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METHOD FOR THE HIERARCHICAL DYNAMIC SELF-ORGANISATION OF COMPUTING NODES IN SELF-ORGANISING TELECOMMUNICATIONS SYSTEMS

Introduction

The theoretical basis for the transition to hierarchical dynamic self-organisation of computing nodes in self-organising telecommunications systems lies in the development of the edge and fog paradigms, within which computation, data storage, control and network functions are distributed along a continuous chain from the cloud level to end devices [1]. This approach creates the architectural conditions for moving away from rigidly centralised data processing and transferring some control decisions directly to peripheral nodes, which is particularly important for systems with variable topology, highly dynamic workloads and strict requirements for processing speed [2].

Analysis of recent research and publications

Recent review studies on fog and edge environments highlight that such systems are characterised by resource heterogeneity, multi-tier architecture, localised processing, and highly dynamic states [3, 4]. It has been shown that fog architecture does not replace the cloud layer, but functionally complements it, providing support for applications with strict constraints on latency, processing location, and resource availability [3]. At the same time, key open issues include resource coordination, maintaining a specified service level, effective orchestration, and resilience to environmental changes [3, 6]. It is also emphasised that dynamic function migration, resource virtualisation and changing load profiles require adaptive mechanisms for organising computing nodes [4–17].

A separate area of research concerns the placement of services and tasks in fog/edge environments. Relevant studies have systematised the main optimisation criteria, the most commonly used of which are latency, cost, power consumption and resource utilisation [5]. However, in most such approaches, the structural organisation of the network is treated as a predefined operating environment, whilst its adaptive reconfiguration in response to changes in traffic or node status remains outside the scope of the main model [5, 18]. Works on orchestration in fog computing also note that coordinating decisions across different system levels is one of the central challenges, and that centralised control mechanisms do not always ensure adequate scalability and performance in large and dynamic environments [6]. This indicates a gap between the tasks of processing optimisation and the tasks of self-organisation of the network structure itself.

Research into the hierarchical clustering of nodes is of considerable interest specifically for telecommunications systems. These works propose approaches to the structural grouping of computing nodes, taking into account their performance, topological proximity, delays and the bandwidth of communication channels, which allows for the formation of more balanced clusters and improves the balance between intra-cluster and inter-cluster interactions [7]. However, such approaches are primarily focused on forming the initial or current cluster structure and do not fully describe the system's behaviour under conditions of mass failures, degradation of coordinating nodes, or a sudden change in the spatial profile of traffic [7].

Further development in this area involves research into the selection of cluster coordinators and the establishment of control channels. Relevant studies have examined local ranking of candidate nodes, as well as the application of failover mechanisms, heartbeat monitoring and automatic role switching in the event of failures [8]. The practical significance of such approaches lies in the transition from a static hierarchy to a managed hierarchical structure, in which individual nodes perform specialised coordination functions and ensure the sustained operation of the cluster [8]. At the same time, the problem of coordinating clustering procedures, the selection of coordinators and the reconfiguration of links within a single method remains insufficiently addressed.

International research confirms that a multi-tiered organisation of nodes provides an effective architecttural foundation for scaling distributed environments, localising solutions and reducing dependence on a global control centre [11, 12, 19]. In such approaches, multi-tiered organisation is viewed not only as a means of structuring the system, but also as a tool for enhancing adaptability, reducing response times to changes in the environment, and increasing the autonomy of individual network segments [11, 12]. At the same time, the effectiveness of multilevel control is achieved only provided there is a clear division of roles between levels, coordination of local and global decisions, and timely reconfiguration of control links in the event of a disruption to normal operation [13, 14].

In recent research, increasing attention is being paid to agent-based and decentralised orchestration models capable of accounting for constraints on nodes' processing, memory, power and communication resources, as well as adapting to mobility and failures [10, 20]. The advantage of such approaches is the absence of a single critical decision-making centre; however, they do not in themselves define the principles for forming a stable structural hierarchy, the mechanisms for delegating roles between levels, or the rules for the system's transition from one stable state to another following a change in topology [10]. This necessitates the combination of local autonomy with hierarchical control logic.

Research into the stability of leader-selection mechanisms under conditions of dynamic topological changes warrants particular attention. It has been shown that classical coordinator selection schemes lose their effectiveness in the event of intense churn, message loss and resource heterogeneity, leading to frequent re-elections, increased overhead traffic and coordination instability [15]. For self-organising telecommunications systems, this means that the mechanism for appointing coordinating nodes must be not only formally correct, but also adaptive, load-tolerant and geared towards the practical operating conditions of the network [15].

The importance of simulation modelling for validating such methods is underscored by the development of specialised modelling tools that support node mobility, clustering and microservice orchestration in edge/fog environments [9]. The use of such tools allows for the investigation not only of steady-state operating modes, but also of reconfiguration scenarios arising from node failures, changes in traffic intensity, or the introduction of new elements into the network [9].

Thus, an analysis of the scientific literature indicates that existing research provides a solid theoretical and practical foundation for developing methods of self-organisation in distributed environments, but do not provide a complete solution to the problem of hierarchical dynamic self-organisation of computing nodes in self-organising telecommunications systems [1, 6, 7, 10, 12, 13]. Existing approaches are predominantly focused either on clustering without a detailed reconfiguration mechanism, or on the selection of coordinators without formalising the multi-level transition between network states, or on the placement of services without an explicit description of the logic for constructing a stable hierarchy [5, 6, 7, 8, 10]. In this regard, there remains a need to develop a method that combines adaptive structural grouping of nodes, robust coordinator selection, event-driven reconfiguration of interconnections, and multi-criteria evaluation of the impact of these decisions on the system's reliability, resilience and performance [11, 12, 13, 15].

Problem Statement

The problem considered in this article is to develop a method for the hierarchical dynamic self-organisation of computing nodes in self-organising telecommunications systems under conditions of variable topology, heterogeneous node resources, dynamic traffic and partial failures. Solving this problem requires combining adaptive clustering of nodes, robust coordinator selection, event-driven reconfiguration of intra-cluster and inter-cluster connections, and preservation of acceptable performance, reliability and resilience indicators under changing environmental conditions.

The purpose of the article

The aim of the article is to develop a method for the hierarchical dynamic self-organisation of computing nodes in self-organising telecommunications systems that ensures the formation of a multi-level control structure and the adaptive reconfiguration of inter-node connections under changing environmental conditions in order to improve network reliability, resilience and scalability.

Summary of the main material

Let us consider a self-organising telecommunications system as a dynamic weighted graph

$$G(t) = \big(V(t), E(t)\big), \quad (1)$$

where $V(t) = \{v_1, v_2 \ldots, v_\text{n}\}$ – a set of computing nodes at a given point in time t; $E(t)$ – a set of logical or physical connections between them.

Each node v_i is characterised by a state vector $s_i(t)$, which includes available computing power $p_i(t)$, amount of free memory $m_i(t)$, available bandwidth $b_i(t)$, energy resource $e_i(t)$, reliability assessment $r_i(t)$, local processing queue $q_i(t)$, connectivity coefficient $g_i(t)$, as well as their position within the management structure.

Every connection$e_{ij} \in E(t)$ is characterised by its latency $d_{ij}(t)$, bandwidth $c_{ij}(t)$, current load $l_{ij}(t)$ and probability of availability $a_{ij}(t)$. The network state is non-stationary, as the set of nodes may change due to the addition of new elements, failures or loss of connectivity, whilst channel parameters vary under the influence of traffic, environmental conditions and routing decisions. Under such conditions, the use of static topology synthesis is insufficient, necessitating the use of dynamic self-organisation mechanisms.

The aim of self-organisation is to establish a multi-level management structure $H(t)$, which, at any given moment, strikes a balance between localised decision-making, fault tolerance, acceptable operational costs and traffic processing efficiency.

Let $H(t) = \{L_1(t), L_2(t), \dots L_r(t)\}$, (2)

Where L_1– the level of standard computing nodes; $L_2(t)$ – cluster coordinator level; $L_3(t)$ – the level of macro-cluster coordinators or regional aggregators.

If necessary, additional management levels can be introduced into the system. However, a node's affiliation with a particular level is not fixed and may change during the system's operation.

The aim of hierarchical dynamic self-organisation is to determine, at each time step, the partition of the set of nodes $V(t)$ into clusters $C_k(t)$, selection of coordinators $u_k(t)$ for each cluster, establishing inter-cluster connections and a higher-level structure, and defining transition rules between configurations $H(t) \rightarrow H(t + \Delta t)$ when the status of nodes, channels and traffic changes, as well as determining the recovery policy in the event of partial network degradation.

Let us denote by $x_{ik}(t)$ a binary node membership variable v_i to the cluster $C_k(t)$, and after $y_{ik}(t)$ – a binary variable indicating whether the node is running v_i the role of cluster coordinator $C_k(t)$. In that case, the restrictions must be observed $\Sigma_k x_{ik}(t) = 1, y_{ik}(t) \le x_{ik}(t), \Sigma_i y_{ik}(t) = 1$ for each cluster $C_k(t)$.

In addition, the clustering procedure must take into account constraints on the maximum cluster size, the permissible intra-cluster delay, the minimum density of internal links, and the maximum load on the coordinator. If, due to $N_k(t)$ specify the set of cluster nodes $C_k(t)$, in which case the coordinator is subject to additional requirements regarding the availability of sufficient reserve resources after the performance of management duties.

It is advisable to define the integral criterion for structural quality in the form of a functional

$$J\big(H(t)\big) = a_1 D(H,t) + a_2 B(H,t) + a_3 R_{cfg}(H,t) - a_4 A(H,t) - a_5 S(H,t), \quad (3)$$

where $D(H,t)$ – average processing and transmission delay; $B(H,t)$ – node load imbalance index; $R_{cfg}(H,t)$ – econfiguration costs; $A(H,t)$ – service availability metric; $S(H,t)$ – survival rate; $a_1 \dots a_5$ – weighting factors.

The aim of self-organisation is to minimize $J\big(H(t)\big)$ given the resource and structural constraints.

Unlike static clustering, the proposed approach considers the optimality of the structure relative to the current state of the network. Consequently, the system does not aim to achieve a single global optimum, but rather transitions sequentially between quasi-stable configurations, each of which is acceptable within a specific time interval. This approach makes it possible, on the one hand, to avoid excessive reconfiguration frequency, and on the other, to avoid maintaining an inefficient configuration following local operational disruptions.

For the practical implementation of the method, it is advisable to identify three classes of events that trigger an analysis of the system's state: resource-related, topological and traffic-related. Resource-related events include those associated with a reduction in a node's available computing resources or the exceeding of specified load thresholds. Topological events are caused by the appearance, loss or degradation of nodes and communication channels. Traffic events are defined by a significant change in the intensity, priority structure or spatial distribution of flows. It is these classes of events that form the basis of the event logic of dynamic self-organisation.

A multi-level organisation involves the sequential formation of a management structure [7, 11, 12]. At the lowest level, local clusters are formed, with a coordinator appointed for each one. At the next level, the coordinators are grouped into a higher-level management circuit, and, if necessary, a similar procedure is repeated to form macro-clusters. This scheme reduces the scope of local tasks and limits the volume of service exchange to the boundaries of functionally related subsets of nodes.

To assess the feasibility of merging nodes v_i and v_j let's introduce a proximity function into a single cluster

$$\varphi_{ij}(t) = \beta_1 \left(\widetilde{d_{ij}}(t)\right)^{-1} + \beta_2 \widetilde{c_{ij}}(t) + \beta_3 \widetilde{h_{ij}}(t) + \beta_4 \widetilde{\tau_{ij}}(t) + \beta_5 \widetilde{g_{ij}}(t), \tag{4}$$

where $\widetilde{d_{ij}}(t)$ – standard delay; $\widetilde{c_{ij}}(t)$ – nominal throughput; $\widetilde{h_{ij}}(t)$ – node resource profile compatibility index; $\widetilde{\tau_{ij}}(t)$ – the volume of traffic exchanged between nodes or related subtasks; $\widetilde{g_{ij}}(t)$ – structural proximity index in the relationship graph; $\beta_1 \ldots \beta_5$ – weighting factors.

As $\varphi_{ij}(t)$ ncreases, it becomes more advantageeous to include the relevant nodes in a single cluster.

In telecommunications systems, cluster formation cannot be based solely on the resource characteristics of the nodes [7, 11, 12, 17]. A cluster must ensure not only the availability of sufficient computational resources, but also high structural connectivity, an acceptable level of intra-cluster delay, and a balanced load distribution. In this regard, the clustering procedure must take into account both structural-topological and functional parameters simultaneously. In the simplest case, this requirement can be met by modifying the graph modularity criterion with additional penalties for exceeding the maximum cluster size, increased intra-cluster latency, and severe resource asymmetry.

Quality criterion for a local cluster $C_k(t)$ it is advisable to specify as

$$Q_k(t) = \lambda_1 M_k(t) - \lambda_2 D_{in,k}(t) - \lambda_3 U_k(t) - \lambda_4 P_k(t), \tag{5}$$

where $M_k(t)$ – modified cluster modularity; $D_{in,k}(t)$ – average intra-cluster delay; $U_k(t)$ – resource and load imbalance index; $P_k(t)$ – a fine for breaching structural restrictions; $\lambda_1 \ldots \lambda_4$ – weighting factors.

The formation of the lower level of the hierarchy boils down to maximising the overall cluster quality score. Once the composition of the cluster has been determined, the task of selecting a coordinator must be addressed. Unlike single-criterion approaches, it is advisable to use a comprehensive ranking

$$R_{ik}(t) = \gamma_1 \widetilde{p_i}(t) + \gamma_2 \widetilde{m_i}(t) + \gamma_3 cen_{ik}(t) + \gamma_4 a_{ik}(t) + \gamma_5 stab_i(t) - \gamma_6 fail_i(t) - \gamma_7 \widetilde{q_i}(t), \tag{6}$$

where $\mathrm{cen}_{ik}(t)$ – the local centrality of a node within a cluster; $a_{ik}(t)$ – the average channel availability metric between the candidate node and other cluster elements; $\mathrm{stab}_i(t)$ – indicator of historical operational stability; $\mathrm{fail}_i(t)$ – failure or degradation rate; $\widetilde{q_i}(t)$ – rated current load.

The node with the highest value is designated as the coordinator $R_{ik}(t)$ provided that the minimum threshold requirements for critical parameters are met [8, 15].

An important feature of the model is coordinator redundancy [8, 15]. For each cluster, in addition to the primary coordinator, an ordered list of backup nodes is formed. This makes it possible to restore the cluster's operational capability without a complete re-clustering. In the event of a coordinator failure, provided the quality of the intra-cluster connections remains acceptable, a local re-election procedure is performed within the existing cluster composition. Only when the quality of the structure falls below a specified threshold is a procedure initiated to split, merge or completely reorganise the cluster.

At the highest level, coordinators from lower levels form a super-graph $GH(t)$, in which the vertices correspond to clusters, and the edges represent the intensity of inter-cluster exchange and the quality of the channels between coordinators. To this end, the clustering procedure or aggregation into macro-clusters may be reapplied to the supergraph. This ensures the recursiveness of the model, whereby lower-level rules are transferred to the coordinator level, with the metrics of individual nodes replaced by aggregated cluster indicators.

Aggregated cluster metrics $C_k(t)$ It is advisable to define these not as simple averages, but as characterristics that preserve the critical features of its state. In particular, the available computing power of the cluster should account for a reserve of resources for the coordinator's service functions; cluster availability should be determined via the minimum or harmonic mean of the availability of key channels; service delay must be assessed as a combination of intra-cluster and inter-cluster components. This approach prevents the smoothing out of bottlenecks during aggregation and reduces the risk of an unduly optimistic assessment of the system's state.

The result is a nested, multi-level management structure in which each level performs its own functions. The lower level ensures local load balancing and a short response loop to changes. The middle level handles inter-cluster coordination and the exchange of information regarding resource

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status. The top level performs global policy functions, including reviewing criterion weights, prioritising traffic and initiating large-scale reconfiguration. This division of responsibilities makes it possible to combine a high speed of local response with the necessary level of global controllability of the system.

The proposed method of hierarchical dynamic self-organisation of nodes is implemented as a cyclical process involving network state monitoring, event detection, structural decision-making, reconfiguretion, and verification of the effectiveness of the resulting configuration. Unlike static clustering algorithms, in the proposed approach, reconfiguration is not performed periodically at fixed time intervals, but is event-driven. This ensures a reduction in operational costs during steady-state operation and a reduction in the system's response time when critical state changes occur.

During the monitoring phase, each node generates a local description of its own state, which includes metrics on computational load, buffering, communication channel quality, traffic intensity with neighbouring nodes, packet loss rates, signs of degradation, and remaining resources. The transmission of this information is organised differentially: at the lower level of the hierarchy, local state vectors are propagated within a potential or current cluster, whilst at higher levels only aggregated indicators are transmitted. This approach complies with the principle of information locality and reduces the load on control channels [10, 11, 12].

The second stage of the method involves detecting events and determining the scale of the response. If the change in state is confined to a local area of influence and does not disrupt the basic connectivity of the system, a local reconfiguration is initiated. If, however, the coordinator's operation is disrupted, a critical inter-cluster channel is degraded, or the balance of inter-cluster traffic is significantly altered, the reconfiguration is escalated to a higher level of the hierarchy. This approach avoids the need for a global reconfiguration in cases where local measures are sufficient, thereby ensuring the scalability of the method [11, 12, 14].

In the third stage, the cluster structure within the event's influence zone is reassessed. Updated values of the proximity function $\varphi_{ij}(t)$, are calculated for the relevant nodes, after which the current cluster boundaries are analysed and the appropriateness of one of four basic solutions is determined: retaining the current structure, local migration of a node between neighbouring clusters, splitting an overloaded cluster, or merging a cluster that has lost its internal density or coordinating node. Restricting the set of feasible solutions to a fixed set of structural actions reduces the complexity of the selection and prevents an unjustified complete restructuring of the network as a result of each individual event.

The fourth stage involves selecting, confirming or replacing the cluster coordinator. If the current coordinator maintains an acceptable rating, the system does not perform a re-election even if there is an alternative candidate with a slightly higher score. The use of this hysteresis rule is of fundamental importance, as it reduces role instability and prevents an excessive number of service transitions. The coordinator is replaced only if their rating falls below the minimum acceptable threshold, if connectivity is lost with a significant portion of the cluster nodes, or if the expected benefit from the replacement exceeds the set threshold value.

The fifth stage involves establishing or adjusting the inter-cluster backbone. Cluster coordinators exchange aggregated metrics on load, availability and latency, after which the inter-cluster connection tables and service exchange routes are updated. In the event of a failure of an individual inter-cluster link, the system searches for an alternative configuration via neighbouring coordinators. If such reconfiguretion is not possible, the merging, splitting or reorganisation of clusters in adjacent network zones is initiated. Consequently, the inter-cluster backbone is regarded not as a fixed superstructure, but as an adaptive element of a multi-level structure.

The sixth stage of the method involves verifying the effects of the reconfiguration. Following each significant structural change, the previous and new values of the quality criteria are compared. If no improvement in key indicators is observed following reconfiguration, and operational costs rise significantly, the system may reject the new configuration and revert to the previous state or switch to a more conservative local solution. This mechanism prevents destructive reconfigurations that are formally permissible but actually lead to a deterioration in the network's condition.

The condition for the feasibility of a transition to global reconfiguration can be expressed as

$$\Delta J_{\text{loc}} + \kappa_{\text{loc}} < \Delta J_{\text{glob}} + \kappa_{\text{glob}}, \qquad (7)$$

where ΔJ_{loc} i ΔJ_{glob} – the expected change in the quality function following local and global reconfiguration, respectively;

κloc and κglob – penalties that take into account administrative costs and the duration of the relevant procedure.

According to equation (7), a global reconfiguration is justified only if the expected benefit exceeds the associated costs.

To limit the frequency of reconfigurations, the method introduces a stabilisation interval T_s, during which the same cluster may only be reconfigured in the event of a critical incident. This helps to reduce structural oscillations. An adaptive threshold is also employed $\theta(t)$, which depends on the current level of network instability. In steady-state operating conditions, the threshold value is higher, which increases the system's conservatism, whereas in crisis conditions it is lowered, ensuring a faster response to changes in the environment.

A key feature of the proposed method is the integration of three control loops: structural, resource-based and coordination. The structural loop is responsible for the formation and modification of clusters, the resource loop for assessing the load and availability of resources, and the coordination loop for assigning roles, synchronising states and maintaining service exchange between levels of the hierarchy. It is precisely this integration that provides grounds for considering the proposed approach as a method of hierarchical dynamic self-organisation, rather than as a collection of separate local heuristics.

The practical value of the method lies in the possibility of its modular implementation. The clustering procedure can be implemented using graph algorithms with dynamic updating of link weights. It is advisable to implement the selection of coordinators as a ranking module with failover mechanisms. The event-driven logic of reconfiguretion can be represented as a state machine or a set of policies. Such modularity simplifies the integration of the method into systems for various purposes, in particular into edge/fog infrastructures and specialised telecommunications networks, in which the functionnal roles of nodes may change during operation.

From an algorithmic point of view, a full global reconfiguration is the most computationally expensive operation; therefore, it should be regarded as a rare operating mode. In the normal case, the main computational load is associated with the local updating of link weights, the re-evaluation of coordinator ratings, and the checking of threshold conditions. If the event's area of influence is significantly smaller than the size of the entire network, the average complexity of a single reaction cycle is reduced to processing only the subgraph $G_{\Omega}(t)$, which ensures the scalability of the proposed method. It is precisely due to the localisation of the reaction that the hierarchical approach has an advantage over fully flat coordination mechanisms.

It is appropriate to present the operation of the proposed method of hierarchical dynamic self-organisation of nodes as a sequence of interrelated stages, as shown in Figure 1. In the first stage, the status of nodes and communication channels is monitored, with the generation of local and aggregated indicators of load, availability and exchange quality. In the second stage, changes in the network status are detected and their criticality is determined. In the absence of a critical event, the system retains the current configuration and proceeds to a new monitoring cycle. In the event of a critical incident, the scale of the response is determined, distinguishing between local cluster reconfiguration and reconfiguration at a higher level of the hierarchy. In the next stage, the cluster boundaries are reassessed, a structural decision is made regarding the preservation, division, merging or migration of nodes, and the suitability of the current coordinator is verified, with the possible selection of a backup node. Following this, intra-cluster or inter-cluster connections are updated, the quality criteria of the new configuration are calculated, and a decision is made regarding its acceptance or rejection. The final stage involves transitioning to a stabilisation interval and initiating a new monitoring cycle, ensuring the closed-loop nature of the self-organisation process (Fig. 1).

To evaluate the effectiveness of the proposed method of hierarchical dynamic self-organisation of nodes, it is advisable to use not a single indicator but a system of interrelated indicators, since any network reconfiguration that improves a single characteristic–such as delay–may simultaneously increase operational costs, the load on coordinators, or the frequency of structural reorganisations. In this regard, the comparison of alternative schemes for organising a self-organising telecommunications system should be carried out on a multi-criteria basis, taking into account performance, reliability, survivability and the costs of restructuring.

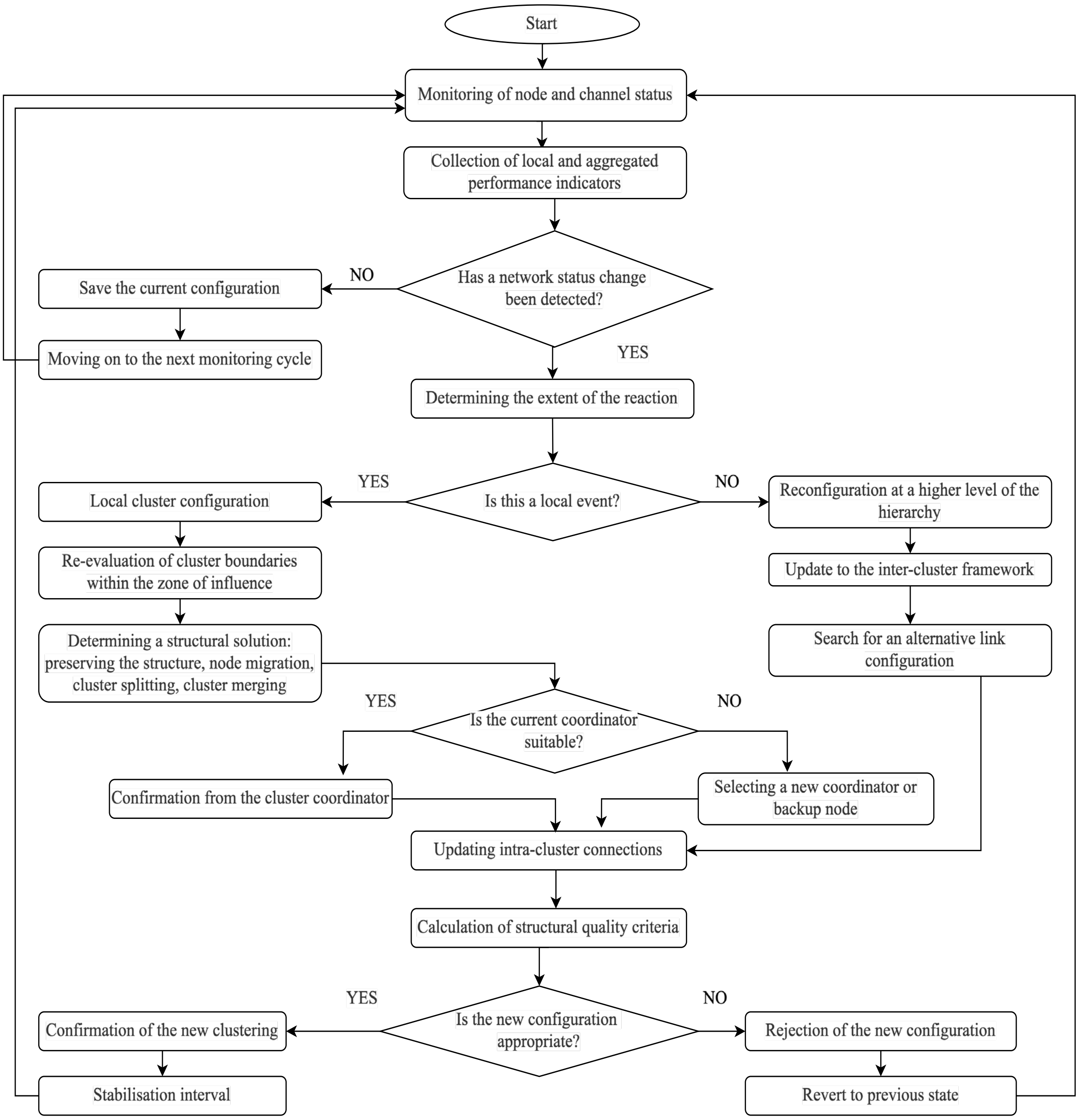

Fig. 1. Block diagram of the method for hierarchical dynamic self-organisation of nodes in a self-organising telecommunications system

One of the key metrics is the average flow service delay, which is best defined as the sum of the transmission time between nodes, buffering time and computational processing time:

$$T_{\text{avg}} = \frac{1}{F} \cdot \sum_f \left(T_{tr,f} + T_{q,f} + T_{proc,f}\right), \qquad (8)$$

where F – the number of streams or sub-streams being served. For self-organising systems, this metric is sensitive to the quality of clustering, the correct selection of coordinators, the length of inter-cluster routes, and the speed of response to changes in the environment; therefore, it reflects not only the network's performance but also the effectiveness of the multi-level control structure.

The second important criterion is the uneven load distribution across nodes, which can be assessed using the normalised root mean square deviation of the integral resource utilisation coefficient:

$$B = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(u_i - \bar{u})^2}}{\bar{u}}, \qquad (9)$$

where u_i – the overall resource utilisation factor of the i-th node, $\bar{u}$ – the average value of this coefficient for the entire network. A decrease in B indicates a more even distribution of the load, which is of fundamental importance for a hierarchical system, as an excessive concentration of functions on individual coordinators increases the risk of cascading degradation and reduces the network's stability. To assess the system's behaviour in emergency and transient modes, it is also necessary to take into account the service continuity index

$$A_{\text{serv}} = \frac{N_{cont}}{N_{all}}, \tag{10}$$

where N_{cont} – the number of threads for which the permissible service interruption interval has not been exceeded; N_{all} – the total number of active threads in the scenario.

Unlike traditional availability, this metric is real-time in nature and is sensitive to brief but critical service interruptions.

Another key indicator is the reconfiguration time

$$T_{rcfg} = t_{recover} - t_{detect}, \tag{11}$$

where t_{detect} – the moment a critical incident is detected; $t_{recover}$ – the moment at which the system transitions to a new stable state.

For self-organising telecommunications systems, this metric has direct practical significance, as even a structurally sound reconfiguration cannot be considered effective if it takes too long and is accompanied by a loss of controllability or a significant deterioration in service performance. It is advisable to present an overall assessment of the system's ability to maintain operational capability using the survivability metric

$$S = \eta_1 C_{conn} + \eta_2 A_{serv} + \eta_3\left(1 - \widetilde{T_{rcfg}}\right), \tag{12}$$

where C_{conn} – connection coefficient of the active part of the network; $\widetilde{T_{rcfg}}$ – standard reconfiguration time; $\eta_1 \dots \eta_3$ – weighting factors.

Unlike simple fault tolerance, the survivability metric reflects a system's ability to maintain a functionally significant portion of the service in the event of partial failures, which is particularly important for systems with multi-tiered management and partial centralisation.

In addition to the main criteria listed above, it is advisable to use supplementary metrics, including the frequency of coordinator re-elections, the frequency of node migrations between clusters, the proportion of service traffic in the total data transfer volume, the number of structural oscillations over a given observation interval, and the decision locality coefficient. The latter can be defined as the ratio of the number of changes made without a global reorganisation to the total number of reconfigurations. It is the combined use of these metrics that enables a correct comparison of centralised, flat, hierarchically unstructured and multi-level control schemes and allows a transition from qualitative judgements to a formalised assessment of system behaviour.

Table 1 summarises the main criteria for evaluating the proposed method.

Table 1

Key criteria for evaluating the hierarchical dynamic self-organisation method

Designation	Indicator	Contents	Desired direction of change
T_{avg}	Average delay	Total transmission, waiting and processing time	Minimise
B	Load imbalance	Degree of imbalance in node resource utilisation	Minimise
A_{serv}	Service continuity	Proportion of flows without critical service interruption	Maximise
T_{rcfg}	Reconfiguration time	Interval for transitioning to a new acceptable state	Minimise
S	Resilience	Overall assessment of service continuity	Maximise

Verifying the effectiveness of the proposed method requires simulation modelling, which must replicate changes in traffic, node failures, channel degradation, the introduction of new network elements, and the control system's response to such events [9, 16]. It is advisable to use specialised edge/fog environment simulators or other software environments capable of replicating mobility, clustering, microservice interaction, and dynamic reconfiguration as the instrumental basis. The basic structure of the experiment should cover at least three alternative network organisation schemes: centralised, flat distributed, and the proposed hierarchical dynamic scheme. The centralised scheme is appropriate as a control variant with maximum global awareness, but low resilience to critical failures of control elements. The flat distributed scheme allows the consequences of interaction to be assessed without designating coordinators and without multi-level localisation of decisions. The hierarchical dynamic scheme is the subject of the study and must be evaluated under identical conditions of load, connectivity and resource availability.

It is advisable to include in the minimum set of experimental scenarios a load-increase scenario, a local failure scenario, in which individual cluster nodes fail sequentially, a scenario involving group failures with the loss of adjacent nodes or the coordinator, a scenario involving changes in the spatial distribution of traffic, and a scenario involving the addition of new nodes.

The recommended structure of simulation scenarios for testing the method is shown in (Table 2).

Table 2

Recommended structure of simulation scenarios for validating the method

Script	Controlled factor	Key metrics	Expected outcome of the method
Increased load	Rated load 0,4–1,3	T_{avg}, B proportion of business traffic	Curbing the growth of delays and imbalances
Local failures	Failure of 1–3 nodes within the cluster	T_{rcfg}, A_{serv}, S	Localisation of the reaction without a global reorganisation
Group failures	Loss of neighbouring nodes or the coordinator	T_{rcfg}, A_{serv}, frequency of re-elections	Sustainable restoration of governance and roles
Changes in the spatial traffic profile	Redistribution of load sources	T_{avg}, B node/thread migration	Structure adaptation without oscillations
Addition of new nodes	Increase in the number of nodes and resources	$B,\ S$, local nature of decisions	Scaling without a complete reconfiguration

It is precisely this combination that makes it possible to assess not only performance under normal operating conditions, but also the system's behaviour in the event of structural degradation, partial failure of control loops, and network scaling. In each scenario, it is necessary to record the values of key criteria and to store time series for subsequent statistical analysis. It is advisable to present the results comparatively in the form of dependencies of average delay on load level, service continuity on the proportion of failed nodes, the load unevenness coefficient on traffic variability, and reconfiguration time on the number of simultaneous failures. It is precisely these graphs that most fully reflect the advantages or limitations of the multi-level approach.

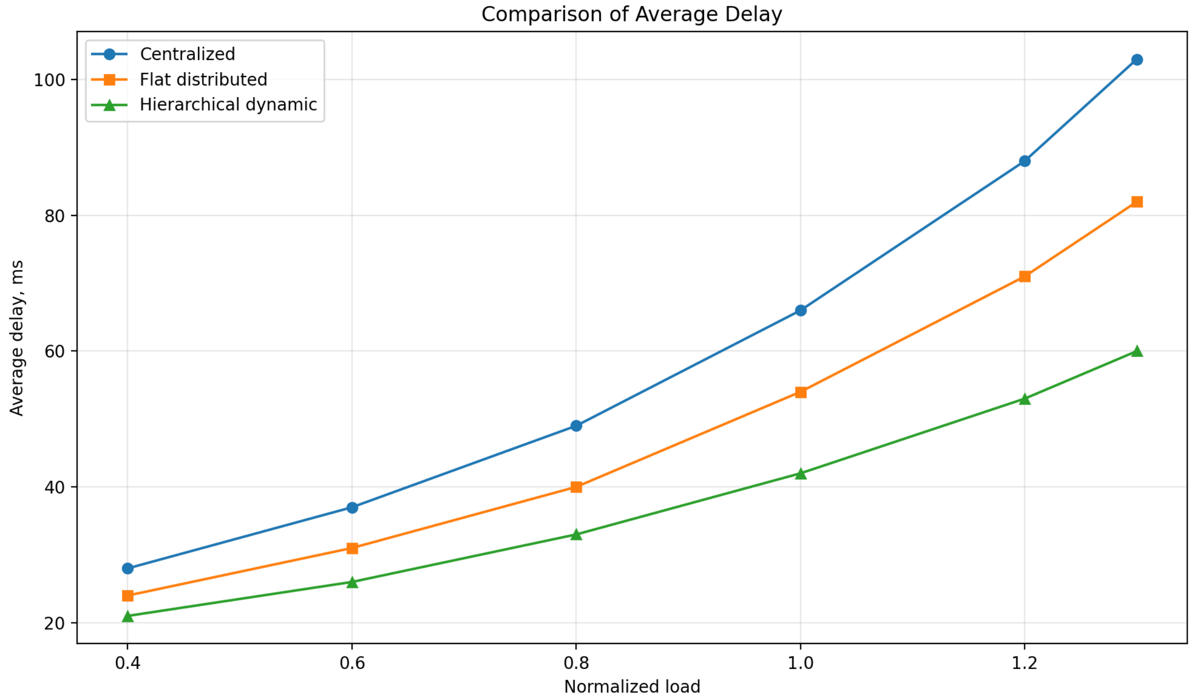

Fig. 2. Comparison of average latency for three network topologies as a function of normalised load

Fig. 2 shows how average delay varies with normalised load for three network topologies. As the load increases, the centralised topology exhibits the fastest rise in delay, due to the concentration of control and computational functions within a narrow decision-making loop. The flat distributed scheme performs better at initial load levels; however, as traffic intensity increases further, its efficiency decreases due to the increase in service exchange between nodes. The proposed hierarchical dynamic scheme is characterised by a more gradual dependence, indicating better localisation of decisions within clusters and a reduction in the load on the global coordination level. Thus, the use of a multi-level control structure allows the growth of average delay to be contained under conditions of increasing load

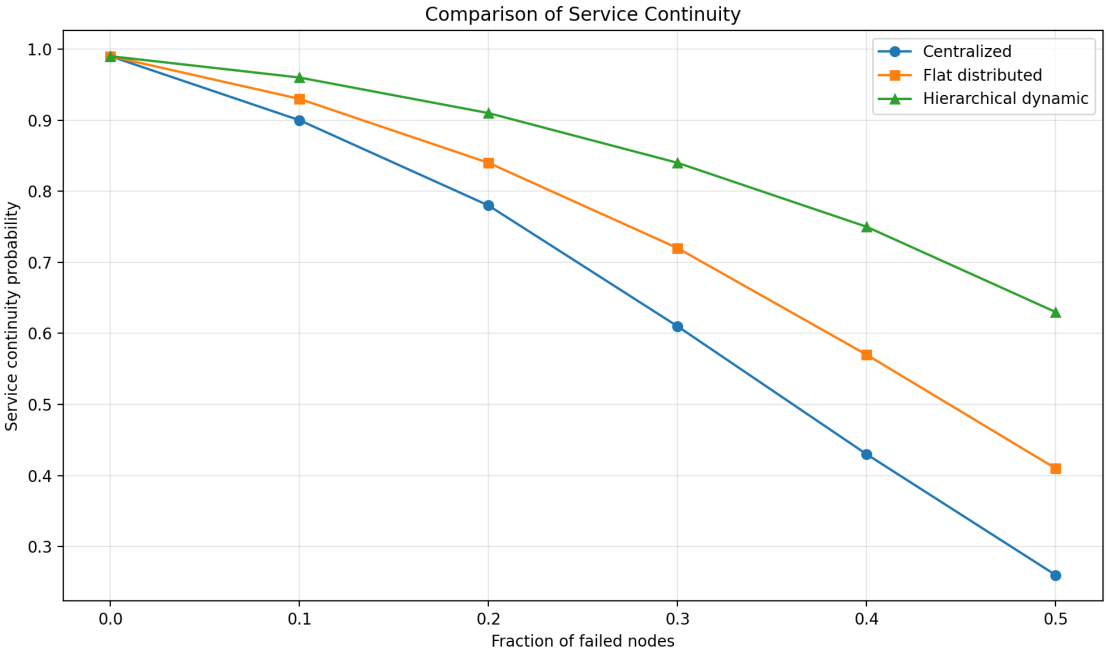

Fig. 3. Comparison of the probability of continuous operation as a function of the proportion of failed components

Fig. 3 shows that as the proportion of failed nodes increases, the probability of continuous service in a hierarchical dynamic architecture decreases more slowly than in centralised and flat architectures.

Consequently, the use of coordinator redundancy, local role re-election and event-driven reconfiguration enhances the system's resilience to partial failures and helps maintain service during transitional states.

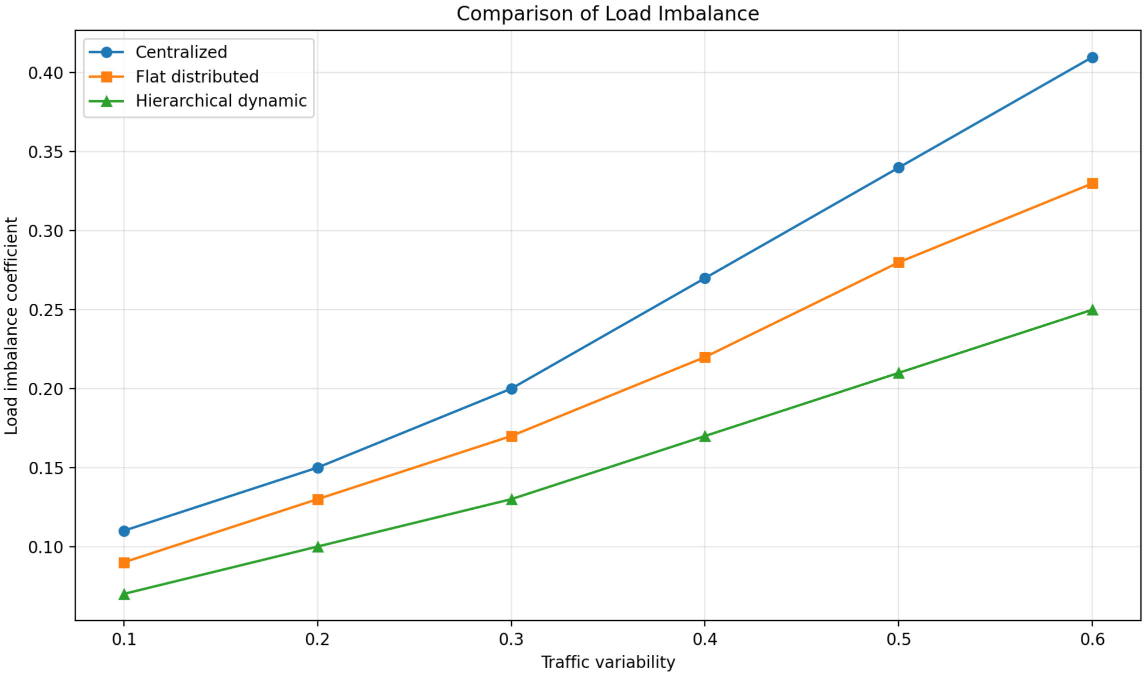

Fig. 4. Comparison of the load unevenness coefficient as a function of traffic variability

Fig. 4 shows that the proposed method achieves a lower load imbalance coefficient compared to other schemes. This indicates a more balanced distribution of resource load between nodes, achieved through adaptive adjustment of cluster boundaries, consideration of resource asymmetry among nodes, and timely local load redistribution. In practical terms, this reduces the risk of coordinator overload and cascading network degradation.

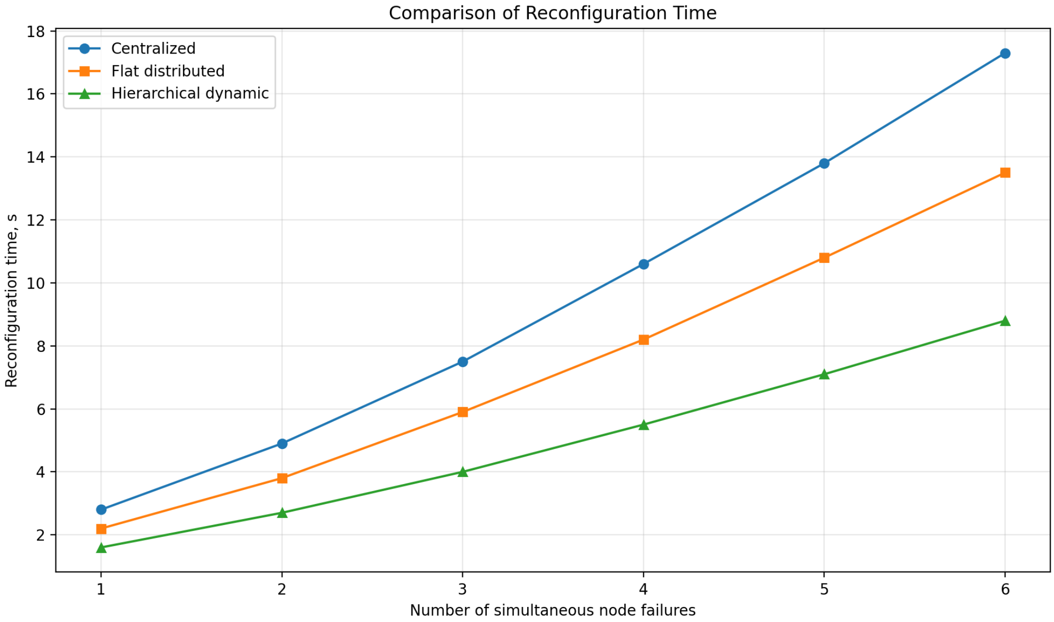

Fig. 5. Comparison of reconfiguration time as a function of the number of simultaneous node failures

The relationship shown in Figure 5 demonstrates that, as the number of simultaneous failures increases, the reconfiguration time in a hierarchical dynamic scheme increases more slowly than in centralised and flat schemes. This means that a significant proportion of recovery actions are performed at lower levels of the hierarchy without the need for full global coordination. Consequently, a multi-level management organisation improves the speed of recovery and the overall resilience of a self-organising telecommunications system.

Taken together, the dependencies shown in Fig. 2–5 indicate that the proposed hierarchical dynamic scheme offers a better trade-off between delay, load balancing, service continuity and reconfiguration time compared to centralised and flat distributed schemes. This confirms the advisability of localising decisions within clusters and using a multilevel control structure to enhance the stability and resilience of a self-organising telecommunications system.

The scientific value of the proposed approach lies in the fact that the self-organisation of nodes is viewed as a controlled, multi-level process whereby the network transitions between valid structural configurations. Unlike approaches in which clustering, coordinator selection and reconfiguration are studied separately, in this work these components are integrated within a single method. From the perspective of the overall logic of the doctoral research, this result occupies an intermediate yet system-forming position between the problems of multi-criteria flow distribution and those of adaptive topology construction.

The practical value of the method lies in its applicability to systems where nodes have their own computing resources and where delays in control decisions are critical [9, 10, 14]. Such systems may include edge/fog infrastructures, distributed computing platforms, autonomous segments of industrial networks, as well as special-purpose telecommunications systems. In all these cases, multi-level self-organisation can be used as a means of reducing dependence on a single coordination centre and increasing network resilience without transitioning to a fully flat, difficult-to-manage interaction. At the same time, the practical implementation of the method requires proper provisioning of coordinator resources, the use of stabilisation mechanisms to prevent structural oscillations, and the adaptation of weighting coefficients to a specific network class. Consequently, the final version of the article should combine a formal description of the model, a rigorous exposition of the method, a multi-criteria evaluation system, and the results of simulation modelling, which will substantiate the effectiveness of the proposed approach in both theoretical and applied aspects.

To provide a clearer understanding of the proposed method, it is advisable to compare the basic classes of approaches to the organisation of distributed telecommunications systems in terms of key functional characteristics. Such a comparison allows us to determine which specific components are supported within centralised, flat distributed and hierarchical approaches, as well as to justify the difference between the proposed method and existing solutions. A summary of the relevant characteristics is given in (Table 3.)

Table 3

Comparative overview of classes of approaches to the organisation of a distributed network

Approach	Node clustering	Selection of coordinators	Event-driven reconfiguration	Survivability assessment
Centralised schemes	Usually absent or set statically	A fixed control centre is used	Is predominantly global in nature	Limited
Flat distributed schemes	Local or situational clustering is possible	Implicit roles or temporary leaders are used	Is implemented locally, but is difficult to coordinate across the entire network	Partial
Individual hierarchical fog-approaches	Supported	Supported	Is implemented in part	Fragmentary
The proposed method	Adaptive clustering is supported	Supported: ranked selection of coordinators with redundancy	Supports both local and global reconfiguration	Supported through a system of interrelated metrics

This comparison shows that centralised schemes provide a high level of global awareness, but are characterised by low resilience to critical failures and significant dependence on a central node. Flat, distributed approaches reduce dependence on a single centre, but complicate decision-making, particularly in conditions of intense traffic fluctuations, link degradation or the need for rapid structural reorganisation. Some hierarchical fog approaches partially address these shortcomings, but typically focus only on individual components, such as clustering, coordinator selection, or function placement. In contrast, the proposed method integrates adaptive clustering, ranked coordinator selection with redundancy, event-driven reconfiguration and multi-criteria network state assessment, which defines its scientific and practical distinction.

Conclusions

This article establishes the scientific and methodlogical basis for a method of hierarchical dynamic self-organisation of computing nodes in self-organising telecommunications systems. It is shown that for systems operating under conditions of variable topology, resource heterogeneity and dynamic traffic, both purely centralised and fully flat distributed control schemes are inadequate. The feasibility of transitioning to a multi-level control structure is justified, combining local decision-making, fault tolerance and the ability to globally coordinate network operation policies.

A formalisation of a self-organising telecommunications system in the form of a dynamic graph is proposed; a model of multi-level node organisation is defined; a proximity function for clustering, an integral coordinator rating, and the event-driven logic of reconfiguration are described. Unlike approaches in which these procedures are considered in isolation, in the proposed method they are integrated into a single mechanism of hierarchical dynamic self-organisation. This is precisely what constitutes the essence of the further development of the method of node self-organisation in self-organised telecommunications systems.

A system of evaluation criteria has been proposed, comprising average delay, load unevenness, the probability of continuous service, reconfiguration time, and an integral survivability metric. It is shown that only the combined use of these metrics ensures a correct comparison of different architectural schemes and allows for the evaluation not only of the system's performance but also of its ability to maintain operability under changing environmental conditions.

The structure of a simulation experiment has been established for the subsequent verification of the proposed method, and a recommended format for presenting comparative results in the form of graphical representations of key indicators has been defined. The demonstration graphs presented do not claim to be final experimental results, but serve a methodological function by setting the form for the future presentation of actual data. This approach ensures the logical completeness of the article's structure as early as the manuscript preparation stage, whilst at the same time avoiding the substitution of real modelling with preliminary assumptions.

Further research should focus on the software implementation of the model, serial simulation modelling, statistically sound comparisons with baseline approaches, and the adaptation of the weighting coefficients of the criterion functional to different classes of self-organising telecommunications systems. This will enable a transition from a theoretically and algorithmically sound model to a

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fully-fledged, experimentally validated technology for constructing multi-level self-organising networks.

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МЕТОД ІЄРАРХІЧНОЇ ДИНАМІЧНОЇ САМООРГАНІЗАЦІЇ ОБЧИСЛЮВАЛЬНИХ ВУЗЛІВ У САМООРГАНІЗОВАНИХ ТЕЛЕКОМУНІКАЦІЙНИХ СИСТЕМАХ

У статті розроблено метод ієрархічної динамічної самоорганізації обчислювальних вузлів у самоорганізованих телекомунікаційних системах, орієнтований на функціонування в умовах змінної топології, неоднорідності ресурсів, динамічного трафіку та часткових відмов. Запропонований підхід базується на формалізації системи у вигляді динамічного зваженого графа та передбачає побудову багаторівневої структури управління з виділенням локальних кластерів, координаторів кластерів і вищих рівнів агрегування. У межах методу визначено функцію близькості для кластеризації вузлів, інтегральний рейтинг вибору координаторів, правила резервування та подієву логіку реконфігурації внутрішньокластерних і міжкластерних зв'язків.

На відміну від підходів, у яких кластеризація, вибір координаторів і перебудова структури розглядаються окремо, у роботі ці компоненти інтегровано в єдиний механізм керованої багаторівневої самоорганізації. Обґрунтовано систему критеріїв оцінювання, що включає середню затримку, нерівномірність завантаження, безперервність обслуговування, час реконфігурації та інтегральний показник живучості. Сформовано структуру імітаційного експерименту для подальшої верифікації запропонованого методу та визначено формат порівняльного подання результатів.

Практична цінність роботи полягає у можливості застосування методу в edge/fog-інфраструктурах, розподілених обчислювальних платформах і спеціалізованих телекомунікаційних мережах, де критичними є стійкість, масштабованість і оперативність реконфігурації.

Ключові слова: самоорганізована телекомунікаційна система; ієрархічна самоорганізація; кластеризація вузлів; координатор кластера; подієва реконфігурація; живучість мережі; edge computing; fog computing.

Lozko O., PastushenkoV.

METHOD FOR THE HIERARCHICAL DYNAMIC SELF-ORGANISATION OF COMPUTING NODES IN SELF-ORGANISING TELECOMMUNICATIONS SYSTEMS

The article develops a method for the hierarchical dynamic self-organisation of computing nodes in self-organising telecommunications systems intended for operation under conditions of variable topology, heterogeneous resources, dynamic traffic, and partial failures. The proposed approach is based on the formalisation of the system as a dynamic weighted graph and provides for the construction of a multi-level management structure with local clusters, cluster coordinators, and higher aggregation levels.

Within the framework of the method, a proximity function for node clustering, an integral ranking for coordinator selection, failover rules, and event-driven logic for the reconfiguration of intra-cluster and inter-cluster connections are defined. Unlike approaches in which clustering, coordinator selection, and structural reconfiguration are considered separately, these components are integrated into a single mechanism of controlled multi-level self-organisation. A system of evaluation criteria is substantiated, including average delay, load imbalance, service continuity, reconfiguration time, and an integral survivability indicator. The structure of a simulation experiment for the further verification of the proposed method is formed, and a format for the comparative presentation of results is defined.

The practical value of the study lies in the possibility of applying the method in edge/fog infrastructures, distributed computing platforms, and specialised telecommunications networks where resilience, scalability, and reconfiguration efficiency are critical.

Keywords: self-organising telecommunications system; hierarchical self-organisation; node clustering; cluster coordinator; event-driven reconfiguration; network survivability; edge computing; fog computing.

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