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A Blockchain-Enhanced Transaction Model for Microgrid Energy Trading

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ABSTRACT In the power sector, microgrids play a supportive role in bridging the adequacy gap in the conventional electricity supply. Trading of the generated energy has recently been improved by blockchain technology which offers a new cheap, secure, and decentralized transaction approach. Its operation is however associated with an undesired inherent delay during energy transactions initiated by the prosumers, thus, failure to timely attend to incidences of urgent demand could end up in catastrophe at the consumer's side. This article thus proposes a cyber-enhanced transactive microgrid model using blockchain technology with optimized participants' permission protocol to ameliorate this challenge. It is demonstrated that the optimized blockchain participants' permission model leads to improved transaction speed and greater convenience. The transaction speed simulation is thereafter performed and it was also demonstrated that the node population has a greater effect than the transaction block size on the transaction speed improvement.

INDEX TERMS Blockchain transaction, block transaction speed, microgrid, prosumers, transaction permission protocol.

I. INTRODUCTION

The world's energy summit advocates for a green energy-driven ecosystem where the means of energy generation is one that renders minimal harm to the environment. Besides, the supply from the conventional grid system at times does not guarantee steadiness and sufficiency. Meanwhile, a major failure in the system could be catastrophic to the consumers if an alternative energy source is unobtainable. For example, in October 2017, the Hurricane Maria disaster put the majority of Puerto Rico in darkness for an extended period [1], [2]. The microgrid is one accommodative vehicle that would easily accelerate the drive and the implementation of such needed technology. It serves both as a supportive and alternative energy matrix relative to the traditional grid.

Some regular consumers have recently become prosumers producing small scale energy from several renewable resources and would require to sell the surplus to the nonproducing and consumption-insufficient consumers [3]. Also, several localities have excess generations, while others have insufficient generations leading to generation-load imbalance, as well as demand-supply imbalance [4]. Some enterprises, such as NEC Corporation, currently encourage building energy management systems that would enhance the dissemination of distributed generations to optimize the demand and supply interaction in the microgrid arena [5]. For instance, a NOBEL project renders enterprise services and energy trading approach to energy management within the neighborhood districts [3], [6]. The Energy Virtual Network Operator (EVNO) being promoted by Keio University, is a company that focuses on providing energy management services by locally matching the energy demand and supply using its management server, as well as autonomous scheduling based on the local content and policies of each power provider. A 27-floor multitenant building in Tokyo developed an infrastructure for Business Continuity Protection (BCP) where it generates and supplies twin 750 kVA emergency power for 48 hours to tenants. In a similar regard, several

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other innovative efforts had been jointly initiated to improve the energy trading experience as well as the costs amongst participants of the microgrid.

Usually, energy trading is managed by utility companies through power balancing decisions and approaches. Big energy middlemen companies also take part in energy trading guided by the existing local policy. However, the entire scheme management process is yet inadequate and various shortcomings still exist. Due to the usual third party escrow, consumers would continue to face transaction bottlenecks [7], [8]. Such include utility companies' associated long transaction protocols, the intermediaries' transaction charges and stringent policies, escrow's inherent technical delay and downtime instigated by high traffic of transaction clients, and wide communication gap between energy buyers and sellers. These lead to an undesired delay in the initiated transactions before they are completed. The result is that in the end, power generation-load balancing would not be far achieved, producers would face a higher cost of energy storage due to prolonged storage, consumers would experience higher transaction costs incurred from the intermediaries and middle traders, and would experience transaction hitches and decelerations leading to the aforementioned delay in transaction completion time. More importantly, there is a need to improve on the transaction efficiency among the energy prosumers and consumers in terms of the transaction speed and convenience through a more enhanced efficiency-driven approach.

Inspired by the increasing IoT-driven peer-to-peer (P2P) communications, this article addresses these problems by introducing a cutting edge and block-chain enabled microgrid energy transaction model with no transaction intermediary. The transaction throughput is further enhanced by optimizing the participants' transaction permission protocol to suit the intended purpose, lessen the transaction time, increase convenience, and foster more trade deals amongst participants, and without countering the participants' original interests in the consortium. Section (ii) explains the blockchain operation and the special features that support its deployment in the microgrid arena. In section (iii), an enhanced blockchain-enabled microgrid transaction model 1 with an optimized transaction permission protocol is presented, described, and compared with the conventional model 2. Section (iv) focuses on the transaction speed analysis and simulation for transaction speed improvement, whilst Section (v) has the conclusion.

II. BLOCKCHAIN REVOLUTION IN MICROGRID

The utilization of the blockchain concept in the microgrids is motivated by the recorded breakthrough in the financial, law enforcement, and industrial sectors of the economy [9]. In the financial sector, transactions by cryptocurrency have been achieved by the Bitcoin technology [10]. Also, in the ''Food Standards Agency'', a nonministerial government department of the government of the United Kingdom, blockchain has been successfully used as a regulatory tool in a cattle slaughterhouse to ensure total compliance in the food sector to protect public health [11]. A similar result is achieved when the blockchain experience gained within the financial sector is applied to the power sector at the microgrid energy trading [12]. The P2P transactions are enabled by the blockchain technology. Previously in New York City, the energy prosumers usually had their surplus solar-generated energy directly sold back to the utility company. However, this did not yield them much gain as the money is not paid to them directly but was being deducted from their previous and subsequent electricity usage bills. Thus, when a failure leading to blackout is experienced in the utility arena, the prosumers would have their solar panels also affected and switched off despite their capability to create their power. However, in April 2016, success was evident in an event set up to experiment for the feasibility of a blockchain-enabled energy trading scheme through a trial known as ''Brooklyn microgrid'', a project facilitated by the LO3 energy Company and Siemens in New York. This witnessed a dispersedly generated solar energy being traded amongst the neighborhood using Ethereum-enabled blockchain technology [13]. Some private buildings tactfully had solar facilities installed on the rooftop [14]. Energy generated in surplus is then sold to other buildings in the neighborhood in a decentralized transaction as shown in Fig. 1 without the need for the regular utility company to act as an intermediary.

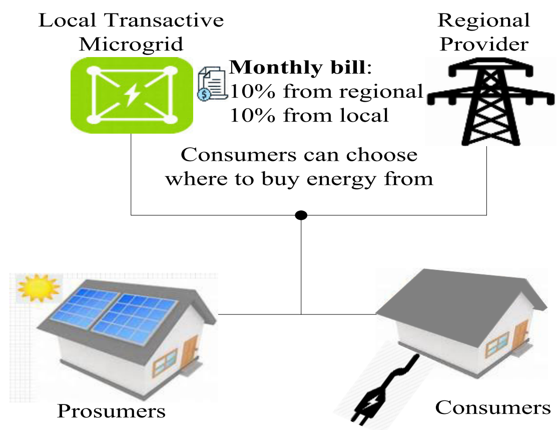


FIGURE 1. The Brooklyn energy trading platform.

While the utility provider still maintains the electrical grid that delivers power, the actual energy is generated, stored, and traded locally by members of the community. This yields a more resilient and sustainable clean energy model. Smart meters record the quantity of surplus generated energy that is made available and visible to the buyers, as well as that purchased by the consumers, whilst blockchain technology effects the transactions amongst the prosumers in a smart, convenient, and secure manner [15].

A. MICROGRID BLOCKCHAIN PLATFORM

Hitherto, the traditional means of financial transactions among participants is a centralized model, where a central

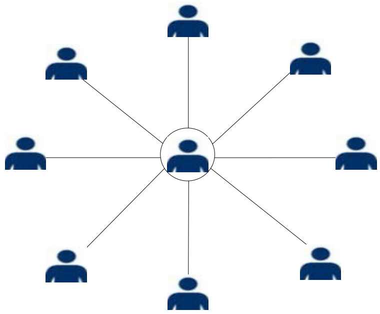


FIGURE 2. Centralized P2P microgrid energy trading.

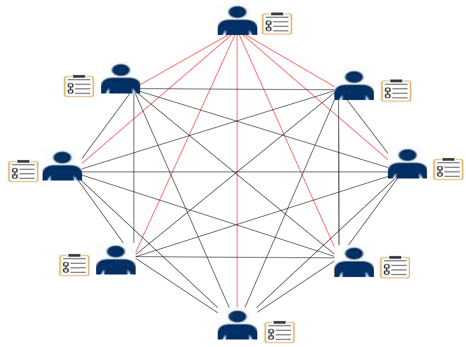


FIGURE 3. Decentralized P2P microgrid energy trading.

mediator processes and completes transactions amongst the participants, as shown in Fig. 2.

LEGEND

 Energy Providers (such as; electricity producers, sellers) and Energy Consumers (such as; energy consumers, buyers, borrowers)

 Escrow Intermediary (such as; banks, exchanges, traders, energy companies)

—— Potential traders and intermediary at both ends of the line.

A remarkable contribution of blockchain is that it introduces a convenient system where transactions are controlled by the participants by a more secure technology. In smart-grids, this is achieved by decentralized energy transactions amongst energy producers and buyers/consumers with the aid of the blockchain technology [2]. Every participant in the market arena is connected to all other participants as seen in the red lines emanating from the topmost participant to other entire participants in the chain as shown in Fig. 3. The Blockchain Smart Transaction is a shared power ledger, which visibly groups each transaction into blocks that are chronologically chain-linked [16]. This is as shown in Fig. 3 and elaborated in Fig. 4.

The transaction protocol and the choice of the data fields are flexible and depend on the consensus of the consortium. The entire transaction database is tightly protected with software-generated alpha-numeric strings which is specific to each block as shown in Fig. 4. The cryptographic strings commonly referred to as the Hash, chains each block to the immediate next and in the sequence of the contained transactions. Each block contains its hash and that of the immediate-preceding block in the order of transaction except the first block which is directly connected to the system origin [17]. Therefore, for any information mutilation to occur, the adversary must alter the hash of the entire blocks, as well as elapse the entire time required to calculate the inherent proof-of-work, a second level security measure associated with the generation of new hashes [18]. Thus, the security of both prosumers and consumers are guaranteed.

III. BLOCKCHAIN-ENABLED MICROGRID TRANSACTIVE MODEL

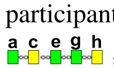
In the power sector, the choice of blockchain is more suitable to the microgrids than in the traditional main power grid [19]. The power generation in the main grid is very large enough to sustain a continuous transmission to long distant consumers and withstand the associated losses. Hence, transactions are easily completed by the customary billing system at the consumers' side using smart meters. Microgrids have a distinctive advantage for minimizing the amount of energy lost through transmission, unlike the traditional practice in the main grid, otherwise, consumers would eventually receive less than what was purchased. Furthermore, the fewer number of microgrid participants supports blockchain features in terms of transaction speed as well as the data processing and storage space [20].

A. CONSORTIUM BLOCKCHAIN TRANSACTIONS

To explain the inherent features of the enhanced blockchain technology in the microgrid transaction, we propose a microgrid energy transaction model (model 1) as shown in Fig. 5. The color of each sphere depicts the participant's permission type. There are two types of permission, the full, and partial permission. The full permission, represented in green, is the conventional type and has permission to validate a created block, whilst the partial permission is in yellow. The radius of each sphere defines the participant's activity delay. Activity delay includes block-creation delay and validation delay. The PowerLedger uses the Proof-of-Stake validation type in the transaction process.

FIGURE 5 LEGEND

A = Blockchain participant, **a** = Transaction block created by participant A



= Transaction Blockchain

Block-creation Notification (BCN) received

BCN and Validation request received

Block validation permission and processing,

Block-validation request sent

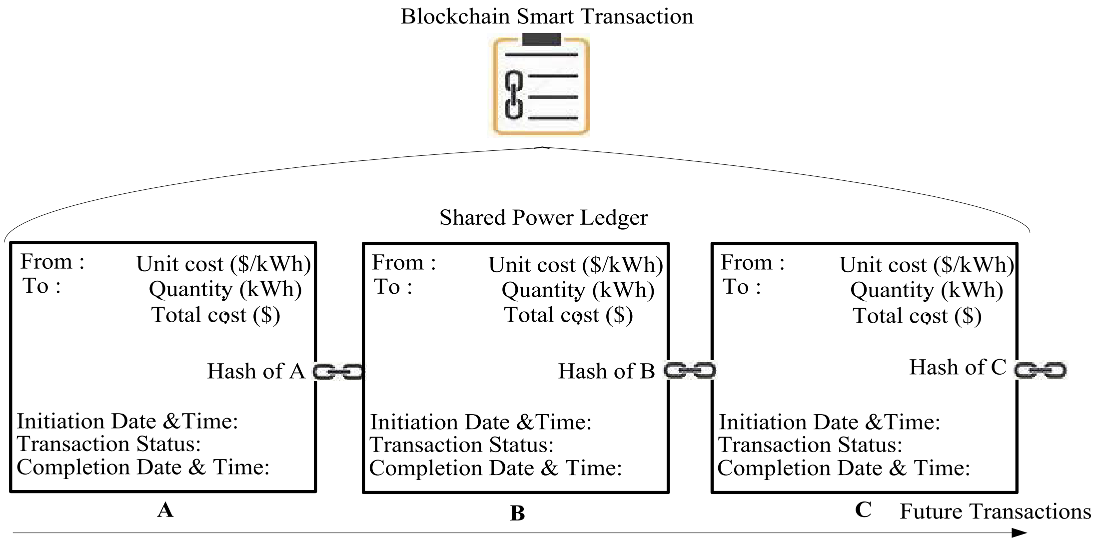


FIGURE 4. **Microgrid smart transactions blockchain.**

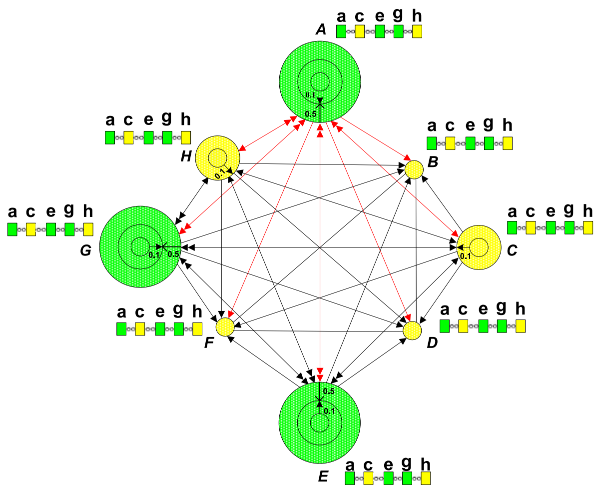


FIGURE 5. **Microgrid partial-permission blockchain transaction model.**

Block creation and Validation are mutually exclusive events

Energy transaction link

1) TRANSACTION PERMISSION PROTOCOL

In the proposed model, the permission levels are of three categories which include: (i) Those that have permission to only view the created blocks, (ii) Those that are permitted to create blocks, but are not authorized to validate other created blocks, and (iii) Those that have full transaction permission, namely, the ability to create transaction blocks, view the created blocks, as well as validate a created block. The group 'i' are producers with self-sufficient consumption that need other consumers' consumption history and patterns to enable them to adapt to their requirements in the future energy generation and storage quantity. Group 'ii' includes the middle traders and prosumers that buy and resell energy. Group 'iii' are strictly P2P consumers whose purchase ability and the subsequent block-creation ability depend on their previous participation in the validation of the earlier blocks created by other prosumers, i.e., they can create their blocks if they had taken part in the validation process of the earlier created blocks. Thus, they would always strive to ensure that they take part in the validation process of every created block. It includes the primary consumers as well as some of the larger energy middle traders. The members' transaction capabilities (permission) in Fig. 5 are defined in Table 1.

TABLE 1. **Members' Transaction Permission from Fig. 5.**

Microgrid Blockchain Members	Group	Receive BCN	Create Block	Validate created block
A	iii	√	√	√
B	i	√	x	x
C	ii	√	√	x
D	i	√	x	x
E	iii	√	√	√
F	i	√	x	x
G	iii	√	√	√
H	ii	√	√	x

In Fig. 5, the spheres *B*, *D*, and *F* are "group i", *C* and *H* are "group ii", while the green spheres *A*, *E*, and *G* represent the "group iii" members. From Table 1, only members *A, C, E, G, and H* can create blocks. Members *B, C, D, F*, and *H* lack validation permission. Only members *A*, *E*, and *G* have validation permission and hence can receive validation requests. All participants are capable of receiving BCN. The participant *A,* for example, has the permission to receive a BCN and validation request from *C, E, G*, and *H*, send both BCN and validation requests to *E, G,* and self, as well as send only BCN to *B, D*, and *F* as demonstrated through the red communication lines and the corresponding arrowheads to and from *A*.

TABLE 2. Microgrid Blockchain Five-member Energy Transaction (From Fig. 5 and Fig. 6).

Blockchain Member	Block created/Energy Purchased (kWh) (Fig.5)	Block created/Energy Purchased (kWh) (Fig.6)	Minimum Validation time + BC time (s) (Fig.5)	Minimum Validation time + BC time (s) (Fig.6)
A	50	50	1.1	2.6
C	150	150	1.1	2.6
E	300	300	1.1	2.6
G	400	400	1.1	2.6
H	500	500	1.1	2.6
Total	1400	1400	5.5	13

TABLE 3. Microgrid Blockchain Cumulative Energy Transaction and Transaction Time.

Blockchain member	Block created/energy purchased (kWh) (Fig. 5_model 1)	Block created/energy purchased (kWh) (Fig. 6_model 2)	Minimum validation time (s) + BC time (s) (Fig. 5_model 1)	Minimum validation time (s) + BC time (s) (Fig. 6_model 2)
A	50	50	1.1	2.6
C	200	200	2.2	5.2
E	500	500	3.3	7.8
G	900	900	4.4	10.4
H	1400	1400	5.5	13

B. PUBLIC BLOCKCHAIN TRANSACTION

To describe the achieved transaction speed via the optimized transaction permission protocol in model 1, we present the second conventional blockchain model (model 2) whose entire participants have full transaction permission as shown in Fig. 6, and both are compared.

Every other feature in Fig. 6 is the same as in Fig. 5 and Table 1 except that every member now has full permission to validate each created block. We quantify the inherent features in the permission protocol by assigning regular quantities to each of the following variables: block-creation time and block-validation time, in both models for assessment. Let x and y be the block-creation time and block-validation time, respectively. We also assign 0.1 second (s) and 0.5s to x and y, respectively for explanatory purpose. We assume a nonsimultaneous validation time amongst participants. Hence, validation is on first-come-first-serve (FCFS) basis. Thus, a typical five-member microgrid energy trading data emerges as shown in Table 2. The data values are regular and consistent between transactions in Fig. 5 (model 1) and Fig. 6 (model 2).

Generally, before a created block is added to the chain, it must be validated by the majority of the validation-capable members. In Fig. 5, the validation-capable members are three (3), hence a minimum of two members are required. Similarly, in Fig. 6, every member is validation-capable, thus, a minimum of five (5) members are required. The minimum delay (transaction time) before each block is added to the chain is thus $(0.5 \times 2) + 0.1 = 1.1$s and $(0.5 \times 5) + 0.1 =$ 2.6s in Fig. 5 and Fig. 6, respectively, for all blocks. This is as shown in Table 2. The cumulative values of the energy transaction and the corresponding transaction time in both models are shown in Table 3.

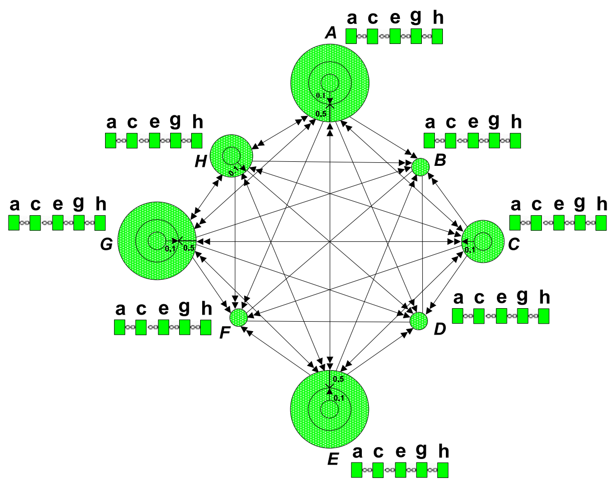


FIGURE 6. Microgrid full-permission blockchain transaction model.

Consequently, it is observed that when the five members individually initiated an energy purchase transaction, the total time to the completion of the last transaction is 5.5 seconds and 13 seconds for Fig. 5 and Fig. 6, respectively for equal 1400kWh total quantity of purchased energy. This is as shown in Fig. 7. The time is found to have been reduced by 57.7% in model 1, thus, an improvement. The time reduction is also visible in the individual transactions amongst the five members.

The assumption herein is that individual transactions are nonconcurrent. In reality, smartgrid energy transactions could be contemporaneous, in which case, the similar transaction-time-reduction effect would be experienced. For example, in the concurrent transaction type (assuming full concurrency), the total transaction time is 1.1 and 2.6 for Fig. 5 and Fig. 6, respectively as shown in Fig. 8. The transaction time in model 1 was also found reduced by an equal percentage (57.7%) as was in the case of the nonconcurrent.

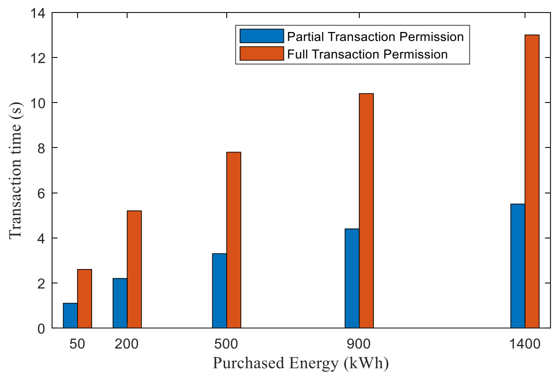


FIGURE 7. Blockchain-enabled smartgrid nonconcurrent transaction.

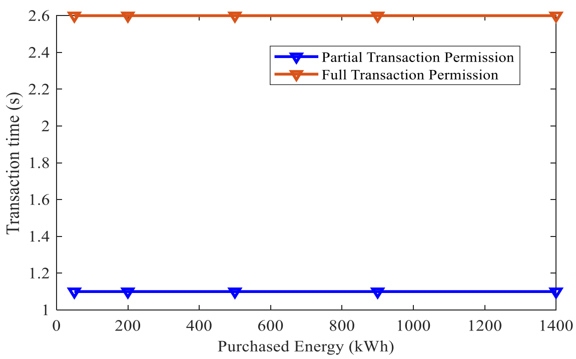


FIGURE 8. Blockchain-enabled smartgrid concurrent transaction.

The consortium whose transaction type comprises of participants with full transaction permission is regarded as the Public blockchain consortium as seen in Fig. 6. Examples are Bitcoin and Ethereum [14]. Otherwise, those with mixed permission have their transactions consolidated on the private blockchain framework as seen in Fig. 5. Similarly, the permission protocol could be optimized to limit the number of members that have permission to receive and view transactions (created blocks) following the members' consensus. This would consequently reduce the large data storage space requirement of members' computing devices.

IV. BLOCKCHAIN TRANSACTION SPEED ANALYSIS

While the block transaction speed is higher in the private blockchain model than in that of the public, some other factors could affect the speed. Experiments have shown in the Bitcoin blockchain network, that for small blocks (less than 20 kB), the block transaction speed variation is negligible with various network topology, however, for larger blocks, this depends mainly on the bandwidth of the network [21], [22]. When the block size is increasingly larger due to increasing transactions, the transaction speed significantly reduces. To speed up the transaction, it is necessary to increase the bandwidth of the network. Assume that the bandwidth of each node's network channel is L and the size of each block is Z, then the time required for a block to be transferred from one node to another can be written as:

$$t_{i1} = n_i Z/L \tag{1}$$

where n_i is the number of blocks concurrently sent from co-nodes. For block transactions in a nonconcurrent manner, $n_i = 1$, hence, (1) becomes (2) as:

$$t_1 = Z/L \tag{2}$$

where t_1 = time required for a block to be transferred from one node to another in a nonconcurrent manner.

Also, the verification time, t_{i2}, is proportional to the number of transactions contained in the block, hence, this could be written as:

$$t_{i2} = kn_i Z/S_0 \tag{3}$$

where k is a constant of proportionality, S_0 is the average unit transaction size. Since the block transaction time comprises of block transfer time and verification time, (1) and (3) can be combined as:

$$t_i = n_i Z(1/L + k/S_0) \tag{4}$$

where t_i is the transaction time when the block transactions are concurrent. When block transactions are nonconcurrent, (5) gives the transaction time, t_i as:

$$t_i = \sum\nolimits_{i=1}^{n} Z_i(1/L + k/S_0) \tag{5}$$

The greater the size of the participants (number of nodes), the longer the transaction time. The specific transaction time is however dependent on the network topology, and it is difficult to write a unified expression. The specific relationship between the transaction time and the number of nodes can, however, be directly obtained by the simulation process [23]. The simulation process is performed using the transaction matrices. The specific relationship between block transaction time T, block size Z, and the number of nodes n can thus be investigated.

A. RELATIONSHIP BETWEEN TRANSACTION TIME, BLOCKSIZE, AND NUMBER OF NODES

The relationship between the transaction time, block size, and the number of nodes, were investigated using the NS3 simulator. The block size is the total weighted size of all the transactions dispatched at the same time in a block. For example, if five (5) individual transactions of 2KB each are dispatched together, the block size is 10KB, and if two (2) of such blocks are however dispatched together (i.e. concurrently), the block size is 20KB. Transaction time is the time delay between "when the block is created and dispatched to the participating nodes" to "when the transactions are completed and added to the chain". NS3 is a network-simulator for internet-based discrete events for research purposes primarily to obtain how the network works using various parameters [24]. NS3 enables the creation of various virtual nodes as well as the installation of devices, internet stacks, etc, to create point-to-point wireless connectivity and communication amongst the nodes [25]. The program randomly generates the node network topology, simulates the nodes transaction and the transaction process of the blocks in the network, and records the block propagation time in the network [26]. The relationship between the block transaction time, block size and the number of nodes was simulated.

The NS3 simulator uses its own set of libraries which can also combine to interface with other external software libraries to achieve optimized performance and visualization [27]. Various parameters are specified on its command-line interface [27]. The three major input configuration parameters required include: "features", "output", and "feature dispatch interval", and are defined in the NS3 command interface as follows:

i. *Features*: Block, node. The "range" of each quantity is numerically defined in its fields as follows:
   * For Block (KB), Min = 10, Max = 5120, step size = 10;
   * For Node (N), Min = 2, Max = 500, step size = 1;

ii. *Output*: Time (second). The *feature-output* transaction type is *linear*, and the *feature dispatch* and *delay* type are *stochastic*.

iii. *Feature dispatch interval:* The NS3 network transaction considered typically emulates the stochastic property of the real-life transaction pattern, thus, the dispatch interval time of the features is stochastically determined by the Monte Carlo equation of discrete-states stochastic systems as shown in (6) and (7) [28]. The equation is suitable for modeling the state intervals of stochastic systems with continuous process and discrete states [29].

$$LIT = (-1/\lambda)\, ln\, U_2 \tag{6}$$
$$SIT = (-1/\mu)\, ln\, U_1 \tag{7}$$

where *LIT* and *SIT* are long interval time and short interval time, respectively, measured in seconds, λ = feature dispatch rate, μ = feature delay rate, U_1 and U_2 are set of generated random numbers ranging between zero (0) and one (1) in the format U (0, 1). $U_1! = U_2$ (U_1 is not equal to U_2). The feature dispatch and delay rate are related by ratios as:

$$\lambda = 1 - \mu \tag{8}$$

$\lambda : \mu$ are conventionally selected in the ratio of 0.2:0.8 or 0.3:0.7 (similar to the data splitting ratios for the training and testing datasets in data training). 0.2:0.8 is selected for both features. The *LIT* and *SIT* are the intervals in the simulator at which new blocks are created and at which new nodes are added to the network. The transition between the long interval and short intervals of time is random.

The random numbers (U_1 and U_2) change each time they are generated, hence, there is no specific interval for *SIT* and *LIT* and would, therefore, record intermediate values, thus, observing stochasticity in the transaction pattern. The *LIT* increases as the value of the current random number approaches zero (0), and the *SIT* decreases as the value of the random number approaches one (1). Thus, the maximum possible interval (LIT_{Max}) would occur when the random number (U_2) is the smallest float (decimal) above zero (0). For instance, for the random numbers of two decimal places, the *LIT* would record a maximum interval of 23.03s at $U_2 =$ 0.01. i.e. $(-1/0.2)\, ln\, 0.01$. Likewise, the *SIT* would record a minimum interval when the random number (U_1) records the largest positive float below one (1).

1) RELATIONSHIP BETWEEN TRANSACTION TIME AND BLOCK SIZE

When simulating the relationship between block transaction time, T and block size, Z, the network size was set fixed at 250 nodes while the block size was varied from 10KB to 5120KB at a step-size of 10KB representing 10KB to 5MB range. The graph of the obtained transaction values is shown in Fig. 9. The block size is considered here to examine and quantify the effect of the growth in the contained transaction sizes on the transaction time in the blockchain technology with the aid of the NS3 simulator. Increased energy transactions translate to increased transaction size.

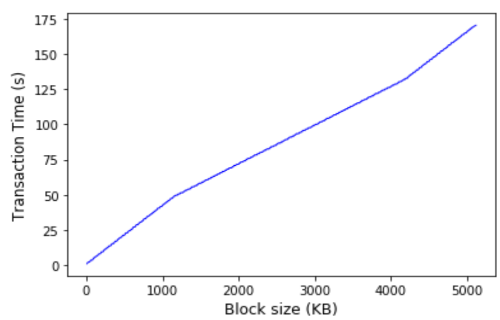


FIGURE 9. Relationship between transaction time and block size.

2) RELATIONSHIP BETWEEN TRANSACTION TIME AND NUMBER OF NODES

When studying the relationship between block transaction time and the number of nodes, N, the block size was kept constant at 2.5MB while the network size was increased from 2 nodes to 500 nodes. It can be seen from Fig. 10 that the block propagation time is approximately proportional to the number of nodes. In the blockchain transaction model, there is no intermediate node. Each node is inherently directly connected to all other nodes, thus, every node has an equal node degree [30]. Negligible influence anomalies were recorded as a result of randomness in the generation of the network topology.

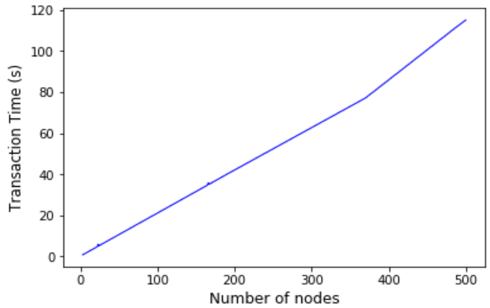


FIGURE 10. Relationship between transaction time and number of nodes.

Fig. 9 and Fig. 10 are presented to graphically reveal the numerical relationship (variation) between the "block size" and "transaction time", and between the "number of nodes" and the "transaction time", respectively as obtained in the simulation process. From these, the final simulation (the regression analysis) is thereafter performed to quantify their individual relative effect on the transaction time.

TABLE 4. Block Size (Z) and Block Size Transaction Time (T_Z) Data Format.

Block size (Z) (10KB – 5120KB)	Block size Transaction Time (T_Z)
10	$T_{Z\ 10}$
20	$T_{Z\ 20}$
30	$T_{Z\ 30}$
.	.
.	.
.	.
5120	$T_{Z\ 5120}$

TABLE 5. Node (N) and Node Transaction Time (T_N) Data Format.

Node(N) (2–500 nodes)	Node Transaction Time (T_N)
2	$T_{N\ 2}$
3	$T_{N\ 3}$
4	$T_{N\ 4}$
.	.
.	.
.	.
500	$T_{N\ 500}$

B. FITTING ANALYSIS, SIMULATION STEPS, AND PROPAGATION TIME FORMULA

The transaction time (T) was individually recorded for each of the block sizes (Z) and the nodes (N) in the format shown in Table 4 and Table 5, respectively from the NS3 output.

A two-step simulation is then performed to unify the outputs (transaction time (T_Z and T_N)) to a single output, T. First, the block size (Z) is simulated and fitted with the Block size time (T_Z) using the DecisionTreeRegressor algorithm which gave the best result and the fitting model is obtained. The block size transaction time (T_Z) is the explanatory variable while the response variable is the block size (Z). The obtained model is thereafter used to predict the new block size (Z_{New}) (the response variable) using the node transaction time (T_N) as the input (the explanatory variable) to the model, thus, the final variables include: the node (N), node transaction time (T_N), and the new predicted block size (Z_{New}) now ranging from 10KB to 3590KB. The data format is shown in Table 6. By "node transaction time (T_N)", we imply the transaction time as a result of the addition of new nodes to the network.

TABLE 6. The final Simulation Data Format.

Node (N) (2–500 nodes)	Node Transaction Time (T_N)	New Predicted Block size (Z_{New}) (10KB –3590KB)
2	$T_{N\ 2}$	Z_2
3	$T_{N\ 3}$	Z_3
4	$T_{N\ 4}$	Z_4
.	.	.
.	.	.
.	.	.
500	$T_{N\ 500}$	Z_{500}

Second, due to the linearity of the block propagation time with the block size and the number of nodes, the three parameters (N, T_N (now known as T), and Z_{New} (now known as Z)) are fitted using the linear regression algorithm to obtain the fitting formula for the transaction time in the format shown in (9).

$$T = aZ + bN + c \tag{9}$$

where *a, b,* are the slope coefficients, *c* is the intercept, Z = Block size, N = number of nodes, T = Transaction time. 499 simulation data points were split into 80% training data and 20% testing dataset and simulated through the Least-squares method. The variation between each two successive data points was spread, yielding a robust model, thus, the 499 data points were adequate to cover the variations and discover the underlying relationships. The relationship between block propagation time, block size, and number of nodes is established from the fitting formula as shown in (10).

$$T = 0.012Z + 0.1393N + 1.23 \tag{10}$$

From the model, every single additional member node joining the blockchain network increases the transaction time by an average of 0.1393 seconds, and every unit additional block size increases the time by an average of 0.012 seconds. This enables us to deduce that the larger blockchain network size has a greater contribution to the transaction time than the block size growth. The ripple effect of the increased network size on the communication bandwidth could be used to explain this deduction. The available bandwidth of the network shrinks as the network size grows. The uniqueness in (10) depends more on the topology of the network hence values would change based on the recorded transaction data, however, the inherent relative variation of the independent parameters with the transaction time remains proportionally unique.

The simulation was performed in the Python Jupyter environment under the linear regression algorithm of Scikit-learn. 80% of the data was used for the training set and 20% for the testing set and the *random state* of the *train_test_split* was seeded (random_state = 90). Testing the accuracy of the formula with 100 datasets of the test data, the coefficient of determination (Adjusted R-square) recorded is 0.98. Given the average deviation of prediction in (11), the average deviation of the 100 sets of data was 0.9291.

$$D_{av} = \left[\frac{1}{n}\sum_{i=1}^{n}(0.012Z_i + 0.1393N_i + 1.23 - T_i)^2\right]^{\frac{1}{2}} \quad (11)$$

where D_{av} = average deviation, T_i is the actual transaction time.

Let each average transaction size be S_0. Then the number of transactions included in each block is:

$$K = Z/S_0 \quad (12)$$

The number of transactions per second is established as K/T. Thus, combining (10) and (12) gives (13).

$$K/T = Z/(S_0(0.012Z + 0.1393N + 1.23)) \quad (13)$$

In (13), it can be seen that K/T is inversely proportional to N and Z. Thus, the transaction speed (K/T) increases as the number of nodes and/or block size decreases. Also, the transaction speed variation is more influenced by the number of nodes than the block size.

The blockchain-enhanced model can be applied in the real microgrid transaction via a "smart contract" automated system comprising an E-Ledger in which every transaction records and data amongst the participants in the microgrid is stored and maintained. It is also applicable in the business pricing and billing process. The smart contract houses every transaction protocol as agreed in consensus amongst the entire participants.

V. CONCLUSION

The enhancement in the robustness of the energy trading scheme to enhance transaction data throughput was described. Following the 57.7% transaction time reduction in model 1 relative to model 2, it is conclusive that transactions are faster in blockchain consortium with optimized transaction permission protocol. Since it is found that the number of nodes has a greater effect than the block size on the transaction speed, the speed is hence better improved by regulating the number of nodes more than the block size. The consequent improvement in the transaction speed would lead to a reduction in the transaction data storage size requirement. The ripple effects include an enhanced energy purchase system, a consequent increase in trade deals which enhances the energy demand and supply balancing system, reduced cost of energy purchase, and improved generation-load matching scheme. The knowledge of the transaction speed assessment would improve the entire transaction approach. Future research expectation would be to examine a more robust means to keep a track of the actual quantity of energy delivered, other than smart meter values, to detect and prevent possible adversary manipulations and attack.

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