An Adaptive Blockchain-based Decentralized Network Computing and Performance Analysis

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***Abstract*— This paper presetns an adaptive chain as one of the most trustworthy blockchain-based network solutions for security and privacy for industrial applications and a Variable Bulk Arrival and Variable Bulk Service (VBAVBS) model in order to provide a quantitative method to support demonstration of the validity, feasibility, and further the potential performance benefits of the adaptive chain. The model assumes variable bulk arrivals of transactions in Poisson distribution, i.e., $M^{1,n}$, where n represents the number of slots across all the mined transactions, and variable bulk services of transactions, each of which applies to a block potentially of different capacity in terms of the number of slots in it, in exponential time, i.e., $M^{1,i,n}$, for posting in the current block, namely, VBAVBS. The difference between VBASBS [22] and VBAVBS is that in VBASBS, the state P_n is the only state to transition back into P_0 while in VBAVBS, every state P_i, $0 < i \leq n$, potentially transitions back into P_0. VBAVBS will reveal the performance advantages of the adaptive chain versus the baseline chain, i.e., VBASBS, with respect to the average time for a slot to stay (or wait) in the block and the average spatial requirement by the slots in the block. Numerical simulations are conducted on Matlab to compute the models and a comparative study will be demonstrated on VBAVBS versus VBASBS.**

Keywords*— *adaptive block size; adaptive chain; baseline chain; blockchain; queueing model

I. Introduction

Blockchain is considered as one of the most trustworthy solutions of network for security and privacy for industrial applications such as financial, energy, IoT, to mention a few. In this context, modeling, and assurance of the performance of the blockchain-based for industrial informatics applications is exigently mandated.

Blockchain technology [1–5] has been investigated by industry and research sectors for the benefit of a transparent decentralized network control to provide a trustworthy industrial systems service. The scalability [6,7,9,10] and dependability [15] issues of the blockchain system have been identified and addressed as the technology matures and saturates in its current form. Quite extensive line of decentralized applications in IoT [12–15] and MEC [20] networks have been deployed and testbeded to exercise various attempts to resolve those issues in [11,21] with respect to security and privacy in IoT based smart grid. Also, it has been reported that the consensus algorithms [2,3] of the blockchain system is driving the mining process to keep the block time constantly to be delayed and eventually to lead to slowing down on the throughput and thereby limiting the capacity and even the functionality and operability of the network, which mandates an excessively powerful server and a high-efficiency yet extremely costly network. After all, blockchain technology in its current form is facing a serious hurdle before finding itself as a true replacement of the current state of the art web2-based internet infrastructure. In this context, it is exigently sought to address and respond to these issues mainly about the scalability [5,9] and performance [19,25] from the specific standpoint of the speed of block posting. As the blockchain technology-based network is seeking a way to break through those underlying technical issues, it has been considered that blockchain [16–18] be proactively adapting to various performance criteria in order to speed up the execution of transactions with respect to block size and requirements.

The main goal of the paper is to propose a dynamically manageable and controllable blockchain for scalability and performance, so called an adaptive chain, and in an effort to demonstrate its validity, feasibility and potential benefit, and a novel yet sound theoretical foundation is to be established to support our claim on the adaptive chain as there is no adequate theoretical model to support the claims in this paper [23–26] to the best knowledge of the authors.

In this paper, with the baseline model of VBASBS [22] (i.e., a $M^{1,n}/M^{n}/1$ type), the primary interest is to develop an embedded Markovian queueing model [24] of the $M^{1,n}/M^{1,n}/1$ type in order to establish a quantitative foundation to design a blockchain-based system with focus on the stochastic behavior of the mined transactions waiting to be posted for the block time as potentially purging at every state, which is possibly being from any state, $P_i(0 < i \leq n)$ back into the state, P_0. As in the baseline model of VBASBS, the proposed model assumes variable bulk arrivals of transactions in Poisson distribution, $M^{1,n}$, where n the number of slots across all the mined transactions, but, variable bulk service of transactions in exponential time, $M^{1,n}$, for posting into the current block at any state in a slot. The primary performance measurements are to be taken in comparison with the baseline model, such as the average number of slots no matter how many transactions are mined under the assumption of the maximum number of slots per block as specified by n; the average waiting time per slot; and the throughput in terms of the average number of slots to be processed per time. The variable bulk arrival rate is assumed to vary linearly proportional to the size of the transactions in a multiple of λ (note that there is only a single stage of a queue of waiting transactions (in terms of slots) assumed for simplicity instead of assuming two independent arrival rates of the transactions, one for the transaction pool and another for the waiting queue for the block posting, thereby assuming only a single bulk arrival rate per slot λ, which might be to some extent different in practice, and the variable bulk service is assumed to take place when the number of slots in the mined transactions reaches at any state, $1, 2, \ldots, n-1, n,$ i.e., a bulk processing of single or multiple transaction(s) in single or multiple slot(s) for posting in a block. The proposed adaptive chain and its VBAVBS model are expected to be extensively applied to various blockchain architectures and systems where scalability is exigently mandated.

The paper is organized as follows: a baseline model (i.e., VBASBS) is reviewed in the following section as the preliminaries to the proposed approach; the new proposed VBAVBS model is presented and solved in the following section; a section will follow to demonstrate numerical simulations versus various blockchain-related parameters and results are shown in comparison with the ones of VBASBS in order to demonstrate the performance-benefits of the VBAVBS; then conclusions and discussion are drawn in the last section.

II. Preliminaries and Literature Review

Blockchain network system can provide services of smart contracts, transactions and data along with IoT-based sensor-devices and storage-servers in an integrated manner and ultimately with the known-best trustworthiness as shown in Fig. 1 [27–31].

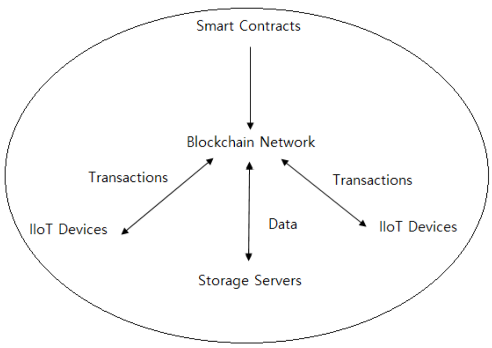

Fig. 1. Integration of transactions and data of smart contract, and IoT-based system in blockchain network [28]

Fig. 2 shows the layer of blockchain service in a typical industrial IoT application infrastructure platform [29].

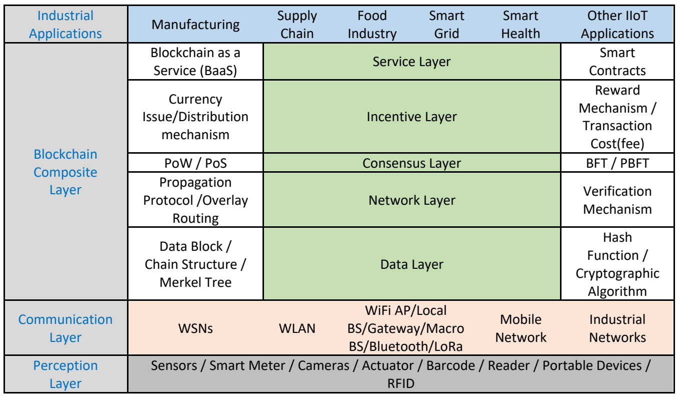

Fig. 2. An overview of blockchain enalbed IoT industrial application infrastructure [29]

Fig. 3 shows various blockchain network applications in the retail industry. The requirement of industrial IoT in E-commerce and retail business are security, autonomy, and light transactions [31].

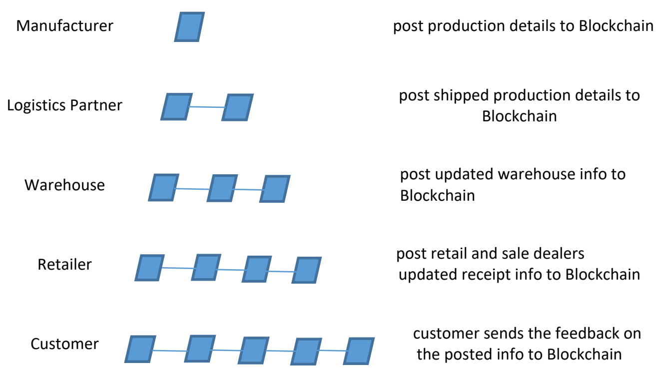

Fig. 3. Tracing product using blockchain in retail industry [31]

In the VBASBS model [22], which is the basis for the proposed VBAVBS model in this paper (note that the concept of an adaptive chain was referred to in [32] in a form of a state transition diagram without any specifications and solutions), an embedded Markovian single-server exponential queueing system (i.e., $M^{1,n}/M^n/1$) has been proposed. Whenever a block completes a service (i.e., posting), it then purges the block of the current round and then receives the influx of new transactions of next round. It is assumed in VBASBS that the purging process takes place at a certain rate yet no transaction is assumed to arrive in the meantime for simplicity of the model, which is onheld in this paper as well. It is assumed in VBASBS that the purging time is exponential at $\frac{1}{\mu}$ when the block is posting the entire batch, which is also onheld in this paper without loss of great generality and for simplicity to maintain the complexity of the model under feasible range. Without loss of generality, it is assumed in VBASBS that transactions arrive at an exponential rate of λ [22].

The underlying block mining and posting process is assumed to take place with fixed-sized slots in a block and the state of a block is determined by the number of slots in it for normalization purpose, which is claimed to be one of the novel assumptions made to make the model flexible and versatile.

The VBASBS model defines the states as follows [22].

P_0 : the state in which there is no transaction (i.e., no slot) arrived in the queue as of yet for the posting in the block, currently, and is held on in the proposed VBAVBS model [22] in this paper.

P_n : the state in which there are n number of slots (i.e., which is the capacity of the queue, equivalently, the maximum number of slots set and voted by the miners or voters) arrived in the queue for the posting in the block, currently, and is held on in the proposed VBAVBS model [22] in this paper.

P_i : the state in which there are i number of slots (where $0 < i < n$) arrived in the queue for the posting in the block, currently, and is onheld in the proposed VBAVBS model [22,32] in this paper.

The transactions arrival rate and the block posting rate are specified as follows [22].

λ: the rate for a slot of a transaction to arrive, and the rate for a transaction to arrive is determined by the number of slots allocated for the transaction in a prorated manner such that a transaction with a size of j number of slots arrives at the rate of $j\lambda$, without loss of generality and practicality as well, which will be onheld in this paper as well.

μ: the rate for the slots of the transactions in the entire block to be posted and purged. Notice that this is a single and unique state transition precisely from P_n back to P_0, which will be onheld in this paper as well regardless the potentially varying number of slots in a block in a normalized manner.

P_i can be generalized and expressed as follows [22].

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

Solving the balance equation in (1) P_i can be expressed in the closed-form (2) as follows [22].

$$P_i = q_i P_0 \left[\left(\frac{i(i+1)}{2}\right) \left(\frac{n}{\left(\sqrt{2\pi n}\left(\frac{n}{e}\right)^n\right)^2}\right) (2^{i-1}(in - 2n + 7i - 14 - i^2) + 8) + i \right] \quad (2)$$

Where,

$0 < i < n$

$q_i = \frac{2}{(n-i)(n-i+1)}$

The state transition diagram of the baseline chain model of VBASBS is shown with all states, λ and μ in Fig. 4.

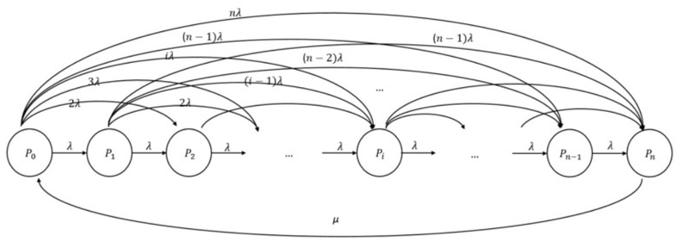

Fig. 4. State transition diagram of the baseline chain model [22]

Fig. 5 shows the state transitions around P_i for the balance equations. The balance equations are such that all incoming transitions from $P_0, P_1, \dots, P_{i-1}$ into P_i are equal to all outgoing transitions from P_i to $P_{i+1}, P_{i+2}, \dots, P_n$.

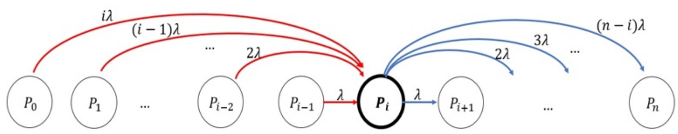

Fig. 5. State transition around P_i for the balance equations of the baseline chain model [22]

Fig. 6 shows the state transitions for the balance equations. The balance equations are such that all incoming transitions to P_0 are equal to all outgoing transitions from P_0. In Fig. 3, it shows that all incomings are only from $P_n$to P_0 and are equal to all outgoings from P_0 to $P_1, P_2, \dots, P_n$.

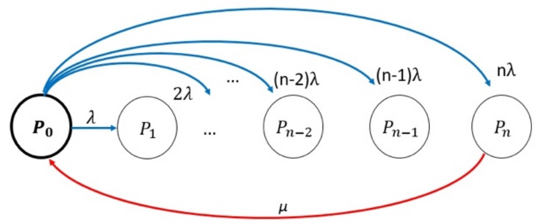

Fig. 6. State transitions around P_0 for balance equations of the baseline chain model [22]

The VBASBS queueing model is introduced and reviewed in this paper as the basis for the VBAVBS model for the proposed adaptive chain as will be shown in the following section. The difference between VBASBS [22] and VBAVBS is that in VBASBS, the state P_n is the only state to transition back into P_0 (i.e., the capacity of the block is constant throughout) while in VBAVBS [32], every state P_i, $0 < i \leq n$, potentially transitions back into P_0 (i.e., the capacity of the block is variable adapting to a certain criteria as desired, e.g., asynchronous transactions control and any other stringent requirements imposed on the execution time of transactions), which is the major contribution of this research.

III. Variable Bulk Service (VBAVBS) Model for Adaptive Chain

The proposed research is designed such that a fundamental and theoretical design of a new blockchain architecture and systems is to be established as a basis; a quantitative method to symbolize the performance of concern is employed in the first place and as the central and primary contribution of this research, as referred to as Variable Bulk Arrival and Variable Bulk Service (VBAVBS) Model, for Adaptive Chain; the theoretical and quantitative design is to be simulated in an extensive yet numerical manner as a method for validation; it is hypothesized to observe the simulation results in good agreement with expectations and intuition with loss of generality and practicality. In fact, note that in or-der to further validate the new quantitative model, an experimental prototype is also being built as of yet and planned to be published in the near future.

In an effort to adequately present the theoretical models and steps as the methods for the proposed adaptive chain, every main step along the assumptions, definitions and derivations are demonstrated with every necessary yet possible detail since they are believed to be critical to comprehend the model for computation and simulation.

The state for the adaptive chain is basically identical to VBASBS and only the state transition probabilities differ from the ones in VBASBS. The random variables employed to express the state transition rates are defined as follows, without loss of generality and practicality, under the assumption of random and independent arriving transactions with respect to the transactions arrival rate and block posting rate (i.e., the service rate) since there is no constraints presumed on the sequence of arriving transactions and block posting process.

λ: refer to the definition in the previous section as in section II.

μ: the rate for the slots of the transactions in the entire queue to be posted and purged.

Notice that this is an every state transition precisely from P_n back to P_0, P_{n-1} back to P_0,…, P_2 back to P_0, and P_1 back to P_0 with $\frac{\mu}{n-(n-1)}, \frac{\mu}{n-((n-1)-1)}, \ldots, \frac{\mu}{n-1}, \frac{\mu}{n}$ respectively.

Fig. 7 shows the balance equations for the adaptive chain model which is the random variables employed to express the state transition rates. The definitions are all same with VBASBS except λ and μ.

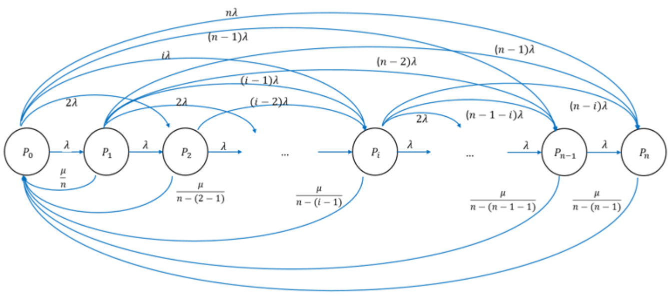

Fig. 7. State transition diagram of the adaptive chain model

Fig. 8 shows the state transition diagram around P_i of adaptive chain model. All outgoing transitions equal all incoming transitions for P_i.

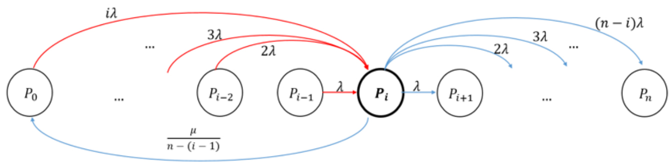

Fig. 8. State transition diagram around P_i of the adaptive chain model

The balance equations for the adaptive chain model are as follows.

$$(\lambda + 2\lambda + 3\lambda + \cdots + n\lambda)P_0 = \lambda \frac{n(n+1)}{2} P_0$$

$$\left(\lambda \frac{n(n+1)}{2}\right) P_0 = \frac{\mu}{n} P_1 + \frac{\mu}{n-1} P_2 + \frac{\mu}{n-2} P_3 + \cdots + \mu P_n$$

$$= \mu\left(\frac{1}{n} P_1 + \frac{1}{n-1} P_2 + \cdots + \frac{1}{2} P_{n-1} + P_n\right)$$

$$\left(\lambda + 2\lambda + 3\lambda + \cdots + (n-i)\lambda + \frac{\mu}{n-(i-1)}\right) P_i$$

$$= \lambda P_{i-1} + 2\lambda P_{i-2} + 3\lambda P_{i-3} + (i-1)\lambda P_1$$

Where,

$0 < i \leq n,$

P_i can be obtained as follows [22].

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

Where,

$0 < i \leq n$

$$q_i^{-1} = \left(\frac{(n-i)(n-i+1)}{2} + \frac{\mu}{\lambda(n-i+1)}\right)^{-1}$$

$$= \frac{2\lambda(n-i+1)}{(n-i)\lambda(n-i+1)^2 + 2\mu}$$

Then, P_i can be solved and expressed as follows.

$$P_i = \frac{2\lambda(n-i+1)}{(n-i)\lambda(n-i+1)^2 + 2\mu}$$

$$P_0\left[\frac{i^4-i^2}{4}\left(\frac{1}{\left(\frac{\sqrt{2\pi(1-r_1)}\left(\frac{1-r_1}{e}\right)^{(1-r_1)}}{\sqrt{2\pi(-n+1-r_1)}\left(\frac{(-n+1-r_1)}{e}\right)^{(-n+1-r_1)}}\right)\left(\frac{\sqrt{2\pi(1-r_2)}\left(\frac{1-r_2}{e}\right)^{(1-r_2)}}{\sqrt{2\pi(-n+1-r_2)}\left(\frac{(-n+1-r_2)}{e}\right)^{(-n+1-r_2)}}\right)\left(\frac{\sqrt{2\pi(1-r_3)}\left(\frac{1-r_3}{e}\right)^{(1-r_3)}}{\sqrt{2\pi(-n+1-r_3)}\left(\frac{(-n+1-r_3)}{e}\right)^{(-n+1-r_3)}}\right)}\right) + i\right] \tag{3}$$

Due to the two imaginary roots from the cubic formula equation, it has been shown to express all the steps to find a closed-form which has two imaginary roots in the closed-form in (3). To avoid the imaginary value number in the result, it simulated the formula before going to get the two imaginary roots. $P_0 + \sum_{i=1}^{n-1} P_i + P_n = 1$ and P_0 can be solved as shown in (4), (5), and (6)

$$P_0\left(1+\left(q_1\left[\sum_{j=1}^{1} j+1\right]\right)\right.$$
$$+\left(q_2\left[\sum_{j=1}^{2} j\left[\sum_{k=1}^{i-1}\left[\prod_{l=1}^{k-1} q_l\right]k\right]+2\right]\right)+\cdots$$
$$\left.+\left(q_{n-1}\left[\sum_{j=1}^{n-1} j\left[\sum_{k=1}^{n-2}\left[\prod_{l=1}^{k-1} q_l\right]k\right]+2\right]\right)+\frac{\lambda}{\mu}\left(\frac{n(n+1)}{2}\right)\right)$$
$$=1 \tag{4}$$

$$P_0\left(1+\sum_{i=1}^{n-1}\left(q_i\left[\sum_{j=1}^{i} j\left[\sum_{k=1}^{i-1}\left[\prod_{l=1}^{k-1} q_l\right]k\right]+i\right]\right)+\frac{\lambda}{\mu}\left(\frac{n(n+1)}{2}\right)\right)=1 \tag{5}$$

$$P_0 = \frac{1}{\left[1+\sum_{i=1}^{n-1}\left(q_i\left[\sum_{j=1}^{i} j\left[\sum_{k=1}^{i-1}\left[\prod_{l=1}^{k-1} q_l\right]k\right]+i\right]\right)+\frac{\lambda}{\mu}\left(\frac{n(n+1)}{2}\right)\right]} \tag{6}$$

The performance measurements of primary interests in the adaptive model are expressed in $L_Q, W_Q, W,$ and L as in Equations (7), (8), (9), and (10) respectively.

L_Q : the average number of customers (i.e., equivalently the average number of transactions) in the queue (i.e., the block currently being mined) as same as in [22].

$$L_Q = \sum_{i=0}^{n} iP_i \tag{7}$$

W_Q : the average amount of time a customer (i.e., equivalently, a transaction) in the queue (i.e., the block currently being mined) as same as in [22].

$$W_Q = \frac{L_Q}{\lambda} \tag{8}$$

W : the average amount of time a customer (i.e., equivalently, a transaction) in the system (i.e., the transaction pool in the blockchain) as same as in [22]

$$W = W_Q + \frac{1}{\mu} \tag{9}$$

L : the average number of customers (i.e., equivalently, the average number of transactions) in the system (i.e., the transaction pool in the blockchain) as same as in [22]

$$L = \lambda W \tag{10}$$

IV. Numerical Simulation Results of Proposed VBAVAS Model

In this section, the results of each primary performance metric is presented numerically along with plots on the graphs in an extensive manner, and key observations are highlighted and discussed.

The following graph plots L_Q (i.e., from (7)) on the comparison of the baseline model versus the adaptive model in n for given pairs of λ and μ. Observe that as λ goes 0.005 to 0.05, at μ=0.0667, the ratio of L_Q between adaptive vs. baseline swings from 85%, 69%, 63%, and 67% to 18%, 21%, 31% and 39%, respectively, as n increases in Fig. 9.

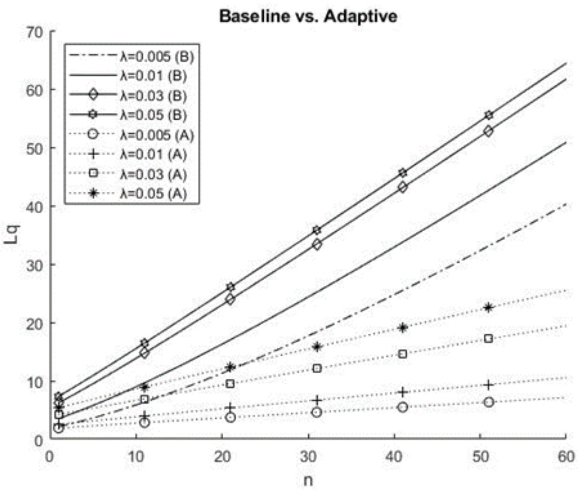

Fig. 9. L_Q versus n for given pairs of λ and $\mu = 0.0667$, (A): Adaptive, (B): Baseline

The following graph plots W_Q (i.e., from (8)) on the comparison of the baseline model versus the adaptive model in n for given pairs of λ and μ. Observe that as λ goes 0.005 to 0.05, at μ=0.0667, the ratio of W_Q between adaptive vs. baseline swings from 85%, 68%, 61%, and 63% to 17%, 20%, 31% and 38%, respectively, as n increases in Fig.10.

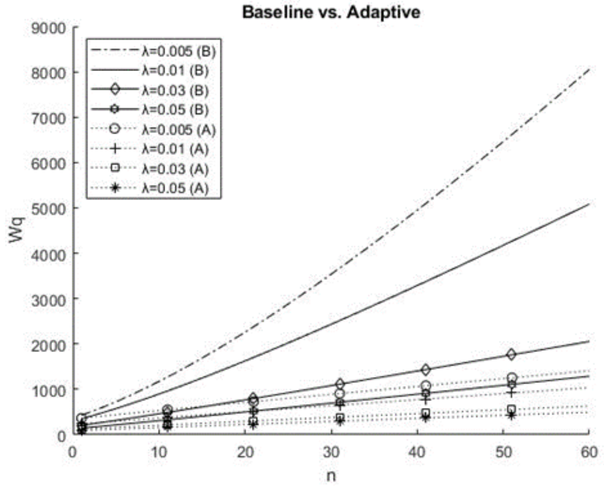

Fig. 10. W_Q versus n for given pairs of λ and $\mu = 0.0667$, (A): Adaptive, (B): Baseline

The following graph plots W (i.e., from (9)) on the comparison of the baseline model versus the adaptive model in n for given pairs of λ and μ. Observe that as λ goes 0.005 to 0.05, at μ=0.0667, the ratio of W between adaptive vs. baseline swings from 85%, 69%, 63%, and 67% to 18%, 21%, 31% and 39%, respectively, as n increases in Fig. 11.

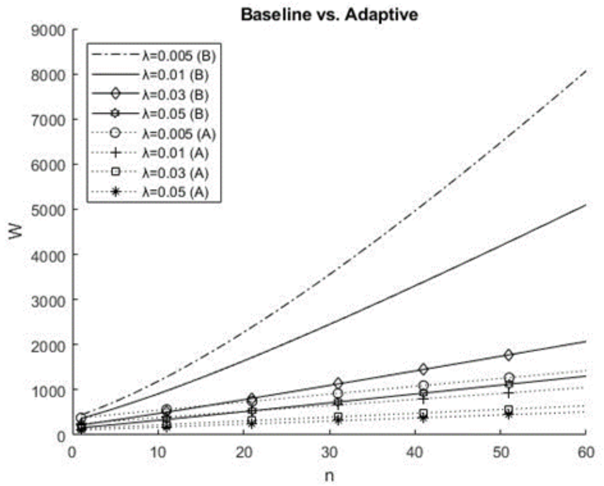

Fig. 11. W versus n for given pairs of λ and $\mu = 0.0667$, (A): Adaptive, (B): Baseline

The following graph plots L (i.e., from (10)) on the comparison of the baseline model versus the adaptive model in n for given pairs of λ and μ. Observe that as λ goes 0.005 to 0.05, at μ=0.0667, the ratio of L between adaptive vs. baseline swings from 85%, 69%, 63%, and 67% to 18%, 21%, 31% and 39%, respectively, as n increases in Fig. 12.

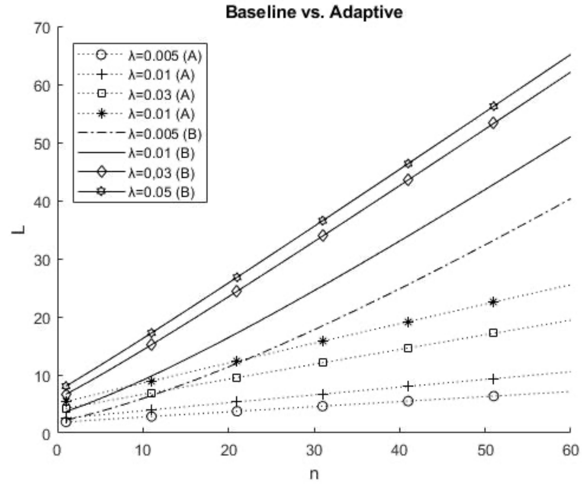

Fig. 12. L versus n for given pairs of λ and $\mu = 0.0667$, (A): Adaptive, (B): Baseline

The throughput (γ) per block in the adaptive chain model can be obtained from (11). The following graph plots γ versus n for given pairs of λ and μ. Observe that as λ goes 0.005 to 0.05, at μ=0.0667, the ratio of γ between adaptive vs. baseline swings from 85%, 68%, 61%, and 63% to 17%, 20%, 31% and 38%, respectively, as n increases in Fig. 13.

$$\gamma = \mu P_n = \mu \frac{\lambda}{\mu} \frac{n(n+1)}{2} P_0 = \lambda \frac{n(n+1)}{2} P_0 \qquad (11)$$

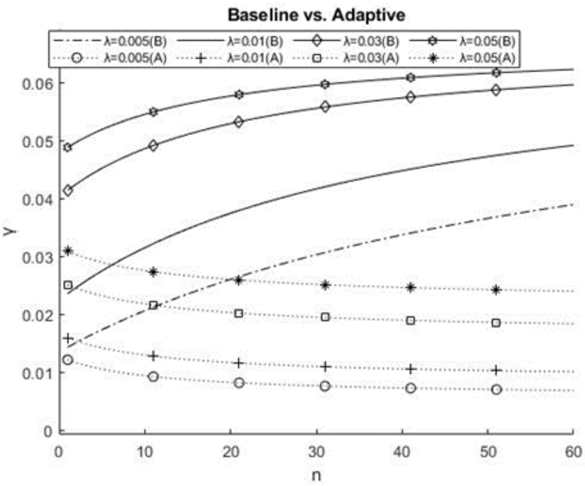

Fig. 13. Throughput versus n for given pairs of λ and $\mu = 0.0667$, (A): Adaptive, (B): Baseline

V. Conclusion

This paper has presented an adaptive chain, as a blockchain-based decentralized network computing VBAVBS solution to trustworthy industrial systems, along with a queueing model of the $M^{1,n}/M^{1,i,n}/1$ type in order to establish a quantitative method to assess the performance of the proposed adaptive chain. The model assumes variable bulk arrivals of transactions in Poisson distribution, i.e., $M^{1,n}$, and variable bulk services of transactions, each of which applies to a block potentially of different capacity in terms of the number of slots in it, in exponential time, namely, VBAVBS. The novelty that distinguishes VBASBS from VBASBS is that in VBASBS, the state P_n is the only state to transition back into P_0 (i.e., the capacity of the block is constant throughout) while in VBAVBS, every state $P_i, 0 < i \leq n$, potentially transitions back into P_0 (i.e., the capacity of the block is variable adapting to a certain criteria as desired, e.g., asynchronous transactions control and any other stringent requirements imposed on the execution time of transactions), which represents the normalized size of the block at various and random sizes of the block. VBAVBS reveals the performance advantages of the adaptive chain versus the baseline chain through extensive numerical simulations on Matlab to compute the models and a comparative study has been conducted on VBAVBS versus VBASBS. In order to base clearly on the results as presented in Section 3, analyses on key results are summarized as follows: each primary performance metric has been presented numerically along with plots, the results have demonstrated graphically with comparisons of the proposed model and baseline model. It has been observed that the mined transaction waiting times to be posted for the block delay, W_Q, in a block, the ratio between VBAVBA versus VBASBS is reduced by 85% and 67%, respectively, at $\lambda = 0.005$ and 0.05 and at $\mu = 0.0667$ when $n = 1$. As increasing the number of $n = 60$, the ratio of the adaptive to the baseline of W_Q in a queue, is 17% and 38% at $\lambda = 0.005$ and 0.05, respectively at $\mu = 0.0667$. Likewise, the ratio of the adaptive vs. baseline model with respect to W, L, L_Q, γ, have also been extensively compared, which reveals that the effectiveness and efficiency of the proposed adaptive chain is significant in a quantitative manner. Lastly, as a sequel to this work, a prototype is being built to demonstrate and validate the claims made in this paper by redesigning the Ethereum source code.

REFERENCES

[1] S. Nakamoto, "Bitcoin: A Peer-to-Peer Electronic Cash System," 2008, [Online]. Available: https://bitcoin.org/bitcoin.pdf

[2] G. Wood, "Ethereum: A Secure Decentralised Generalised Transaction Ledger," Petersburg Version 4ea7b96 – 2020-06-08. Yellow Paper. Jun 8 2020. [Online]. Available: https://ethereum.github.io/yellowpaper/paper.pdf

[3] V. Buterin, "A Next Generation Smart Contract & Decentralized Application Platform," White Paper, 2014. [Online]. Available: https://cryptorating.eu/whitepapers/Ethereum/Ethereum_white_paper.pdf

[4] F. Knirsch, A. Unterweger, D. Engel, "Implementing a blockchain from scratch: why, how, and what we learned," EURASIP Journal on Information Security volume 2019, Article number: 2 (2019)

[5] D. Yang, C. Long, H. Xu, S. Peng, "A Review on Scalability of Blockchain," *ACM ICBCT'20: Proceedings of the 2020 The 2nd International Conference on Blockchain Technology*, March 2020. Pages 1–6. https://doi.org/10.1145/3390566.3391665

[6] H. Subramanian, "Decentralized Blockchain-Based Electronic Marketplaces," *Communications of the ACM*, Volume 61, Number 1, December 2017. [Online] Available: https://doi.org/10.1145/3158333

[7] D. Vujii, D. Jagodi, S. Rani, "Blockchain technology, bitcoin, and Ethereum: A brief overview," *2018 17th International Symposium INFOTEH-JAHORINA (INFOTEH).* DOI: 10.1109/INFOTEH.2018.834554

[8] S. Rouhani, R. Deters, "Performance Analysis of Ethereum Transactions in private blockchain," *2017 8th IEEE International Conference on Software Engineering and Service Science (ICSESS).* DOI: 10.1109/ICSESS.2017.8342866

[9] A. Chauhan, O. P. Malviya, M. Verma, T. S. Mor, "Blockchain and Scalability," *2018 IEEE International Conference on Software Quality, Reliability and Security Companion (QRS-C).* DOI: 10.1109/QRS-C.2018.00034

[10] I. Weber, V. Gramoli, A. Ponomarev, M. Staples, R. Holz, A. B. Tran, P. Rimba, "On Availability for Blockchain-Based Systems," *2017 IEEE 36th Symposium on Reliable Distributed Systems (SRDS).* DOI: 10.1109/SRDS.2017.15

[11] Qi Zhang, Petr Novotný, Salman Baset, Donna N. Dillenberger, Artem Barger, Yacov Manevich, "LedgerGuard: Improving Blockchain Ledger Dependability," *ICBC* (2018).

[12] F. Lombardi, L. Aniello, S. D. Angelis, A. Margheri, V. Sassone, "A Blockchain-based Infrastructure for Reliable and Cost-effective IoT-aided Smart Grids," *Living in the Internet of Things: Cybersecurity of the IoT – 2018*. DOI: 10.1049/cp.2018.0042

[13] K. Gai, Y. Wu, L. Zhu, Z. Zhang, M. Qiu, "Differential Privacy-Based Blockchain for Industrial Internet-of-Things," *IEEE Transactions on Industrial Informatics* (Volume: 16, Issue: 6, June 2020). DOI: 10.1109/TII.2019.2948094

[14] K. Gai, Y. Wu, L. Zhu, M. Qiu, M. Shen, "Privacy-Preserving Energy Trading Using Consortium Blockchain in Smart Grid," *IEEE Transactions on Industrial Informatics* (Volume: 15, Issue: 6, June 2019). DOI: 10.1109/TII.2019.2893433

[15] K. Gai, Y. Wu, L. Zhu, L. Xu, Y. Zhang, "Permissioned Blockchain and Edge Computing Empowered Privacy-Preserving Smart Grid Networks," *IEEE Internet of Things Journal* (Vomue:6, Issue:5, Oct 2019). DOI: 10.1109/JIOT.2019.2904303

[16] Q. Li, J. Ma, Y. Chaing, "Blockchain Queue Theory," arXiv:1808.01795v1 [cs.CE]. 6 Aug 2018

[17] P. Thakkar, S. Nathan, B. Viswanathan, "Performance Benchmarking and Optimizing Hyperledger Fabric Blockchain Platform," *2018 IEEE 26th International Symposium on Modeling, Analysis, and Simulation of Computer and Telecommunication Systems (MASCOTS)*, 08 Nov 2018. DOI: 10.1109/MASCOTS.2018.00034

[18] S. Pongnumkul, C. Siripanpornchana, S. Thajchayapong, "Performance Analysis of Private Blockchain Platforms in Varying Workloads," *2017 26th International Conference on Computer Communication and Networks (ICCCN)*, Sep 2017. DOI: 10.1109/ICCCN.2017.8038517

[19] P. Zheng, Z. Zheng, X. Luo, X. Chen, X. Liu, "A detailed and real-time performance monitoring framework for blockchain systems," *ACM ICSE-SEIP '18: Proceedings of the 40th International Conference on Software Engineering: Software Engineering in Practice*, May 2018. Pages 134–143. https://doi.org/10.1145/3183519.3183546

[20] M. Liu, F. R. Yu, Y. Teng, V. C. M. Leung, M. Song, "Distributed Resource Allocation in Blockchain-Based Video Streaming Systems With Mobile Edge Computing," *IEEE Transactions on Wireless Communications* (Volume: 18, Issue: 1, Jan. 2019). DOI: 10.1109/TWC.2018.2885266

[21] S. Rai, K. Hood, M. Nesterenko, G. Sharma, "Blockguard: Adaptive Blockchain Security. Distributed, Parallel, and Cluster Computing," Jul 2019. arXiv:1907.13232v1

[22] J. Seol, A. Kancharla, Z. Ke, H. Kim, and N. Park, A Variable Bulk Arrival and Static Bulk Service Queueing Model for Blockchain. *BSCI '20: Proceedings of the 2nd ACM International Symposium on Blockchain and Secure Critical Infrastructure*, October 2020, Pages 63–72, https://doi.org/10.1145/3384943.3409423

[23] Xiaoqiong Xu, Gang Sun, Long Luo, Huilong Cao, Hongfang Yu, Athanasios V. Vasilakos, "Latency performance modeling and analysis for hyperledger fabric blockchain network, Information Processing & Management," Volume 58, Issue 1, 2021, 102436, ISSN 0306-4573, https://doi.org/10.1016/j.ipm.2020.102436.

[24] R. A. Memon, J. Li, J. Ahmed, A. Khan, M. I. Nazir, M. I. Mangrio. Modeling of Blockchain Based Systems Using Queuing Theory Simulation. 2018 15th International Computer Conference on Wavelet Active Media Technology and Information Processing (ICCWAMTIP), 2018, pp. 107-111, doi: 10.1109/ICCWAMTIP.2018.8632560.

[25] Krieger U.R.; Ziegler M.H.; Cech H.L. (2019) Performance Modeling of the Consensus Mechanism in a Permissioned Blockchain. In: Gaj P., Sawicki M., Kwiecień A. (eds) Computer Networks. CN 2019. Communications in Computer and Information Science,

[26] J. Mišić; V. B. Mišić; X. Chang; S. G. Motlagh; M. Z. Ali. Modeling of Bitcoin's Blockchain Delivery Network. in *IEEE Transactions on*

Network Science and Engineering, vol. 7, no. 3, pp. 1368-1381, 1 July-Sept. 2020, doi: 10.1109/TNSE.2019.2928716.

[27] R.Lakshmana Kumar, Firoz Khan, Seifedine Kadry, Seungmin Rho, "A Survey on blockchain for industrial Internet of Things," Alexandria Engineering Journal, Volumne 61, Issue 8, August 2022, Pages 6001~6022

[28] Sanjeev Kumar Dwivedi, Priyadarshini Roy, Chinky Karda, Shalini Agrawal, and Ruhul Amin, "Blockchain-Based Internet of Things and Industrial IoT: A Comprehensive Survey," Security and Communication Networks 2021, Volume 2021 Article ID 7142048, https://doi.org/10.1155/2021/7142048

[29] Gang Wang, "SoK: Applying Blockchain Technology in Industrial Internet of Things," Applying Blockchain for Industrial IoT, International Association for Cryptologic Research (IACR) 2021

[30] Mohd Javaid, Abid Haleem, Ravi Pratap Singh, Shahbaz Khan, Rajiv Suman, "Blockchain technology applications for Industry 4.0: A literature-based review," Blockchain: Research and Applications (2021), https://doi.org/10.1016/j.bcra.2021.100027

[31] T. Alladi, V. Chamola, R. M. Parizi and K. R. Choo, "Blockchain Applications for Industry 4.0 and Industrial IoT: A Review," in IEEE Access, vol. 7, pp. 176935-176951, 2019, doi: 10.1109/ACCESS.2019.2956748

[32] J. Seol, and N. Park, An Asynchronous Chain and A Variable Bulk Arrival and Asynchronous Bulk Service Model. *BSCI https://doi.org/10.1145/3594556.3594628in the 5th ACM International Symposium on Blockchain and Secure Critical Infrastructure (BSCI 2023), July 10th -14th, Melbourne, Austraila*