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Adaptive Consensus Mechanisms for Smart Contract Optimization

Abstract. *The paper proposes an adaptive hybrid consensus model for a social platform blockchain system that integrates PoS, DPoS, and PoA. The model provides dynamic adjustment of consensus modes depending on the Download network and transaction type, and also takes into account the reputation of validators to increase the reliability of verifications. This approach will help to increase throughput, reduce transaction processing time, and optimize energy consumption with classical mechanisms. The approach allows for an effective combination of performance and security of blockchain systems, and promising areas for further research include the use of machine learning for load forecasting and integration into hybrid blockchains with cross-chain smart contracts.*

Keywords *– smart contracts, model optimization, blockchain, adaptive systems, social networks, traffic analysis, information system*

Introduction. Today's social media has seen a rapid increase in the volume of decentralized transactions, covering a wide range of interactions, from basic user actions such as liking, commenting, or following to complex reward systems and micropayments. In such digital ecosystems, smart contracts play a key role in ensuring transparency, authenticity, and automation of processes [1].

At the same time, traditional consensus-building mechanisms, including Proof of Stake (PoS), Delegated Proof of Stake (DPoS), and Proof of Authority (PoA), reveal a number of limitations in the context of dynamically changing network loads [2]. This is especially noticeable when processing large data streams, for example, with the YouTube API, where the level of user activity can reach thousands of transactions per second, which leads to delays in block validation and a decrease in the efficiency of smart contract execution.

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The purpose of this study is to develop and experimentally verify an adaptive hybrid consensus mechanism (AHC – Adaptive Hybrid Consensus), which is able to dynamically change the parameters of transaction reconciliation depending on the type of user activity and the current level of network load. The proposed approach is aimed at optimizing the performance and stability of smart contract execution in decentralized social environments, how described is this article [3].

Mathematical model. The proposed Adaptive Hybrid Consensus (AHC) model for evaluating the effectiveness of consensus models combines three classical mechanisms: Proof of Stake (PoS), Delegated Proof of Stake (DPoS), and Proof of Authority (PoA). They are combined into a single multi-layered architecture that is able to dynamically adapt to changes in network load and transaction types. This approach provides a balance between speed, security, and resource efficiency, which is an important aspect when using decentralized social networks with uneven user activity and allows us to reflect the performance and adaptability of mechanisms in dynamic conditions.

Accordingly, key performance indicators have been formalized, such as: Transaction Processing Time (TPT) – average transaction processing time (ms), Throughput (TPS) – number of transactions processed per second, Consensus Energy Index (CEI) – energy consumption per transaction in relative units, and Network Adaptability Coefficient (NAC) – performance stability coefficient under variable network load conditions. Based on these parameters, the computational complexity level of the system can be defined as:

$$C_t = f(L_t, T_u) = \alpha L_t + \beta T_u, \quad (1)$$

where C_t - current difficulty level, $L_t -$ load at a certain point in time and T_u- type of interaction with weighting factors for selection.

To ensure adaptability, the model analyzes the current transaction rate and validator trust index, adjusting consensus parameters in real time. Under high load, it prioritizes high-throughput mechanisms (PoA or DPoS), while at lower loads it favors energy-efficient modes (PoS), maintaining an optimal balance between performance, stability, and energy consumption.

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The integral efficiency of the adaptive model is determined through the generalized efficiency function:

$$E_{AHC} = \alpha * \frac{TPS}{TPT} + \beta * NAC - \gamma * CEI, \quad (2)$$

where α,β,γ are the weighting factors representing the relative importance of throughput, stability, and energy efficiency, respectively. Their values can be determined empirically according to the network configuration or adjusted dynamically based on the observed load distribution. The normalization condition:

$$\alpha + \beta + \gamma = 1, \alpha, \beta, \gamma \in [0,1], \quad (3)$$

ensures proportional balance among performance-oriented parameters, enabling the model to maintain equilibrium between transaction speed, consensus stability, and energy consumption under variable operating conditions.

Software implementation. Real data for modeling was data obtained from the YouTube API, which reflects key aspects of user behavioral activity in a decentralized environment, including publications, comments, subscriptions and reactions. The collected events were transformed into a structure of smart contracts in JSON format, where each record contains parameters of the transaction type, event timestamp, unique transaction identifier and its weight, which characterizes the intensity of interaction. This approach provides the ability to simulate realistic scenarios of social interaction under variable load conditions. The generated smart contracts are used as input data for a test blockchain environment implemented on the basis of the Node.js, Nest.js, Hyperledger Fabric and PostgreSQL technology stack. This architecture provides modularity, scalability and the ability to integrate consensus mechanisms of different types for their further comparison.

Thus, in a containerized Docker environment consisting of five nodes with computing resources of 2–4 CPUs per node. This configuration ensured the representativeness of the experiment for evaluating real scenarios of scaling blockchain networks. The obtained results of the quantitative comparison are shown in Table 1, which allows for a comprehensive analysis of the advantages and limitations of the proposed adaptive consensus mechanism.

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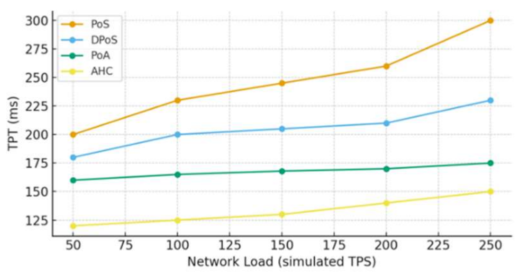
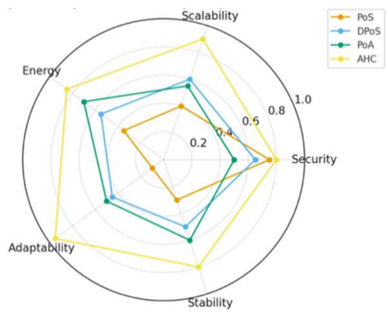
Tabl.1. Comparison of the effectiveness of consensus mechanisms

Mechanisms	TPT (ms)	TPS(s)	CEI	NAC
PoS	260	75	1.00	0.58
DPoS	210	95	0.82	0.67
PoA	170	120	0.76	0.64
AHC	140	155	0.71	0.81

Thus, the proposed AHC model outperforms classical consensus algorithms across all key metrics. It achieves higher throughput (TPS), reduced transaction latency (TPT), and lower energy consumption (CEI), confirming the efficiency of adaptive resource allocation under varying network loads. The model also demonstrates superior adaptability and stability by minimizing validation overhead for low-risk transactions (e.g., micropayments or social interactions) while preserving full verification for critical operations.



a)



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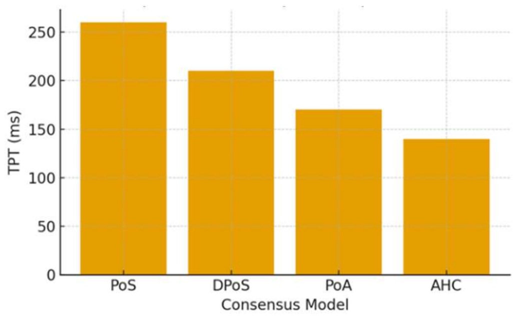

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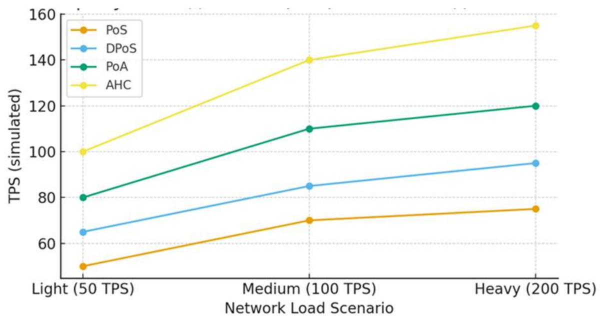

d)

Figure 1. Visual representation of consensus mechanism metrics

Fig. 1 presents a comparative analysis of consensus models - PoS, DPoS, PoA, and AHC. Fig. 1, a illustrates the dependence of average transaction time (TPT) on network load (TPS). With increasing load, latency rises in all models, but AHC maintains the lowest TPT, demonstrating superior scalability and adaptability.

Fig. 1,b summarizes the relative performance of each mechanism according to five criteria - scalability, security, stability, adaptability and energy efficiency. The

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AHC model shows the highest balance between all criteria, in contrast to PoS, which is inferior in stability, and PoA, which has lower security, although high energy efficiency.

The bar chart in Fig. 1, c displays the average transaction confirmation time for each model under a standard load. The worst results are observed in PoS, while AHC again shows the lowest latency, confirming its optimization potential for smart contracts in dynamic network conditions.

Fig. 1, d illustrates the change in throughput (TPS) depending on the load (light, medium, high). AHC demonstrates a stable and significant increase in performance with increasing load, while traditional mechanisms have a noticeably lower scaling rate. Thus, the AHC model combines the speed of PoA, the delegated efficiency of DPoS and the security of PoS, providing a flexible balance between performance and reliability in real time.

Due to the dynamic adjustment of complexity and the integration of the reputation mechanism of validators, AHC demonstrates high adaptability to load fluctuations and the potential for implementation in blockchain platforms and social networks. And the results obtained confirm that the adaptive hybrid model (AHC) provides the best balance between speed, stability, and energy efficiency, outperforming traditional approaches in the context of intelligent load management in blockchain networks for executing smart contracts and rational use of computing resources, and maintains system stability under changing conditions.

Conclusions. The proposed Adaptive Hybrid Consensus (AHC) model achieves significant performance improvement compared to the classical PoS, DPoS, and PoA mechanisms. Experimental results showed that AHC provides an increase in throughput (TPS) relative to PoS and a reduction in the average transaction processing time to 140 ms. Expert evaluation also confirmed the superiority of the model in terms of adaptability, stability and security. The model effectively combines the speed of PoA, the flexibility of DPoS and the security of PoS, automatically switching modes according to the load and type of transactions. This approach allows optimizing the operation of blockchain systems of social networks, reducing energy con-

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sumption without losing the reliability of checks. The practical application of AHC is appropriate in decentralized social interaction platforms, where high scalability and fast system response are required.

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Адаптивні механізми консенсусу для оптимізації смарт-контрактів

Юрій Цудзенко, Богдан Павлишенко

У роботі запропоновано адаптивну гібридну модель консенсусу для блокчейн-систем соціальних платформ, що інтегрує PoS, DPoS та PoA. Модель забезпечує динамічне регулювання режимів консенсусу залежно від навантаження мережі та типу транзакцій, а також враховує репутацію валідаторів для підвищення надійності перевірок. Такий підхід допоможе підвищити пропускну здатність, скоротити час обробки транзакцій та оптимізувати енергоспоживання порівняно з класичними механізмами. Підхід дозволяє ефективно поєднувати продуктивність та безпеку блокчейн-систем, а перспективними напрямами подальших досліджень є застосування машинного навчання для прогнозування навантаження та інтеграція у гібридні блокчейни з крос-ланцюговими смарт-контрактами.

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