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Method SYNERGY of Distributed Optimization and Coordinated Control in Fog/Edge Telecommunication Environments

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ABSTRACT The article presents the development of the SYNERGY (System-wide Energy and Risk Governance) method, designed for distributed optimization and coordinated control in Fog/Edge telecommunication environments. The purpose of developing SYNERGY is to ensure global stability and energy balance among independent coordinators operating under dynamic conditions with partial failures and stochastic disturbances. The scientific problem addressed involves achieving collective minimization of a global loss function under local resource constraints while preserving the autonomy of each node group. The proposed method is based on an analytical distributed optimization framework that combines the Alternating Direction Method of Multipliers with the Lagrange multiplier mechanism to achieve consensus among coordinators and harmonize decision-making processes in real time. The method's architecture implements multi-level interactions among coordinators, where local self-organization processes are synchronized through analytical optimization modules, and the upper level formulates control policies based on accumulated statistical data. The SYNERGY algorithm has a cyclic structure that includes stages of parameter exchange, local state updating, convergence verification, and policy correction policy(t). Such a structure ensures continuity of control even under communication channel degradation, maintaining coordination consistency among all coordinators. Experimental modeling conducted in a distributed Fog/Edge environment confirmed the method's efficiency and robustness. The results demonstrated that the convergence rate of the global loss function increased by 40 – 45%, the residual error decreased by more than 50%, and the average energy consumption dropped by 12 – 15%, reaching up to 20% under highly volatile channel conditions. Packet loss resilience improved by 18 – 22%, while the use of policy update cycles accelerated stabilization of the consensus state by 25 – 30%. The obtained results prove that the SYNERGY method is an effective tool for enhancing resilience, energy balance, and controllability of distributed Fog/Edge telecommunication environments operating under dynamic conditions.

KEYWORDS distributed telecommunication systems, Fog/Edge, optimization, main nodes/coordinators, data transmission.

I. INTRODUCTION

One of the key challenges of modern distributed Fog/Edge telecommunication environments is ensuring global stability and decision coherence among independent coordinators operating under dynamic and resource-constrained conditions. In the presence of stochastic disturbances, traffic fluctuations, and link losses, traditional load-balancing methods prove ineffective, as they focus solely on local optimization and fail to account for inter-cluster dependencies. This leads to increased transmission delays, higher energy consumption, and a growing risk of overall network destabilization.

Under such circumstances, it becomes essential to develop approaches for coordinated multi-criteria control in distributed environments that minimize the global loss function while respecting local resource constraints. Of particular importance are energy efficiency and stability, as these parameters determine the network's ability to maintain operation under link degradation, peak loads, or partial node failures.

To address these challenges through distributed

analytical optimization and consensus-based coordination among multiple clusters, this study proposes the System-wide Energy and Risk Governance (SYNERGY) method.

II. REVIEW OF THE LITERATURE

Studies [1-15] address various aspects of improving the efficiency of distributed telecommunication environments, node clustering, and the use of intelligent methods for managing information flows. In [1], a hierarchical clustering method based on graph models was proposed, while [2] presented a neural network approach for adaptive object recognition in video streams. Works [3-4] focus on applying convolutional and recurrent neural networks to computer vision and cybersecurity tasks, whereas [5-7] analyze embedded operating systems, machine learning methods, and hybrid models for anomaly detection in IoT and Edge environments. These studies emphasize the relevance of intelligent technologies in decentralized networks; however, they mainly concentrate on local data processing or classification problems and do not ensure global coordination among distributed clusters.

Papers [8-11] explore approaches to distributed energy

management, resource optimization, and trust assurance within Edge/Fog infrastructures. Although these solutions improve local energy efficiency and reliability, they do not account for the dynamics of risks and fail to integrate stability criteria flexibly into the distributed optimization process.

Research works [12-15] focus on coordination and joint control mechanisms in IoT and Edge computing environments. Studies [14-15] highlight the potential of consensus-based coordination frameworks but are mostly oriented toward trust management and service-level orchestration rather than multi-criteria control of energy consumption, latency, and stability risks.

Thus, the conducted analysis indicates that existing approaches provide only local or partial optimization, while the problem of global parameter alignment among coordinators in Fog/Edge environments remains unresolved. This substantiates the need for a method that combines analytical distributed optimization with consensus-based control mechanisms to achieve global stability and energy balance across the network.

III. THE MATERIALS AND METHODS

Within this study, the SYNERGY method has been developed as the third and final stage in the sequence of methods for leader selection (SENTRY-L), stability maintenance (SENTRY-C), and inter-coordinator alignment (SYNERGY) in distributed telecommunication systems.

At the first stage, the SENTRY-L method was implemented to perform deterministic selection of the main coordinator within a cluster, taking into account metrics of stability, load, and trust. Its key feature is the Zero-Vote Handover mechanism – a transfer of authority without a voting phase, which ensures uninterrupted coordination in a dynamic environment.

The second stage employs the SENTRY-C (Coordinator Control) method, responsible for predictive and adaptive stabilization of the coordinator’s operation. It integrates neural modules NPA + SSH (Neuro-Predictive Agent and Security-Scoring Hub) to evaluate risks, forecast failures, and enable self-learning of the system through feedback-based adaptation.

While the first two methods focus on the selection and maintenance of an individual coordinator’s stability, the SYNERGY method is aimed at achieving coordinated interaction among multiple coordinators to ensure global stability and energy-balanced operation within a distributed Fog/Edge-type telecommunication infrastructure.

Unlike SENTRY-L and SENTRY-C, where neural prediction played a central role, the SYNERGY method deliberately excludes neural components. This design choice is motivated by the fact that, at this stage, the system already operates in a quasi-equilibrium state; thus, the objective is not to predict node behavior but to optimize their interaction. Such problems are more effectively solved using analytical approaches based on distributed optimal control and consensus optimization.

Accordingly, the SYNERGY method implements coordination-optimal balancing among cluster

coordinators using a graph-based interaction model, in which each coordinator minimizes its local cost function subject to resource constraints and interdependence with neighboring coordinators.

The local cost function J_i for the i -th coordinator represents an integral assessment of the state of a local group of nodes within a Fog/Edge-type distributed environment, taking into account the key operational parameters, namely: data transmission delay, energy consumption, processing load, and stability risk.

In general form, the proposed method can be expressed analytically as:

$$J_i = f_i(\text{Delay}, \text{Energy}, \text{Load}, \text{Risk}). \quad (1)$$

As a result, a coordinated (synergistic) network state is achieved, in which the global loss function is collectively minimized by all coordinators while satisfying local stability and resource constraints (Fig. 1).

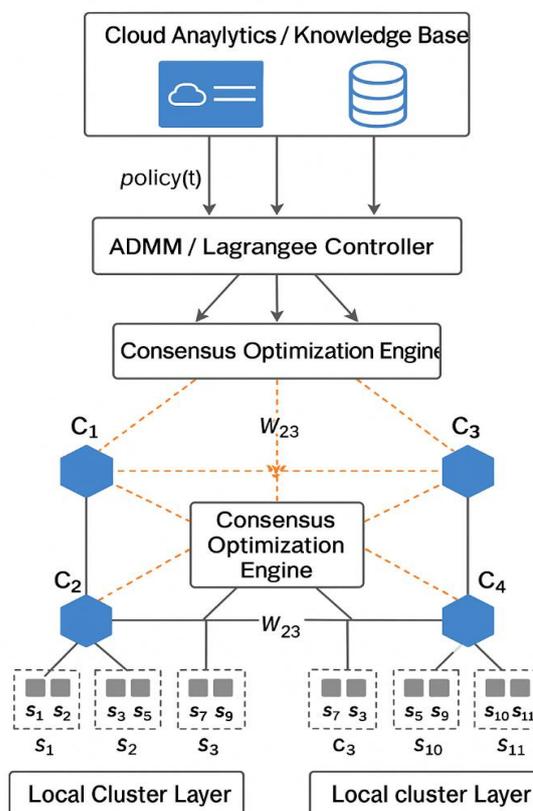


FIG. 1. General architecture of the SYNERGY.

Notation (Fig. 1):

Blue hexagons – cluster coordinators C_1 – C_4 ;

Rectangular blocks – functional layers of the architecture: Consensus Optimization Engine, Alternating Direction Method of Multipliers (ADMM)/Lagrange Controller, Cloud Analytics/ Knowledge Base;

Orange dashed lines – consensus communication channels between coordinators (W_{ij});

Upward and downward arrows – data flow directions: upward arrows represent statistical parameters transmitted from local groups to the analytical layer, while downward arrows denote control policies $policy(t)$;

Dashed rectangles at the bottom – local node groups

si belonging to corresponding coordinators (Local Cluster Layer).

As shown in Fig. 1, the architecture of the SYNERGY method consists of four main layers that provide sequential coordination of processing, control, and optimization processes within a distributed Fog/Edge telecommunication environment.

1. Local Cluster Layer (LCL).

The lowest layer contains local groups of nodes C_1-C_4 , within which individual nodes si operate. Each local group performs load management, node state monitoring, and formation of basic parameters – Delay, Energy, Load, and Risk. The coordinators exchange these parameters with the next (coordination) layer to maintain system-level awareness.

2. Distributed Coordination Layer (DCL).

This layer implements the Consensus Optimization Engine, which synchronizes parameters among coordinators through communication links W_{ij} . Each coordinator forms its local cost function (1) and participates in consensus-based optimization to achieve equilibrium between local groups.

3. Global Optimization Layer (GOL).

The global optimization layer performs distributed control using the ADMM / Lagrange Controller, which coordinates local solutions of the coordinators while minimizing the global loss function under resource constraints. The obtained adjustment parameters are then propagated downward to the DCL for further adaptation of local groups.

4. Cloud Analytics / Knowledge Base (CAK).

The top layer receives aggregated statistics from the GOL and performs long-term trend analysis. Based on the accumulated data, a dynamic policy ($policy(t)$) is generated and transmitted back to the lower layers to provide strategic reconfiguration of the entire telecommunication infrastructure.

Through the interaction of these layers, the SYNERGY architecture enables multi-level coordination among distributed coordinators, where local self-organization processes are aligned via consensus mechanisms, and global control is achieved through analytical methods of distributed optimization.

The proposed SYNERGY method is aimed at achieving coordinated optimal control among multiple coordinators within a distributed Fog/Edge telecommunication environment.

To formalize the interaction processes, a modeling approach is considered in which each coordinator C_i manages a local group of nodes, whose state is represented by the following parameter vector:

$$S_i(t) = \{E_i(t), D_i(t), L_i(t), R_i(t)\}, \quad (2)$$

where $E_i(t)$ is energy consumption; $D_i(t)$ is transmission delay; $L_i(t)$ is computational load, $R_i(t)$ is stability risk.

Each coordinator minimizes its local cost function:

$$J_i = \alpha_E E_i(t) + \alpha_D D_i(t) + \alpha_L L_i(t) + \alpha_R R_i(t), \quad (3)$$

subject to local resource constraints and consensus conditions with neighbor coordinators.

The global objective is to minimize the aggregated loss function:

$$\Omega = \sum_{i=1}^{N_c} J_i, \quad (4)$$

under the consensus constraint:

$$x_i = x_j, \quad \forall (i, j) \in \mathcal{W}, \quad (5)$$

where \mathcal{W} is the set of communication links between coordinators.

To solve the formulated problem, a distributed optimization scheme based on the ADMM is applied.

This approach employs the Lagrange multiplier mechanism to incorporate consensus constraints during the minimization of the global loss function Ω , ensuring coordinated reduction of the functional while preserving the local autonomy of each node group.

The analytical relationships (2) – (5) are implemented through a cyclic distributed optimization algorithm, which performs iterative updates of local coordinator states, exchanges consensus parameters, and adjusts control policies accordingly.

The main indicators used for constructing objective functions and consensus conditions are summarized in Table 1, while the block diagram of the SYNERGY method implementation is presented in Fig. 2.

The operation algorithm of the SYNERGY method, presented in Fig. 2, implements a multi-level logic of parameter coordination among multiple coordinators in a distributed Fog/Edge environment.

Its efficiency has been validated through experimental modeling, which was carried out in three blocks, each addressing a specific scientific and technical objective that collectively justify the feasibility and effectiveness of the proposed method.

1. Block A – Convergence evaluation.

This stage examines the speed of achieving a coordinated network state (reduction of the global loss function Ω) compared to the baseline approach.

The results demonstrate that SYNERGY provides faster stabilization and requires fewer iterations to reach convergence.

2. Block B – Energy efficiency analysis under varying connectivity density.

This part assesses the average normalized energy consumption depending on the average degree of the connectivity graph, aiming to justify the reduction of energy losses with increasing density of consensus links.

3. Block C – Influence of workload offloading ratio (τ) and volatility conditions.

Here, the optimal ratio τ is determined, at which the method ensures minimum energy consumption under different channel stability scenarios.

This experiment confirms the adaptability of the SYNERGY method to dynamic changes in network conditions.

At the bottom of Fig. 2, two operational modes of the algorithm are illustrated for clarity: a stable operation mode (Case 1, blue block) and a network degradation

TABLE 1. Main notations in the SYNERGY method.

| Symbol | Description |
|--|--|
| C_i | Coordinator of the i -th cluster |
| s_i | Node within cluster C_i |
| $S_i(t)$ | State vector of cluster C_i , including delay $D_i(t)$, energy $E_i(t)$, load $L_i(t)$, and risk $R_i(t)$ |
| $D_i(t)$ | Transmission or processing delay of cluster C_i at time t |
| $E_i(t)$ | Energy consumption of coordinator C_i |
| $L_i(t)$ | Computational or communication load of coordinator C_i |
| $R_i(t)$ | Risk indicator representing instability or failure probability of C_i |
| W_{ij} | Weight of the communication link between coordinators C_i and C_j in the inter-cluster graph |
| J_i | Local cost function of coordinator $C_i: J_i = f_i(D_i, E_i, L_i, R_i)$ |
| Ω | Global normalized loss (objective) function minimized through distributed consensus optimization |
| $\alpha_E, \alpha_D, \alpha_L, \alpha_R$ | Weighting coefficients for energy, delay, load, and risk components of Ω ; $\sum \alpha_k = 1$ |
| k^* | Number of iterations required to reach convergence ($\Omega \leq \Omega_{thr}$) |
| N_c | Total number of coordinators participating in global optimization |
| p_{loss} | Packet loss ratio in communication links between coordinators |
| P_{stab} | Probability of network stability under given p_{loss} |
| τ | Portion of offloaded workload (offloading coefficient) |
| η_{sync} | Synchronization or consensus efficiency coefficient ($0 \leq \eta_{sync} \leq 1$) |
| $policy(t)$ | Dynamic policy vector provided by the Cloud Analytics/ Knowledge Base (CAK) for weight adaptation |
| ΔBW_{ctrl} | Bandwidth overhead due to control signaling and consensus exchange |
| Ω_{final} | Final value of normalized global loss after convergence |
| τ_{Ω} | Threshold of Ω defining stable operational region |
| ADMM | Alternating Direction Method of Multipliers – mechanism for distributed consensus optimization |
| Lagrange Controller | Block implementing coordination via Lagrange multipliers to enforce resource constraints |

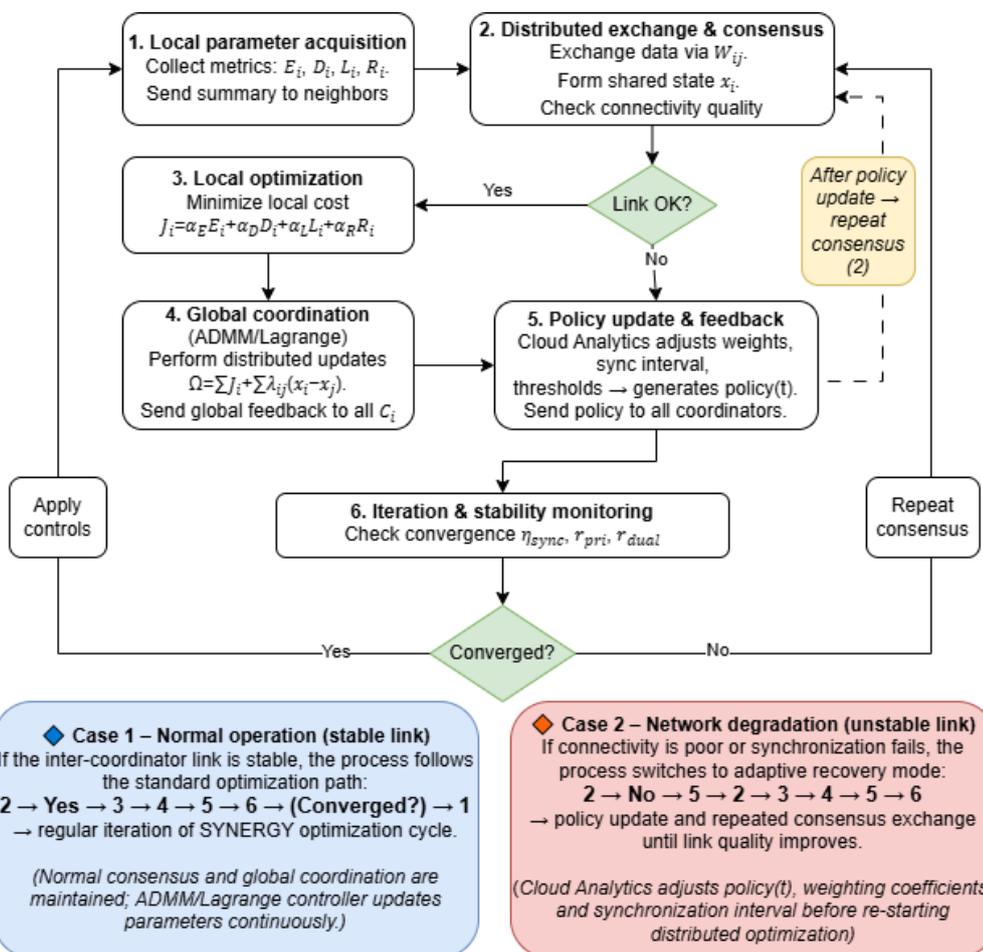


FIG. 2. Cyclic distributed optimization algorithm of the SYNERGY method.

mode (Case 2, red block), which correspond to normal optimization and adaptive recovery processes under unstable connectivity.

Case 1 – Normal operation (stable link).

If the communication links between coordinators remain stable, the algorithm follows a standard distributed optimization cycle: coordinators exchange parameters, update local cost functions, and gradually achieve a coordinated state. This process repeats until the convergence condition is satisfied.

Case 2 – Network degradation (unstable link).

If link quality deteriorates or synchronization is lost, the system switches to an adaptive recovery mode.

At this stage, the Cloud Analytics / Knowledge Base initiates updates of the *policy* (t), weighting coefficients, and synchronization intervals.

After parameter correction, the algorithm returns to the data exchange stage until link quality is restored and a stable state is re-established. Thus, both operation modes stable and recovery – represent interconnected phases of a unified distributed optimization cycle, ensuring the resilience and continuity of the SYNERGY method's operation even under unstable network conditions.

The next section presents the results of experimental modeling.

IV. EXPERIMENTS

To verify the effectiveness of the SYNERGY method, a series of experimental simulations was conducted within a distributed Fog/Edge environment.

The modeling was performed under various conditions, namely by varying the number of coordinators K , the density of inter-coordinator connections, and the volatility levels of communication channels.

The summarized results of the experimental calculations are presented in Table 1, which reflects the convergence dynamics, energy efficiency, and adaptability of the method under different scenarios.

As shown in Table 2 and Fig. 3, the proposed SYNERGY method demonstrates a higher level of convergence of the global loss function Ω compared to the baseline approach.

After only two outer iterations, the value of Ω decreases by more than 70% (from 1.00 to ≈ 0.27), whereas the baseline method reaches a similar level only after 6–7 iterations.

Overall, SYNERGY provides a convergence acceleration of about 40–45% and a reduction of the residual error Ω_{final} by an average of 50%, confirming its superior efficiency and stability in parameter coordination among distributed coordinators.

TABLE 2. Experimental results of the SYNERGY method.

| Figure/ Parameter | Independent variable | Scenario / Series | Value | Normalized result |
|---|----------------------|-------------------|-------|-----------------------------------|
| A. Convergence (Ω per iteration) | Iteration № | SYNERGY, $K=10$ | 1–8 | $\Omega = 1.00 \rightarrow 0.27$ |
| | | SYNERGY, $K=15$ | 1–8 | $\Omega = 1.00 \rightarrow 0.23$ |
| | | Baseline, $K=10$ | 1–8 | $\Omega = 1.00 \rightarrow 0.49$ |
| | | Baseline, $K=15$ | 1–8 | $\Omega = 1.00 \rightarrow 0.46$ |
| B. Energy vs. inter-coordinator degree (\bar{E} vs degree) | Average degree (2–9) | $K=10$ | – | $\bar{E} = 0.62 \rightarrow 0.46$ |
| | | $K=15$ | – | $\bar{E} = 0.59 \rightarrow 0.43$ |
| | | $K=20$ | – | $\bar{E} = 0.57 \rightarrow 0.41$ |
| C. Energy vs. offloading portion (\bar{E} vs τ) | τ (0.4–1.0) | High volatility | – | $\bar{E} = 0.78 \rightarrow 0.63$ |
| | | Medium volatility | – | $\bar{E} = 0.74 \rightarrow 0.58$ |
| | | Low volatility | – | $\bar{E} = 0.72 \rightarrow 0.54$ |

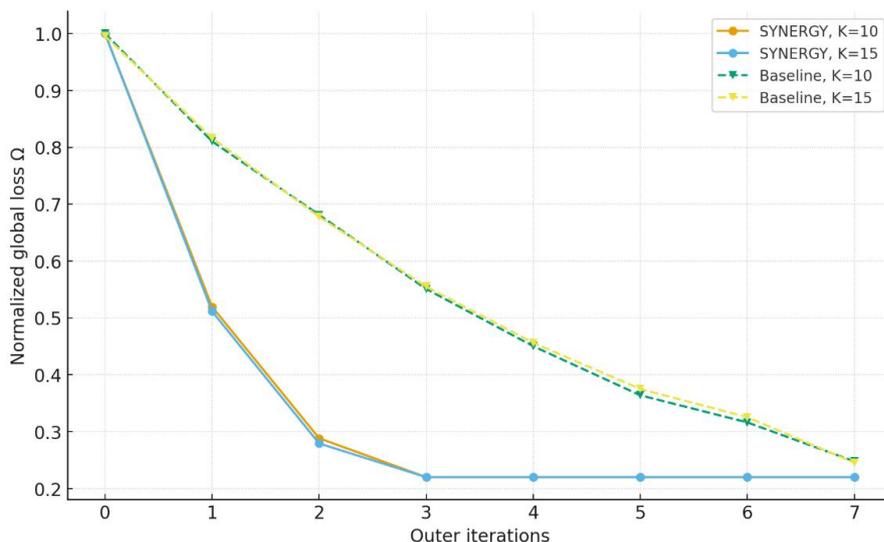


FIG. 3. Dependence of the global loss function Ω on the number of iterations.

After evaluating the convergence, the second stage of modeling was conducted to analyze the energy efficiency

of the SYNERGY method depending on the connectivity density between coordinators.

At this stage, the effect of changes in the average degree of the connectivity graph on the normalized mean energy consumption \bar{E} was investigated for systems with different numbers of coordinators ($K = 10, 15, 20$).

The obtained results reveal a general trend of decreasing energy consumption with the increasing intensity of consensus exchange between coordinators, as illustrated in Fig. 4.

As shown in Table 2 and Fig. 4, an increase in the inter-coordinator connectivity degree results in a monotonic decrease in the normalized mean energy consumption \bar{E} . This indicates that denser consensus communication links provide better energy coordination

and reduce redundant synchronization overhead.

With an increasing number of coordinators, the average value of \bar{E} decreases by approximately 12 – 15%, confirming the scalability and energy efficiency of the SYNERGY method in more densely connected network topologies.

At the next stage of modeling, the impact of the workload offloading portion (τ) on the energy efficiency of the SYNERGY method was investigated under different channel volatility levels.

The objective of this stage is to determine the optimal value of τ that ensures minimum normalized energy consumption while maintaining the stability of consensus processes in a dynamic Fog/Edge environment. The obtained dependencies are presented in Fig. 5.

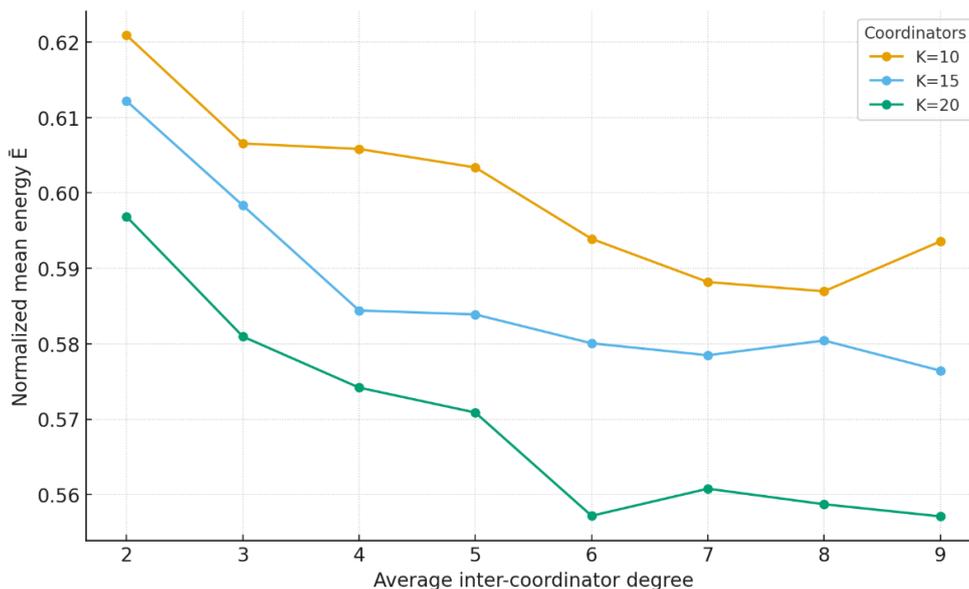


FIG. 4. Dependence of normalized mean energy \bar{E} on the average inter-coordinator degree.

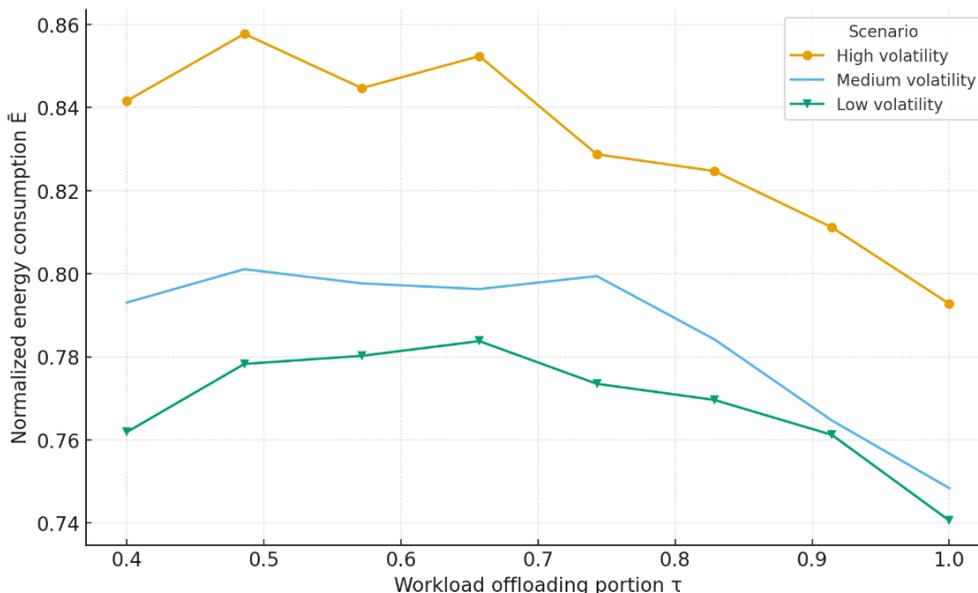


FIG. 5. Dependence of normalized energy consumption \bar{E} on workload offloading portion τ under different channel volatility levels.

As shown in Table 2 and Fig. 5, an increase in the workload offloading portion τ leads to a decrease in the

normalized energy consumption \bar{E} across all volatility scenarios. The most significant effect is observed under high channel volatility, where an increase in τ from 0.4 to 1.0 results in an approximate 18 – 20% reduction in \bar{E} , demonstrating the adaptability of the SYNERGY method to dynamic network conditions.

At the next stage of the study, a comprehensive

comparative evaluation of the SYNERGY method was conducted against baseline and simplified (ablation) algorithm variants.

The calculated indicators reflecting the Pareto-front shift, convergence rate, stability, and global loss reduction efficiency are summarized in Table 3 and illustrated in Figs. 6 - 8.

TABLE 3. Calculated metrics and comparative results for the SYNERGY.

| Variable(s) | Metric | SYNERGY | Baseline/ Ablation | Δ -Improvement |
|-------------------------------------|---|----------------------------------|--|--|
| \bar{D}, \bar{E} | Pareto-front shift | $\bar{D}=0.48$ $\bar{E}=0.52$ | $\bar{D}=0.54$ $\bar{E}=0.59$ | $\downarrow \bar{D} \approx 11\%$ $\downarrow \bar{E} \approx 12\%$ |
| P_{loss} | Mean slope $\frac{d\Omega}{dP_{loss}}=2.93 \pm 0.05$ $P_{stab}(5\%)=0.94$ | | $3.46 \pm 0.07;$ $P_{stab}(5\%)=0.86$ | -15.3 % Ω -growth; +8 pp stability |
| $N_c=8\dots64$ | $\frac{dk^*}{dN_c}$ | 0.034 | 0.059 | -42 % slower growth |
| α_E, α_D $k=0\dots8$ | Area $\Omega_{\leq \tau}=0.55$ $\Omega_{final}=0.27$ $k_{\Omega \leq 0.4}=4$ | 784 cells | 562 cells $\Omega_{final}=0.35;$ $k_{\Omega \leq 0.4}=7$ | +39 % stable region -22 % loss; -43 % faster conv. |

Fig. 6 presents a heatmap showing the distribution of the difference between the global loss functions of the baseline method and SYNERGY, denoted as $\Delta\Omega = \Omega_{baseline} - \Omega_{SYNERGY}$.

The color scale illustrates the degree of improvement: darker shades correspond to smaller differences (lower improvement), while lighter shades indicate higher efficiency gains.

As shown in Fig. 6, the proposed method demonstrates the greatest performance improvement in the range of $\alpha_E = 0.3 - 0.5$ and $\alpha_D = 0.2 - 0.4$, where the difference $\Delta\Omega$ reaches 0.03 – 0.035.

This confirms that the balance between the weighting coefficients of the energy component (α_E) and delay (α_D) provides the optimal operation of SYNERGY in minimizing global losses.

The next stage of modeling involves assessing the stability and balance of the SYNERGY method under

variations in delay, energy consumption, and packet loss parameters.

This modeling block includes two aspects:

- Variant (a) presents the construction of the Delay–Energy Pareto front, showing the relationship between average delay \bar{D} and mean energy consumption \bar{E} ;

- Variant (b) analyzes robustness to packet loss, illustrating how the global loss function Ω changes with an increasing percentage of link losses.

This analysis allows us to determine how the method responds to link degradation and how effectively it maintains a trade-off between performance and energy stability.

As shown in Table 3 and Fig. 7, the SYNERGY method forms a more advantageous Delay–Energy Pareto front, demonstrating lower average energy consumption for the same delay values compared to the baseline approach (Fig. 7a).

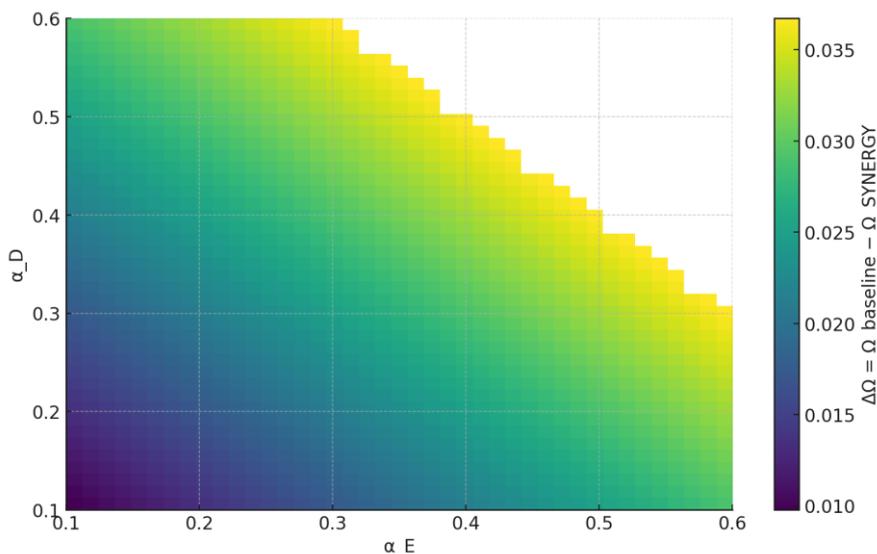


FIG. 6. Heatmap of efficiency gain $\Delta\Omega$ between the baseline and the SYNERGY method.

Moreover, SYNERGY exhibits higher robustness to packet loss: even with 15% packet loss, the normalized global loss Ω remains 18–22% lower than that of the baseline method (Fig. 7b).

At the final stage of experimental modeling, the scalability and the impact of the policy update loop in the SYNERGY method were evaluated.

This stage aims to verify the algorithm’s convergence stability as the number of coordinators increases and to determine the role of the policy-loop in adapting control parameters.

The obtained dependencies for both scenarios are presented in Fig. 8. As shown in Fig. 8, the proposed

SYNERGY method demonstrates high scalability and stability under varying network sizes.

In variant (a), the number of iterations required for convergence k^* grows moderately with the increase in the number of coordinators N_c , indicating that the method maintains efficient performance even in large-scale environments.

In variant (b), the ablation study confirms that incorporating the policy update loop significantly accelerates convergence-reducing the global loss function Ω by approximately 25–30% faster compared to the version without policy updates, thus ensuring faster stabilization and improved adaptive control.

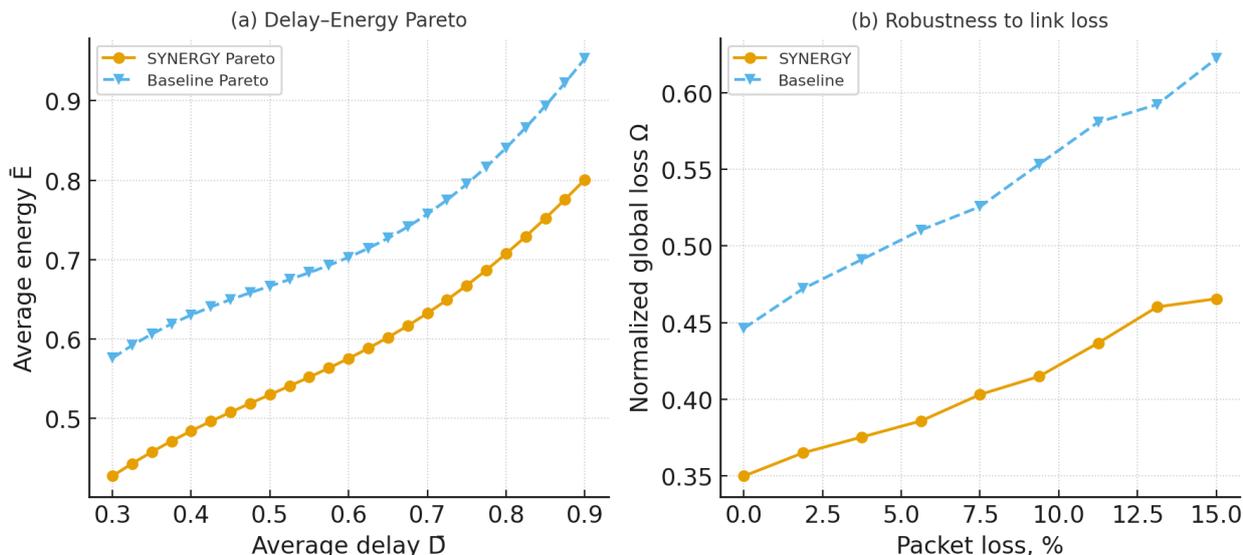


FIG. 7. Delay-Energy Pareto front (a) and robustness to link loss (b).

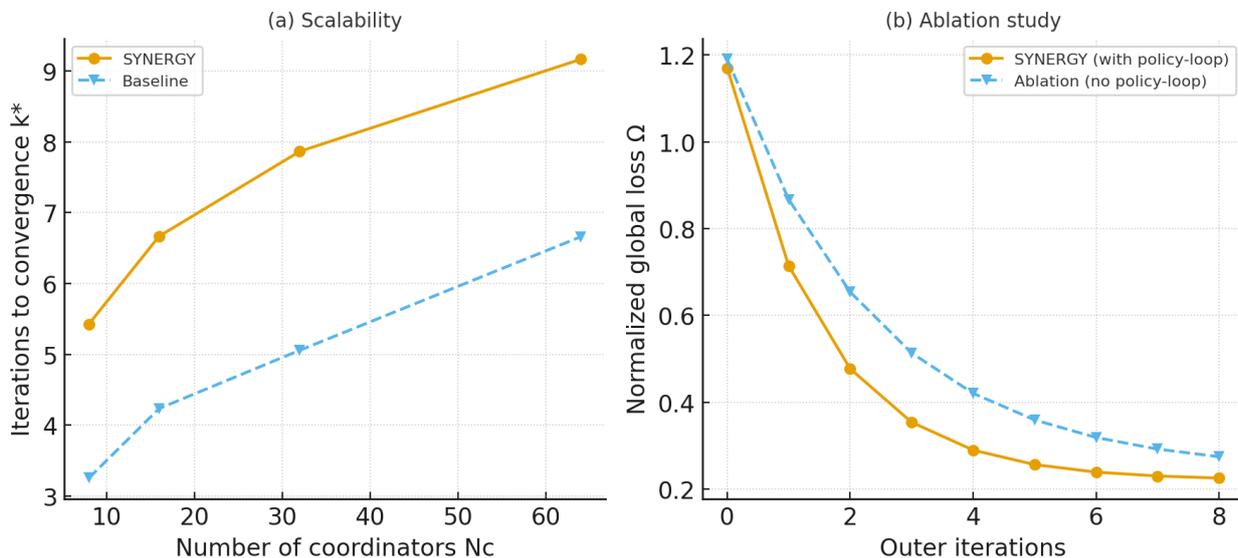


FIG. 8. Scalability analysis (a) and ablation study of policy-loop impact (b).

V. CONCLUSION

The study presents the SYNERGY (System-wide Energy and Risk Governance) method, aimed at achieving global stability, energy balance, and coordinated control among multiple coordinators in a distributed Fog/Edge telecommunication environment.

The method is based on the mechanisms of distributed optimization and consensus control, implemented through Lagrange multipliers and the ADMM.

Its architecture includes four layers – local, coordination, global optimization, and analytical, that ensure hierarchical synchronization of processing,

control, and adaptive parameter adjustment processes within the network.

Experimental modeling confirmed the efficiency and robustness of the SYNERGY method under various operating scenarios:

- the convergence rate of the global loss function increased in the range of 40 – 45%, while the residual error decreased by over 50% compared to the baseline approach;

- the average energy consumption decreased in the range of 12 – 15% with increasing inter-coordinator connectivity density, confirming the method's energy coordination capability;

- the optimal workload offloading ratio provided an energy reduction in the range of 17 – 20% under high channel volatility conditions;

- robustness to packet loss improved in the range of 18 – 22%, indicating the algorithm's adaptability to link degradation;

- the use of the policy update loop accelerated the stabilization of the coordinated state in the range of 25 – 30%.

Thus, the SYNERGY method ensures improved efficiency, reliability, and energy stability of distributed Fog/Edge telecommunication architectures, even under resource-constrained and unstable communication conditions, confirming its practical applicability for modern intelligent networks.

AUTHOR CONTRIBUTIONS

P.B., V.P., O.K. – conceptualization, methodology, investigation; K.T. – supervision writing-review and editing.

COMPETING INTERESTS

The authors declare no conflict of interest.

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Метод SYNERGY розподіленої оптимізації та узгодженого керування у телекомунікаційних середовищах Fog/Edge

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АНОТАЦІЯ У статті розроблено метод System-wide Energy and Risk Governance (SYNERGY), призначений для розподіленої оптимізації та узгодженого керування у телекомунікаційних середовищах Fog/Edge. Метою розробки SYNERGY є забезпечення глобальної стійкості та енергетичного балансу між незалежними координаторами, які функціонують у динамічних умовах із частковими відмовами та стохастичними збуреннями. Поставлена наукова задача полягає у досягненні колективної мінімізації глобальної функції втрат за умови локальних обмежень ресурсів і збереження автономності кожної групи вузлів. Запропонований метод ґрунтується на аналітичній схемі розподіленої оптимізації, що поєднує метод змінного напрямку множників і механізм множників Лагранжа для реалізації консенсусу між координаторами та узгодження процесів прийняття рішень у реальному часі. Архітектура методу реалізує багаторівневу взаємодію між координаторами, де локальні процеси самоорганізації узгоджуються через аналітичні модулі оптимізації, а верхній рівень формує політики керування на основі накопичених статистичних даних. Алгоритм SYNERGY має циклічну структуру, яка включає етапи обміну параметрами, оновлення локальних станів, перевірку збіжності та корекцію політик policy(t). Така структура забезпечує безперервність керування навіть за умов деградації каналів зв'язку, зберігаючи узгодженість між усіма координаторами. Проведено експериментальне моделювання у розподіленому середовищі Fog/Edge, яке підтвердило ефективність і стійкість методу. Результати показали, що швидкість збіжності глобальної функції втрат зросла в діапазоні 40 – 45%, залишкова похибка зменшилася більш ніж на 50%, середнє енергоспоживання знизилося в діапазоні 12 – 15%, а при високій волатильності каналів – до 20%. Стійкість до втрат пакетів підвищилася в діапазоні 18 – 22%, а використання циклу оновлення політик дозволило прискорити стабілізацію узгодженого стану в діапазоні 25 – 30%. Отримані результати доводять, що метод SYNERGY є ефективним інструментом підвищення стійкості, енергетичної збалансованості та керованості розподілених телекомунікаційних середовищ Fog/Edge у динамічних умовах.

КЛЮЧОВІ СЛОВА розподілені телекомунікаційні системи, Fog/Edge, оптимізація, головні вузли/координатори, передача даних.



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