A Quantitative Study on Hybrid Consensus Protocol and Performance across PoW and PoS-Based Blockchain in Edge/Cloud Computing Network

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Abstract— **This paper presents work on how to model and assure the performance of a Hybrid Consensus Protocol deployed in blockchain cloud ecosystems, in a quantitative manner. The hybrid consensus protocol to be investigated in this work is assumed to verify (validate) transactions and blocks across Proof of Work (PoW) and Proof of Stake (PoS). A PoW consensus protocol-based chain model and a model for a PoS-based chain model [7] are employed with a random variable β to represent the rate of PoW consensus protocol deployed versus $1-\beta$ to represent the rate of PoS. Basic performance of interest will be simulated and assessed such as average transaction waiting time, average block capacity required and throughput per block under the influence of β and the number of validators (either 1 for PoW or m for PoS) along with transaction arrival rate λ, block posting rate μ and network traffic $\frac{\lambda}{\mu}$. Unlike traditional blockchain modeling, this work focuses on scenarios where hybrid consensus is leveraged across heterogenous blockchain nodes distributed across cloud and edge infrastructures. Further extensive simulations will be conducted, and the results will be shown to provide a close-up insight into the impact of βand m on scalability and reliability in decentralized cloud networks, offering insights for secure and efficient blockchain deployment in cloud-edge environments.**

Keywords—blockchain, proof of work, proof of stake, hybrid consensus protocol, performance, cloud, edge computing

I. INTRODUCTION

Since the introduction of blockchain technology[1,2,4,5,7,8] one of the areas of critical importance has been the search for better means of ensuring consensus as to the integrity of transactions. Trust is paramount. The methods used to achieve consensus and thus assurance of trustworthy management of transactions have fallen into two general categories of protocols, these being Proof of Work (PoW) [1] and Proof of Stack (PoS)[2,4]. Each offers clear advantages but also faces critical limitations in scalability, energy consumption, latency and sustainability particularly in context of distributed cloud and edge infrastructures [8, 9, 10].

While some work in providing a third category, analysis in terms of quantitative analytical tools for understanding behavior has often lagged for both PoW and PoS, especially in dynamic resource diverse environments such as muti-tier cloud edge networks. This paper continues the work in prior papers regarding quantitative description of behaviors with the introduction of an alternative to strict PoW and PoS methodologies in the form of a hybrid of the two methodologies across blockchain cloud deployments. This Hybrid Consensus Protocol aims to harness the strengths of both PoW and PoS and balance the tradeoffs between decentralization and sustainability in blockchain clouds.

The increasing adoption of blockchain technology across various sectors demands a flexible yet robust consensus framework capable of adapting to diverse operational demands and network conditions across cloud and edge layers. The hybrid model proposed here allows the consensus mechanism to dynamically shift between PoW and PoS based on predefined network parameters and transactional requirements across blockchain based cloud infrastructures. The goals of this hybrid scheme include enhancing blockchain's adaptability and efficiency [6] while mitigating the significant energy consumption associated with PoW and the potential security concerns in PoS systems. The subsequent sections will delve into the modeling approach, simulation results, and the practical implications of our findings in real-world blockchain applications.

This research contributes to the ongoing dialogue in the blockchain community about achieving an optimal balance between competing priorities in consensus mechanisms, offering a pathway towards a more sustainable and efficient blockchain Clouds infrastructure. A quantitative study will be presented in this work on how to model and assess the performance of a blockchain network system with, namely, a Hybrid Consensus Protocol. The hybrid consensus protocol to be investigated in this work verifies across Proof of Work (PoW) and Proof of Stake (PoS). Without loss of generality and practicality, for decentralization-critical transactions PoW would be a natural choice of consensus protocol, otherwise, for relatively less decentralization-critical transactions yet instead sustainability-desired transactions PoS would be an alternative choice. The baseline chain model[3] is assumably a PoW consensus protocol-based chain model and the model as proposed in [7 is a PoS-based chain model. The specific question in this work is how to determine the balance of the deployment of consensus protocols across PoW or PoS in a quantitative manner. In this context, it is proposed to employ a random variable β to represent the rate of PoW consensus protocol deployed versus $1-\beta$ to represent the rate of PoS. It is proposed that the baseline chain model be employed in the context of a cumulative binomial distribution with respect to $\binom{m}{1}$ to represent a PoW-based chain with one validator (or a certain small constant number of validators) in place along with a multinomial distribution with respect to the number of transaction slots to validate the transactions and block at the rate of β, while the PoS-based chain model be employed in the context of cumulative binomial distribution with respect to $\binom{m}{k}$ to represent a PoS-based chain with k variable number of multiple validators in place given m maximum number of validators available to participate in the transactions and block validation process at the rate of $1-\beta$. The proposed hybrid consensus protocol-based chain model will be used to assess the basic performance of interest such as average transaction waiting time, average block capacity required and throughput per block under the influence of β and m along with transaction arrival rate λ, block posting rate μ and network traffic $\frac{\lambda}{\mu}$. Further extensive simulations will be conducted and the results will be studied in depth to provide a closeup insight into the impact of W and m on a few performance of interest.

II. PRELIMINARIES AND LITERATURE REVIEW

A quantitative model to estimate the performance of a PoS (Proof of Stake) consensus protocol-based blockchain (e.g., Ethereum) has been proposed in [7]. A PoS-based chain model in consideration in this work has the number of validators (m) in the network as a variable in the model such that $m = 1$ in PoW and $m \gg 1$ in PoS. A unified binomial distribution can be assumed with respect to the number of validators and then the probability to have a block to be posted is assumed to be the base probability in the binomial distribution with respect to the full number of transaction slots (n) pending on the current block to be posted [14], thereby establishing a quantitative model to express the steady-state probability to have n number of trasactions slots with $1 \le j \le m$ number of validators across the blockchain network given transaction slots arrival rate (λ) and block posting rate (μ/j) by j number of validators. The quantitative model is expected to establish a theoretical foundation to guide the PoS-based chain developers with specific respect to performance.

PoW consensus protocol is built based on a computationally competitive race by miners to win the gas fee paid by the transactions pending on a block to be posted [1], which depletes the energy over the network causing a sustainability concern. In contrast or as an alternative, PoS consensus protocol is validates a block by participating validators assigned based on weighted probabilities as determined by the amount of stakes held by the participating master nodes (also called validators, stakers or forgers) and how much of those holdings these participants are willing to commit or stake as collateral in the construction and validation process [2,4]. PoW is typically desired in a more trustworthiness-stringent transactions while PoS can be employed where more energy efficiency is desired. PoW and PoS, each has pros and cons as addressed above and it is sought how to select the consensus protocols adaptively and in a balanced manner in the ratio of PoW and PoS in order to optimize the energy consumption and thereby improving the sustainability while maintaining the blockchain-intrinsic trustworthiness by selecting a consensus protocol that is more effective for each transaction in execution.

III. HYBRID CONSENSUS PROTOCOL MODEL

The hybrid consensus protocol architecture proposed in this framework is specialized to fit the demands of cloud-integrated blockchain environments by seamlessly integrating elements of both Proof of Work (PoW) and Proof of Stake (PoS) mechanisms within the blockchain network. This architecture dynamically switches between PoW and PoS protocols based on predefined rules or network conditions, such as transaction volume or network congestion across cloud infrastructures.

In this model, the system primarily relies on PoS-based consensus to maintain scalability, energy efficiency and low-latency validation which are relevant requirements in edge and cloud deployments. During normal operation, the system predominantly relies on PoS for consensus across participating nodes in the blockchain cloud, benefiting from its scalability and energy efficiency. However, in times of increased demand or potential threats to the network's security, scenarios common in open or untrusted edge environments the architecture automatically transitions to PoW, leveraging its robustness and resistance to attacks. This hybrid approach aims to combine the strengths of both consensus mechanisms while mitigating their respective weaknesses, providing a enhanced tamper resistance and security for cloud blockchain systems to ensure optimal performance and security in diverse operating conditions of the system. The transition between PoS and PoW is governed by a probabilistic switching function modeled as:

$$P_{0\le i\le n}\big|_{j=1}^{m} = \sum_{j=1}^{m}\left(\beta\left(\binom{m}{1}P_n(1-P_n)^{m-1}\right) + (1-\beta)\left(\binom{m}{j}(P_n)^j(1-P_n)^{m-j}\right)\right)$$

where β is the likelihood to select PoW as a consensus protocol with a single validator who has computed the hash address of a block to be chained, and thus $1-\beta$ the likelihood to select PoS as a consensus protocol with one or multiple validators.

Ther equation is further equivalently represented as:

$$P_{0\le i\le n}\big|_{j=1}^{m} = \beta\left(\binom{m}{1}(P_n)(1-P_n)^{m-1}\right) + \sum_{j=1}^{m}\left((1-\beta)\left(\binom{m}{j}(P_n)^j(1-P_n)^{m-j}\right)\right)$$

The state probabilities of the protocol are further governed by a recursive probabilistic framework to model validator selection and system evolution over n validation rounds:

$$P_i = q_i P_0 \beta(1-\beta)^{-1}\left[\sum_{j=1}^{i} j\left[\sum_{k=1}^{i-1}\left[\prod_{l=1}^{k-1} q_l\right]k\right] + i\right]$$

subject to the normalization condition:

$$P_0 + \sum_{i=0}^{n-1} P_i + P_n = 1.0$$

which expands to:

$$P_0 + \sum_{i=0}^{n-1} q_i P_0 \beta(1-\beta)^{-1} \left[\sum_{j=1}^{i} j \left[\sum_{k=1}^{i-1} \left[\prod_{l=1}^{k-1} q_l \right] k \right] + i \right] + \left(\lambda \frac{n(n+1)}{2} \right) P_0 (\mu)^{-1} = 1.0$$

finally, solving the initial probability results:

$$P_0 = \frac{1}{1 + \sum_{i=0}^{n-1} q_i \beta(1-\beta)^{-1} [\sum_{j=1}^{i} j [\sum_{k=1}^{i-1} [\prod_{l=1}^{k-1} q_l] k] + i] + \left(\lambda \frac{n(n+1)}{2} \right) (\mu)^{-1}}$$

For cloud-native blockchain systems that need to adjust to changing loads and differing levels of trust while maintaining a low energy footprint and high fault tolerance, this probabilistic hybrid model is particularly well-suited. Because cloud applications are decentralized but performance-sensitive, the framework supports PoS blockchain clouds as its primary execution mode while keeping PoW for strategic backup.

IV. NUMERICAL SIMULATIONS AND RESULTS

The simulation aims to analyze the performance metrics of a blockchain system employing a Hybrid Consensus Protocol, Key metrics such as average waiting time per transaction (W), average block size (L), and system throughput (γ) are scrutinized. Various parameters including the consensus protocol deployed, number of validators (m), transaction arrival rate (λ), and block posting time (1/μ) are explored across nine combinations of λ (High, Medium, Low) and μ (High, Medium, Low), each set at a 15-second interval mirroring real-world conditions akin to Ethereum's typical block delay. The deployment of the consensus protocol, β, is tested across variable values, with β representing PoW and (1-β) denoting PoS protocol. This comprehensive approach aims to unravel the complex interplay among system parameters, validator count, and performance metrics within the blockchain network.

The following graph plots L (average number of transactions) vs n for given pairs of λ and μ in the Baseline, PoS and Hybrid Model.

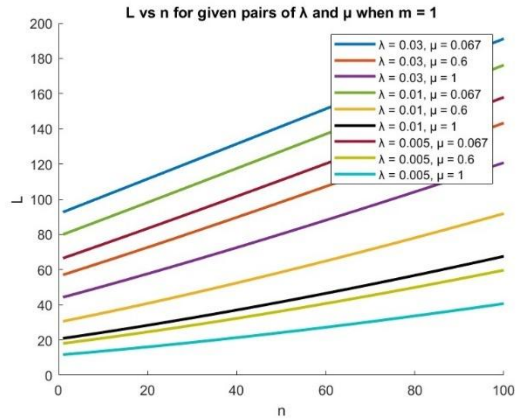

Fig 1: Baseline: L vs n for given pairs of λ and μ

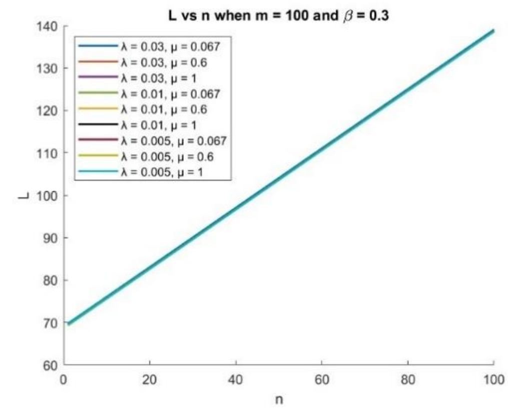

Fig 2: PoS: L vs n for given pairs of λ and μ

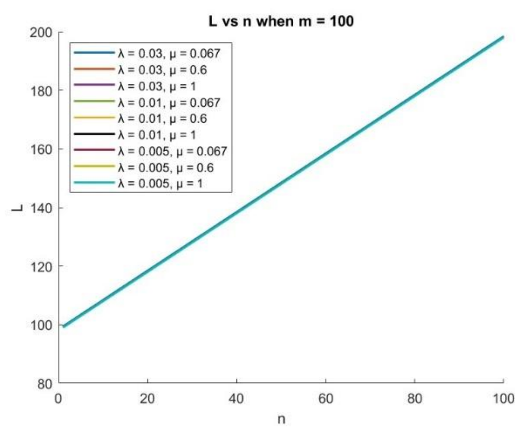

Fig 3: Hybrid: L vs n for given pairs of λ and μ

Figures 1, 2, and 3 illustrate the average number of transactions in the transaction pool awaiting mining selection, determined by $L = \lambda W$. It is evident that for a given arrival rate and service rate at a specific n, the value of L monotonically increases with an increase in the value of n. Notably, the observation indicates that the value of L is not significantly dependent on the values of λ and μ in the PoS and Hybrid Model scenarios. However, in the baseline model, a higher arrival rate results in a greater number of transactions in the transaction pool, and conversely.

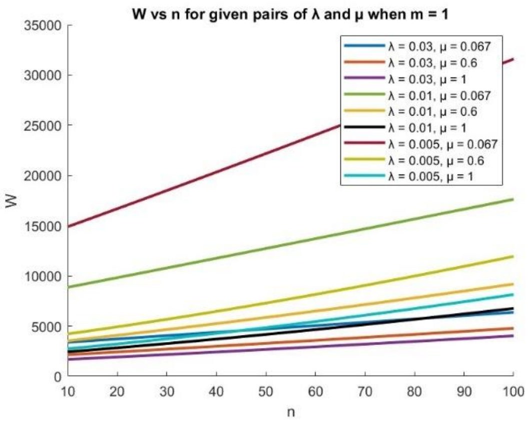

Fig 4: Baseline: W vs n for given pairs of λ and μ

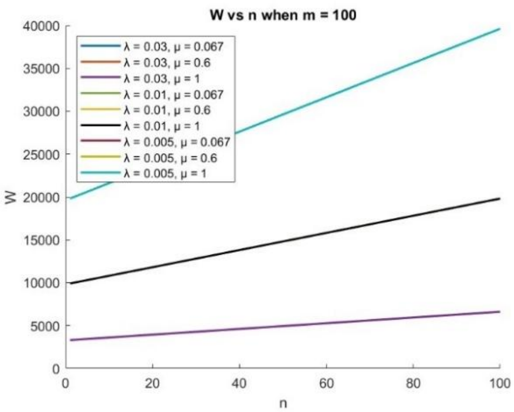

Fig 5: PoS: W vs n for given pairs of λ and μ

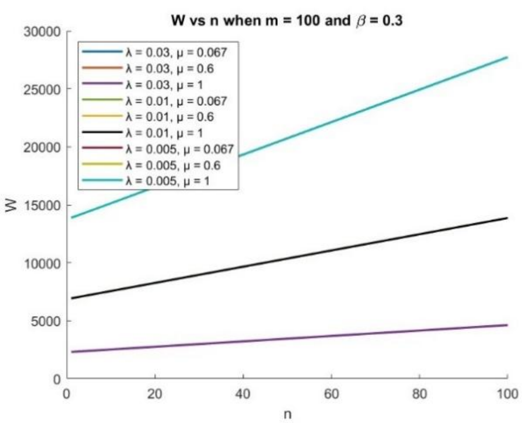

Fig 6: Hybrid: W vs n for given pairs of λ and μ

Figures 4, 5, and 6 depict the relationship between W and n across the baseline, PoS, and Hybrid Models. The graphs suggest that the Hybrid Model exhibits the shortest waiting time per transaction, followed by the Proof of Stake (PoS) consensus protocol. Interestingly, both PoH and PoS display a similar increasing trend in waiting time, primarily influenced by the transaction arrival rate. Conversely, in the Baseline Model (PoW), the waiting time per transaction (W) is contingent upon both the transaction arrival rate and block service rate, resulting in the highest waiting time when both λ and μ are low. This observation underscores the intricate dynamics within the cloud/edge system.

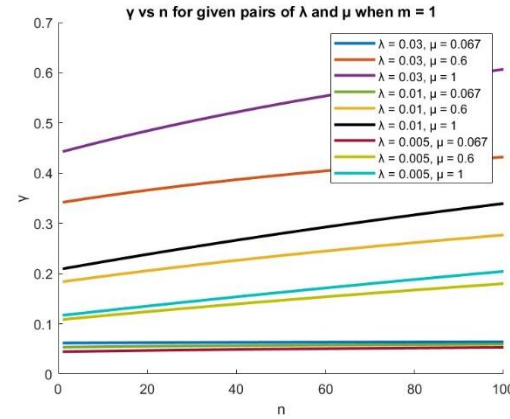

Fig 7: Baseline: γ vs n for given pairs of λ and μ

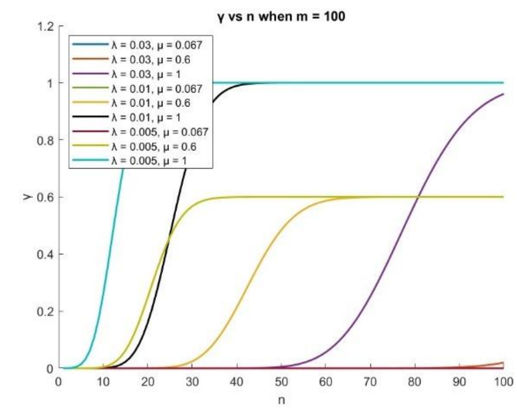

Fig 8: PoS: γ vs n for given pairs of λ and μ

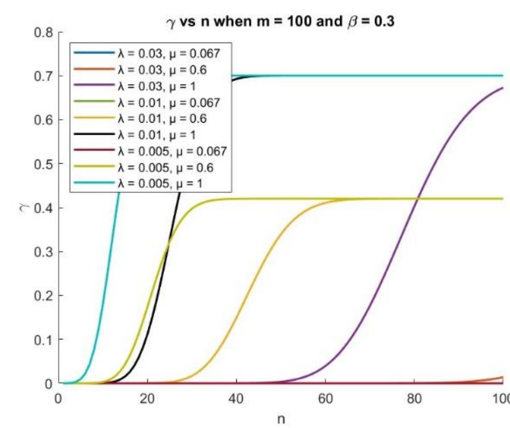

Fig 9. Hybrid: γ vs n for given pairs of λ and μ

The graphs in Figures 7, 8, and 9 depict the relationship between the number of iterations (n) and transaction throughput. As anticipated, the transaction throughput is notably high in the PoS model due to the presence of validators, which facilitates faster processing and block posting. While the Hybrid model outperforms the Baseline model, it falls slightly short of the efficiency achieved by the PoS Model. This underscores the Hybrid model's ability to strike a balance between the characteristics of PoW and PoS, thereby offering commendable performance in terms of transaction throughput.

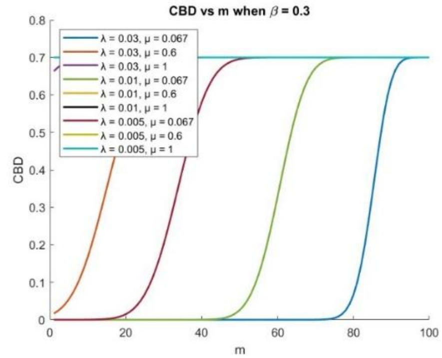

Fig 10: Hybrid: CBD vs m for given pairs of λ and μ when $\beta = 0.3$

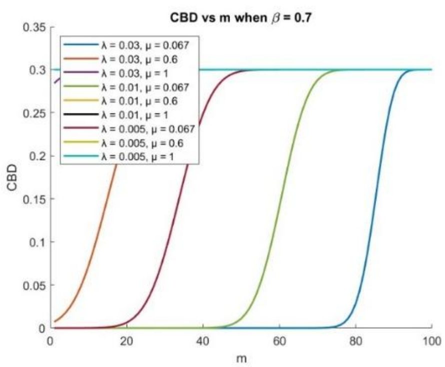

Fig 11: Hybrid: CBD vs n for given pairs of λ and μ when $\beta = 0.7$

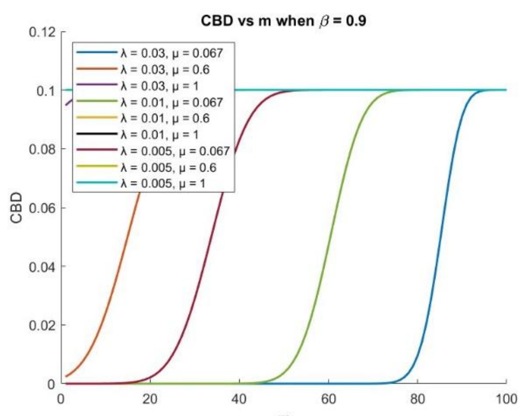

Fig 12: Hybrid: CBD vs n for given pairs of λ and μ when $\beta = 0.9$

The comparison between the Cumulative Binomial Distribution (CBD) and the number of validators in the proposed PoH Model, as depicted in Figures 10, 11 and 12, offers valuable insights influenced by diverse combinations of λ and μ. In these scenarios, the number of validators, m ranges from 0 to 100, with the consensus protocol variable, beta, set to [0.3, 0.7, 0.9]. Across all graphs, a common theme emerges: an increase in CBD correlates with an increase in the number of validators. Notably, the maximum CBD is observed when β is low, while CBD decreases when β is high. This observation underscores the efficiency, sustainability, and optimality of the PoH protocol. When β is set to 0.7, the system achieves a maximum CBD of 0.7, representing a balanced integration of PoH and PoS protocols. Furthermore, a trend emerges wherein a higher transaction arrival rate necessitates a larger number of validators for expedited transaction posting. These observations shed light on the intricate relationship between distribution and the number of validators, crucial for system performance and resource allocation within the cloud/edge network.

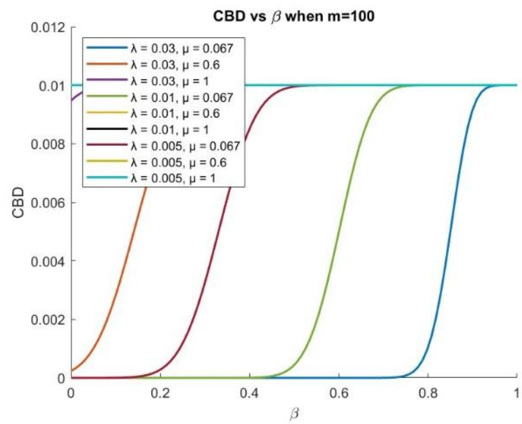

Fig 14: Hybrid: CBD vs β for given pairs of λ and μ

Figure 14 examines the cumulative binomial distribution (CBD) in relation to the consensus protocol variable, β, with the number of validators set to 100, providing valuable insights into system behavior. As the influx of transaction arrival rate increases, β also increases, indicating a greater utilization of both PoS and PoW consensus protocols. Conversely, a lower transaction arrival rate results in a lower value of β, demonstrating a balanced utilization of the Hybrid consensus protocol. This observation highlights the adaptability of the system in dynamically adjusting the consensus protocol based on transaction demand, thereby optimizing network performance.

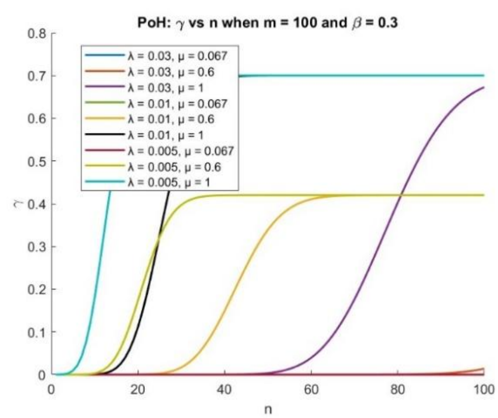

Fig 15: γ vs n for given pairs of λ and μ when $\beta = 0.3$

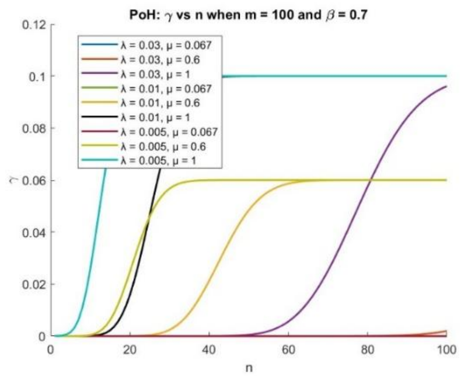

Fig 16: γ vs n for given pairs of λ and μ when $\beta = 0.7$

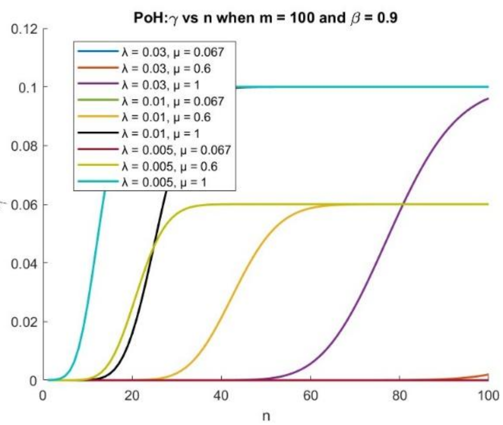

Fig 17: γ vs n for given pairs of λ and μ when $\beta = 0.9$

The graphs in Figures 15,16 and 17 depict the relationship between the number of iterations (n) and transaction throughput (γ), considering varying amounts of consensus protocol employed in the system between PoW and PoS. Notably, throughput demonstrates a peak value when β is low and the least throughput when β is high. The trend of high throughput is observed when the transaction arrival rate is low and the block posting rate is high. Conversely, lower throughput is observed when the arrival rate is high and the block posting rate is low. These observations signify that a lower value of β, representing the PoS protocol, results in higher system throughput, and vice versa. A balance is obtained when a β value of 0.7 is used. These observations illuminate the intricate relationship between block size dynamics and transaction behavior, underscoring their significance for system performance and resource allocation in the network based on the consensus protocol employed and the significance of PoH protocol.

V. Conclusions

This paper has presented a work on how to model and assure the performance of a cloud blockchain network system operating over cloud-based infrastructures using a Hybrid Consensus Protocol . The protocol investigated in this work is assumed to prove (validate) transactions and blocks across Proof of Work (PoW) and Proof of Stake (PoS). Basic performance of interest was simulated and assessed such as average transaction waiting time, average block capacity required and throughput per block under the influence of β and the number of validators (either 1 for PoW or m for PoS) along with transaction arrival rate λ, block posting rate μ under varying network loads and validator configurations.

Our results demonstrate that the hybrid model effectively navigates trade-offs between performance and sustainability. As the usage of PoS increases, transaction waiting time decreases, while system throughput peaks making it suitable for edge level validation scenarios. Conversely, higher PoW participation ensures decentralization and trust, particularly valuable in cloud-based block validation layers. The proposed modeling approach offers actionable insights for infrastructure designers aiming to optimize resource allocation across distributed blockchain systems. By allowing dynamic consensus tuning, the model supports scalable, trust-aware deployment strategies that meet the diverse performance and energy constraints of cloud and edge computing environments. Ultimately, this work lays the groundwork for designing cloud-native hybrid consensus protocols that maintain decentralization while achieving operational efficiency in real-world blockchain deployment.

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