thresh}})$, and time lag $P_{\tau_{\text{infr}}}(\eta_{\text{thresh}})$, and also band efficiency angle tangent $\tan \alpha$.

Thus the scientific problem of interest consists in the absence of an integrated multi-loop adaptation of TCN in dynamically changing external operation conditions (destructive factors and changes in topology) and an intensive information flow on the basis of the system of generalized information exchange efficiency indicators (Fig. 2).
The relevance of elaborating the new methodological tools for arranging the integrated adaptation in TCN results from a number of objective reasons.

First of all, it results from the inapplicability of conventional approaches to and parameters and indicators of TCN information efficiency evaluation, which is conditioned by their insufficient information value, objectivity, and precision in the conditions of the parallel transmission and storage of information in the system\cite{1 – 20}.

Secondly, it results from the need for having a single solution of the adaptation problem for all the three lower operational levels of the TCN (its transport network), i. e., physical, channel-wide, and network\cite{23}.

Thirdly, it results from the need for combining in a single task the static (topology) and the dynamic (distribution of information flows and influence of destabilizing factors) structural space of the TCN. This can be implemented only using mathematical tools as the tensor analysis of the TCN\cite{22 and 24}.

Fourthly, it results from the need for enhancing the opportunities for service information exchange in the TCN and implementing structural adaptation by new techniques from the spectral theory of graphs \cite{23 and 25}.

Fifthly, it results from the need to elaborate algorithmic support and software for implementing the research results in practice as the controller of the TCN management and monitoring system for the adaptive control of network-wide parameters, procedures, and algorithms (by analytical and imitative modeling).

The major tasks it is necessary to solve for achieving the research purpose of attaining a more efficient information exchange in the TCN on the basis of optimizing the utilization of its information resources, proceeding from the above specified factors that determine the need for elaborating the methodology for the integrated multi-loop TCN adaptation, accepted.

\textbf{Fig. 2:} Model representation of integrated multiloop adaptation of TCN
assumptions, and specific features of operating the TCN in the context of intensive information flows and destabilizing factors are exposed below (Fig. 2).

1. Analyze the existing approaches to evaluating TCN for information efficiency to elaborate new TCN information efficiency evaluation techniques and suggest a system of generalized parameters and evaluation indicators that can be used in solving the adaptation task.

2. Suggest the modification of the tensor technique of TCN information efficiency analysis and evaluation for the case when the TCN’s performance is affected by destabilizing factors. This modification must be implemented by correcting the behavior and conversion formulas of the TCN parameters. Elaborate a new orthogonal TCN model using the additional frame of reference for the region of interferences. Analyze the model’s performance using the new system of information efficiency indicators.

3. Elaborate techniques of finding the principal structural TCN parameters using the spectral theory of graphs and use these techniques in formulating the criteria of the structural synthesis of a stable TCN topology. Elaborate the technique of finding co-spectral structures and develop algorithms of transforming basic TCN topologies, taking into account the properties of the system’s structural redundancy.

4. Combine the tasks of making TCN structurally sustainable and information efficient to determine the phases and elaborate the technique of forming structurally sustainable and information efficient TCN so as to form DB of backup TCN structures when ensuring structural adaptation.

5. Elaborate algorithms, models, and techniques for implementing the integrated multi-loop adaptation of TCN (for individual adaptation loops) in the context of intensive information flows and destabilizing factors.

The solution of the above enumerated problems on the basis of the tensor methodology using the implemented techniques, algorithms, and procedures allowed elaborating the generalized analytical model of TCN information efficiency evaluation for the case of variations in the information inflow intensity and the influence of destabilizing factors. This model includes standard (basic) elementary structures such as the fully connected, the star, the hierarchical (tree-structured), the cellular, and the mixed structure (with cellular and tree-structure topological elements). That said, the above represented indicator, i.e., performance coefficient $\eta_{\text{intrf}}$, taking into account destabilizing factors (interferences), is calculated by refining cybernetic capacity $P_{\text{TCN}}$ by finding the extent of information losses as

$$P_{\text{loss}} = N_{\text{loss}} \cdot V_{\text{rept. trans}} \left| T \leq T_{\text{add}} \right.$$

where $N_{\text{loss}}$ is the number of lost (including received by error $N_{\text{er}}$) packets against preset time lag limit $T \leq T_{\text{add}}$; $V_{\text{rept. trans}}$ is the repeated transmission flow in density, taking into account the CCH throughput limit ($C_{\text{trans}}$).

Considering the influence of destabilizing factors, the cybernetic TCN capacity is

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\[ P_{TCN} = P_{TCN} - P_{loss}, \]

where \( P_{TCN} = N G |_{T \leq T_{extr}} \); \( N \) is the aggregate number of packets in the system (from the external and and transit information flows, including lost packets and packets received with errors).

That said, the TCN’s performance efficiency reduction coefficient for the system’s current \((i)\) state is determined as
\[ k_{inter i} = \frac{P_{inter i}}{P_{TCN i}}. \]

Considering the influence of destabilizing factors in the TCN, the refined current values of the information transmission performance coefficient are calculated as
\[ \eta_{inter i} = \frac{P_{TCN i}'}{P_{IdNtw} \cdot 100\%}, \]

where \( P_{IdNtw} = \sum_{j=1}^{M} N_j \) \( out \) \( V' \) is the capacity of the ideal network, with out conflicts, repeated transmissions and losses of packets, with the maximal levels of information transmission in the CCH and information storage in SN buffer memory (BM); this capacity determines the system’s physically achievable information transmission and storage capabilities, proceeding from available hardware and software (primal network of single-channel systems (SCHS) in the tensor TCN model); \( j \) is the conditional SCHS number; \( N_j \) and \( out \) \( V' \) is the aggregate state determined by transit and external (received from the user) packets and the information outflow (productivity) of the \( j \) SCHS, respectively.

The generalized analytical TCN model is implemented in the Maple 15 specialized math suite and in the Borland Delphi 7 software. For the model’s operation algorithm see Fig. 3.

The structures of the analyzed TCN are formed in Unit 1. The initial data (unit 2) introduced for calculating the principal TCN parameters are:

1. overall number of cybernetic elements in TCN \( n_{el} \), \( CP \), and \( SN \), including the ones having information inflow \( n_{usl} \) and directing it to the system’s exit \( n_{vis} \);
2. time lag limit \( T_{odr} \), intra-network CCH throughput limit \( C_{odr} \), and throughput limit for channels ensuring the provision of information from the system \( C_{vis} \), packet length \( L_{pack} \);
3. information inflow and interference flow vectors (tensors of the first order) \( \gamma^b \) and \( \gamma^c \), respectively, that support the TCN operation mode, including the interim information storage in the SN BM;
4. range of intensity changes in inflow and interference flow, \( \gamma^b_{shaga} \) and \( \gamma^c_{shaga} \), respectively;

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5. number of packets in the CE-CCH $n_c$ and in the BM-CE $n_s$ of mutually independent SCHS of the primal network ($\alpha$ frame of reference).

![Diagram of the generalized analytical model of evaluating TCN information efficiency](image)

**Fig. 3:** Algorithm of the generalized analytical model of evaluating TCN information efficiency

6. transformation tensors $A^{\beta}_{\alpha}$, $A^{\beta}_{\alpha}$, $C^{\alpha}_{\beta}$ that ensue the formation of connected TCN models from the primal network of SCHS ($\alpha$ frame of reference transformed to $\beta$ frame of reference) 22.

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Algorithm's units 3 and 4 cover two organized cycles of sequential iterations. The first cycle ensures the formation of three implementations of initial information inflow tensor $\gamma_{p,i}^{in0}$; relation $\eta_{intr}(\gamma_p^{in})$ is derived for each of these, considering the influence of destabilizing factors, described using interference flow tensor $\gamma_{p,i}^{shaga}$. The second internal cycle ensures the iterative increment of inflow $\gamma_{t,i}^{in} = \gamma_{t,i}^{in} + \gamma_{shaga}$ and interference flow $\gamma_{t,i}^{shaga}$ at a preset intensity rate.

The packet queues in the SN BM are formed (restricted), considering the existence of an extra interference component (units 5 – 8). The primal network parameters are calculated and the characteristics of the joint TCN model found using transformation formulas in units 9 and 10. The condition for the design value of $T_{extr}[t]$ (unit 11) with preset limit $T_{extr2}$ is checked and the flow management procedure implemented in units 12 – 14. The implementation of the inflow management procedure results in a consistent registration of acquisitions in the SN BM in the context of variations in the information inflow and interference flow's intensities, which allows tracking changes in the aggregate (overall) numbers of packets $N_{summar}[t]$ and lost packets $N_{loss}[t]$ and, henceforth, determine refined effective cybernetic capacity $P_{TCN}[t]$. Considering information loss capacity $P_{load}[t]$ (units 15 – 17). Unit 18 is responsible for calculating the ideal network’s full cybernetic capacity $P_{IdNtw}[t]$. The information exchange in the TCN is evaluated for efficiency in unit 19 against the value of $\eta_{intr}$, which is followed by the increment (iteration) of the inflow and the interference flow (unit 20). After the internal cycle’s work is done (30 iterations), the TCN efficiency function $\eta_{intr}(\gamma_{p,i}^{in})$ is derived for each of the three external cycle implementations $\gamma_{p,i}^{in0}$, which is followed by averaging each point of the plot for the three implementations (unit 21). Unit 22 determines threshold information transmission performance coefficient $\eta_{thrsh}$. Then points, where the threshold level crosses the plot $\eta_{intr}(\gamma_{p,i}^{in})$, and the TCN bandpass for inflow $\gamma_{thrsh}(\eta_{thrsh})$ are found (unit 23). Unit 24 is used for calculating inflow increments $\Delta \gamma_{in}$ (for each iteration of the efficiency function) and information transmission performance coefficient $\Delta \eta_{intr}$, whereas unit 25 is used to determine TCN band efficiency angle tangent $\Delta \alpha = \Delta \eta_{intr}/\Delta \gamma_{in}$. Then condition $|\Delta \eta_{intr}| \leq \Delta \eta_{adr}$ is checked (unit 26): if it is met, a command is sent to the modeling results output unit (unit 28) to indicate that the TCN runs in quasi-optimal information exchange mode and the principal results are displayed, including $\eta_{intr}(\gamma_{p,i}^{in})$, $\eta_{intr \ max}$, $\gamma_{thrsh}(\eta_{thrsh})$, and $\Delta \alpha$; otherwise, unit 27 is used to check the sign identity of $\Delta \alpha$, which determines the TCN’s operation in hyperintense or underintense information exchange mode; then the results are shown in unit 28.
III. Results and Discussion

The loaded operation mode of the analyzed TCN structures with the intermediate storage of information was provided by conducting the analytical modeling for the star, the hierarchical (tree-shaped), the cellular, and the mixed (with parts of the cellular and tree-shaped TCN) TCN at inflow variation rate $\Delta \gamma_{in} = 1$ Mbit/s, whereas the analytical modeling for the fully connected TCN was performed at $\Delta \gamma_{in} = 2$ Mbit/s. For the performance results of the generalized analytical tensor model of information exchange in the TCN, considering the destabilizing factors and imitative modeling in the LiteIDE X suite by multi-threaded programming based on the classical approach using queuing systems (QS) see Fig. 4.
To make an analytical comparison, the analytical relations of each of the examined TCN structures (solid lines) are averaged against the external cycle iterations and placed in a single frame of reference with the imitative modeling results (dashed lines) in Figs. 4a – e, and the summary plot drawn according to the analytical surveys of all the topologies is presented in Fig. 4f. The test ranges of inflow variations chosen for examining the TCN efficiency functions and evaluating information transmission performance coefficient increments $\Delta \eta_{intra}$ are similar to the ones in increment (decrement) sections $\eta_{thres}(\gamma_{in})$ of the imitative models.

The analysis of the modeling results in the standard points of $\eta_{intra}(\gamma_{in})$ dependences allows concluding that the elaborated models are functional as well as their basic approaches to examining TCN, considering the influence of destabilizing factors. The calculations of the principal system-wide parameters of the examined TCN topologies reveal an identical pattern of behavior in the course of information exchange (transition of states and operational modes) with changes in the flow environment and external factors. That said, the information efficiency values in the form of the information transmission performance coefficient estimates in the generalized tensor TCN model differ by no more than 3 % from the estimates derived by imitative modeling. In its respect, this allows generally defining as correct the mathematical description of information processes and accepted assumptions, when building the models, and classifying the results as reliable. Maximal performance coefficient $\eta_{intra, max}$ in the examined TCN structures is observed in the cellular TCN (39.4 %), followed right behind by the fully connected TCN (35.2 %), whereas $\eta_{intra, max}$ of the hierarchical, star, and mixed TCN ranges from 28.2 to 31.7 %, respectively. Bandpass values $\eta_{intra}(\eta_{thres})$ differ from the imitative modeling data by no more than 0.8 Mbit/s. More consistent performance results for $tg\alpha$ are observed in overintense mode (especially for the fully connected TCN), and averaged (resulting) band efficiency angle tangents $tg\alpha_{res1}$ and $tg\alpha_{res2}$ correspond to the imitative models to an accuracy of $5 – 7^\circ$. The basic TCN topologies it is offered to use according to the modeling results for ensuring the most efficient information exchange possible are:
mixed TCN \( (\eta_{\text{intrf}} \approx 24\%) \) at a low-intensity inflow \( (\gamma_{\text{in}} \leq 4 \text{ Mbit/s}) \) (Fig. 4e);
cellular TCN at a moderate information load \( (\gamma_{\text{in}} = (4; 8.5) \text{ Mbit/s}) \) (Fig. 4c);
fully connected TCN at an intensive information flow \( \gamma_{\text{in}} \geq 8.5 \text{ Mbit/s} \) (Fig. 4a).

IV. Conclusion

As also shown by analyzing the modeling results, the introduction of extra interference region \( \gamma_{\text{in}}^m \) in the tensor TCN model reduces the information transmission performance coefficient by about 5 to 7\% and does not change the trend for the narrowing TCN bandpass (by about 50 to 100\%). The combination of all the three foregoing TCN topologies is highlighted with a solid line in Fig. 4f and allows maintaining the performance coefficient above threshold \( (\eta_{\text{intrf}} \geq \eta_{\text{thresh}} = 15\%) \) and significantly expanding the bandpass for the information inflow (by about 150\%). This confirms the expediency of applying the integrated approach to arranging adaptation in the TCN when the problems of the framework adaptation loop are solved in direct relation to and interaction with the parametric (adjusting the principal parameters of the SN and CP) and the algorithmic loop (managing the information exchange algorithms and procedures in the TCN).

Thus the studies have allowed determining the basics of arranging the integrated multi-loop adaptation of TCN; several ways of solving this problem are presented, using the coherent model representation of the system (considering accepted assumptions) based on generalized information efficiency indicators. That said, the principal TCN adaptation functions are

- control over changes in principal parameters and indicators of particular elements in SN and CP (maintaining required efficiency at the physical and channel-wide level) (parametric loop);
- determination of the direction and selection of the quasi-optimal rate of changes in the system-wide parameters and adaptive management of the system’s operational procedures and algorithms (provision to the efficient operational region at the channel- and network-wide level) (algorithmic loop);
- structural reconfiguration of the TCN by adaptively managing topological redundancy (ensuring and maintaining the system’s operation in the high information efficiency region and at the network-wide level by making use of channel resources) (structural loop).

The elaborated tensor orthogonal and imitative models for TCN with various topologies allow considering at the network-wide level the influence of destabilizing factors on the efficiency of information exchange. In this case, any topological transformations in the generalized tensor model correspond to the transformations of the TCN space structure and are determined by transformation tensor components.

As shown by the modeling results the suggested approach can be used in the information efficiency evaluation and integrated adaptation of TCN on the basis of the system of generalized indicators in the context of variations of inflow and under destabilizing influences. The reliability of the tensor model performance results is confirmed by the imitative modeling data and their compliance with the performance of the actual systems in similar conditions.

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