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# Evaluation of a Simulated Blockchain-based P2P Energy Trading System using an Isolated Rural Area Load Profile

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## Abstract

This study developed a blockchain-based P2P energy trading system and assessed this against IEEE Std 1547.3. The system, which is not internet-dependent, was evaluated using an isolated rural area model to test the performance on a larger network. Three performance metrics were investigated: throughput, latency, and reliability. Test results show that the network throughput is below the standard value of 9.6 kbps. This suggests that the system does not have enough network activity to push above the standard value. Additionally, the minimal data used by the system resulted in very low network latency as compared with the 15-second latency specified in the standard. The system was found to have a reliability of 86.31%, which is lower than the 99.9% standard. This can be attributed to the limitations in the processing capacity of the microcomputers used. Overall, the developed system allowed local energy trades in the simulated networks and still did not use all network resources when simulated on a 60-node isolated rural area network model.

**Keywords:** IEEE Std 1547.3, renewable energy sources, distributed energy resource, Go Ethereum

## Introduction

With the increasing popularity of renewable energy sources (RES), together with developments in the field of Internet and Communication Technology such as smart meters and smart grid, consumers can now use RES to generate their energy. This allowed the formation of local energy trading platforms where local consumers, producers, and prosumers can trade energy locally within the microgrid which is known as peer-to-peer (P2P) energy trading (Schollmeier, 2001). P2P energy trading is different from traditional grids such that consumers will have more options at competitive prices while producers can differentiate their energy, allowing for more competitiveness in the market (Zhang, Wu, Zhou, Cheng, & Long, 2018).

Several efforts were made to develop a decentralized P2P energy trading system. An Arduino microcontroller has been used as node in a blockchain-based P2P energy trading system (Baig, Iqbal, Jamil, & Khan, 2020). However, this system is limited to the computing capacity of the microcontroller used, which may be a problem when dealing with topologies with greater number of nodes. This problem may be addressed by using a Raspberry Pi microcomputer that has a higher computing capacity than an Arduino microcontroller (Kwak & Lee, 2021). Other works used computers to simulate constant network topologies and have demonstrated that blockchain-based P2P energy trading generally increased revenue (Li, Zhang, Chen, Qian, & Xu, 2019) and decreased energy procurement cost (Alskaif, Crespo-Vazquez, Sekuloski, Leeuwen, & Catalao, 2021), as the traditional middle manager is removed.

To the best of the authors' knowledge, however, the above works have only performed functional tests on their developed systems and did not evaluate these against IEEE Std 1547.3, which provides a guideline for monitoring, information exchange, and control for distributed resources interconnected with electric power systems (IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems, 2007). In addition, these works relied on an active internet connection to perform transactions. This poses as a challenge in rural areas where the issues of non-electrification and lack of internet connections are noted.

This study aims to develop a blockchain-based P2P energy trading system and assess it against IEEE Std 1547.3 with its three key metrics: throughput, latency, and reliability. The system will be evaluated using an isolated rural area load profile, being a perfect candidate in applying an internet-independent energy trading system due to the geographical barriers that greatly limit the logistics to and from the area (Bennett, Borders, Holmes, Kozhimannil, & Ziller, 2019) and the lack of internet and mobile connectivity (Correa & Pavez, 2016). In addition, there has been an increase in electricity consumption in rural areas due to continued electrification as well as an increase in the usage of RES (Yao, Chen, & Li, 2011).

The envisioned system will use a microcomputer that functions as a smart meter and the main access point for each user on the system. Additionally, a digital asset called "tokens" will be used to represent the energy generated by a node. Instead of a centralized control system where energy is distributed by considering the generation and demand of the whole system, the nodes will directly request energy from producers or prosumers, making the whole energy distribution more dynamic. When energy is generated by the RES, equivalent tokens will be generated by the hardware and before storing the energy to the node's energy storage. Conversely, when the node consumes energy, equivalent tokens will be deducted so that the coins will always match the energy that can be traded. Thus, the tokens are the digital representation of the energy that a node currently has. By trading tokens in the P2P system, the corresponding amount of energy will be transferred as well. Go Ethereum (Geth) client implementation will be used to run nodes in the network, as it is open-source and claimed to be the most popular Ethereum client. The whole system will run on a virtual private network and will not be dependent on an active internet connection.

## Methodology

### *System Design*

The P2P energy trading system was simulated to allow multiple prosumers and consumers in isolated rural areas to trade energy locally. The process of P2P energy trading is a recurring cycle consisting of three phases: transaction, solution, and execution. The transaction phase is the period where transactions are initiated and queued. All the transactions are collected to be processed in the next phase. In the solution phase, an optimal solution (or as close to optimal as possible) will be generated. Solving all the transactions at once instead of executing each transaction as it was posted will allow for more efficient use of the network resources. The execution phase is where the solution is executed, and power is transferred from node to node. Figure 1 shows the detailed process flow for one cycle.

The transaction phase is the period where nodes can initiate transactions with other nodes. It is in this phase where each node tries to fulfill its energy demand by finding producers or prosumers to trade with. For this system, the process of initiating transactions is very simplified not only due to the assumed absence of internet connectivity but also to make the process more accessible and user-friendly. This simplification potentially removes the technological barrier for the users making the system more accessible to users. The buyers initiate transactions by going to the seller in person and trade cash for energy. Once the rates are agreed upon, the

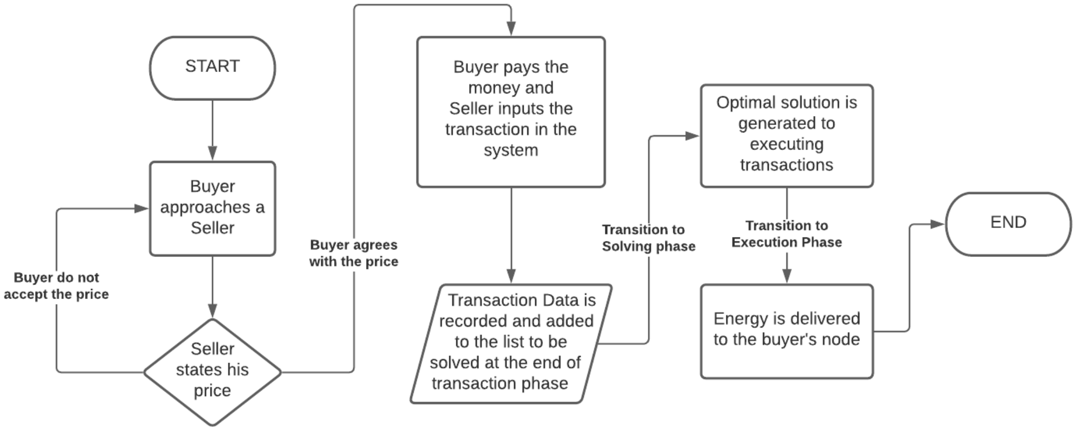

**Figure 1.** Detailed flow chart for a single cycle

seller will input the transaction in the terminal of the microcomputer to be processed. While it may seem that the face-to-face transactions may be inefficient or very primitive, it solves two of the design constraints. The system is not connected to the internet and mobile network is not guaranteed. Thus, meeting face-to-face is preferred. Additionally, this process avoids the need for sellers and buyers to learn the complexity of market trading. Finally, it ensured that the payment is passed to the seller and lets the system guarantee that the transactions are honored.

During the solving phase, all the transactions are analyzed to try to generate an optimal solution when executing all the transactions. Since the network topology is random, chokepoints and multiple paths can appear. Chokepoints can cause a major problem as it can slow down the execution phase of the whole system. This system tries to generate an optimal solution so that all transactions can be completed on time.

During the execution phase, the purchased energy will be sent to the buyer's node. Depending on the solution, this phase can take a long time. After all energy transfers are complete, a report of the energy transaction for the node will be available so that the node can verify the transactions. If a node fails to provide the promised energy, the report can be used as proof to negotiate compensation from the seller. Additionally, repeat cases of not delivering promised power will result in lower priority during the solution phase.

### *Rural Load Profile*

In making plans for the development of rural electrification, consumer load profiles will help design electrical systems to be used in the area since it helps in optimizing the system design which reduces initial costs as well as saving long-term costs. However, as rural areas often have a low rate of electrification or have no prior electrification at all, their load profile is also non-existent or may not be a good indication of their energy usage since their energy usage may change when they have access to electricity. This load profile uncertainty was considered by Mandelli, Brivio, Colombo, & Merlo (2016) in designing off-grid PV systems. On the other hand, an estimated optimized load profile for rural areas shown in Table 1 and Figure 2 below may also be adopted (Javed, Ashfaq, & Singh, 2018). Additionally, Figure 2 shows the corresponding load profile for 24 hours. The optimized load profile was generated based on the energy usage habits in the city centers and then optimizing it based on the energy availability as well as the storage life and performance.

Aside from the lack of electrification, another challenge in rural areas is the lack of internet and

**Table 1.** Optimized rural load profile from (Javed, Ashfaq, & Singh, 2018).

| POWER CONSUMPTION | | | | | | |
|---|---|---|---|---|---|---|
| Load | Quantity | Power Consumption (W) | Total Power (W) | Operating Time | Uses (h/day) | ENERGY REQUIRED (Wh/day) |
| Lamp (LED) | 10 | 20 | 200 | 8h @ Day Time<br>12h @ Night Time | 20 | 4000 |
| Fan | 4 | 60 | 240 | 10h @ Day Time<br>10h @ Night Time | 20 | 4800 |
| TV/PC | 2 | 80 | 160 | 6h @ Day Time<br>2h @ Night Time | 8 | 1280 |
| Domestic Appliances | 5 | 100 | 500 | 4h @ Day Time<br>1h @ Night Time | 5 | 2500 |
| Other Uses | 5 | 100 | 500 | 2h @ Day Time | 2 | 1000 |
| **TOTAL** | | | 1600 | | | 13580 |

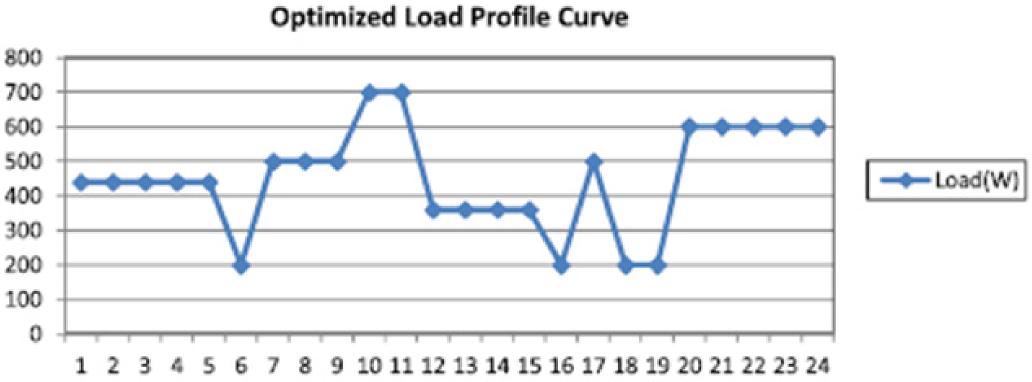

**Figure 2.** Optimized load profile curve from (Javed, Ashfaq, & Singh, 2018).

mobile connectivity (Correa & Pavez, 2016). The isolation as well as the low population density make the construction and maintenance of the needed infrastructure not economically feasible.

*P2P Network Setup*

Go Ethereum (Geth) client implementation was used to run nodes in the network. Geth makes it possible to run multiple nodes in one machine which are called local nodes. These local nodes are just like normal nodes, but it allows simulation of blockchain networks with a limited number of actual machines which greatly helped in development. For this study, the local nodes were restricted to only accept connections from set neighbors to mimic wired connections. Additionally, when a node connects to the network, it does not have any information about the network. To remedy this, the new node inquires the node it connects to the information of the network such as the neighbors in the vicinity, the state of the blockchain, among others.

### *Blockchain*

This study used a type of blockchain called private local blockchain. Private local means that the network will not be exposed to the internet and will be running a separate blockchain from the main Ethereum blockchain. Running a local private blockchain in geth involves creating the genesis block and changing the network ID of the blockchain network. The genesis block is the first block of the blockchain and all nodes in the same blockchain network must be initialized from the same genesis block. The network ID is just an integer value used to differentiate blockchain networks on the internet and has no other bearing on the network. For example, the network ID of the mainnet is 1. Since the system to be developed was not connected to the internet at any point, it was enough that all the nodes will connect to the same network ID

If the blockchain is treated as a database, smart contracts are the way to manipulate the data on the blockchain. Smart contracts are pieces of code that are embedded on the blockchain that all nodes can request to execute. For this study, one smart contract was deployed on the blockchain to facilitate the energy trading system. This smart contract handled the process of the P2P energy trading system itself; it included functions such as managing transactions, validating transactions, and keeping track of the tokens. Additionally, it was also responsible for the generation and consumption of tokens depending on the energy usage of the node.

Metric data of each node were pushed on an external time-series database, influxdb, and then visualized with Grafana, a free dashboard for visualizing time series data. Figure 3 shows an illustration of the data flow. From Grafana, the metric data was visualized and be queried for time series data which can be processed.

### *Performance Metrics*

According to IEEE Std 1547.3, there are four metrics to evaluate the performance of the communication and monitoring systems used in distributed energy resource (DER) applications: throughput. latency, reliability, and security. Throughput refers to the amount of information that the communication network can handle continuously. It is measured in terms of kilobits per second (kbps). Next, latency is the time delay between the issuance of a command and the completion of the command. Examples of commands can include information requests, remote activation of equipment, among others. Latency is measured in seconds. Reliability refers to the mean time between failures. It is usually expressed as the expected time between communication failures and can be caused by hardware or software failure. Finally, security

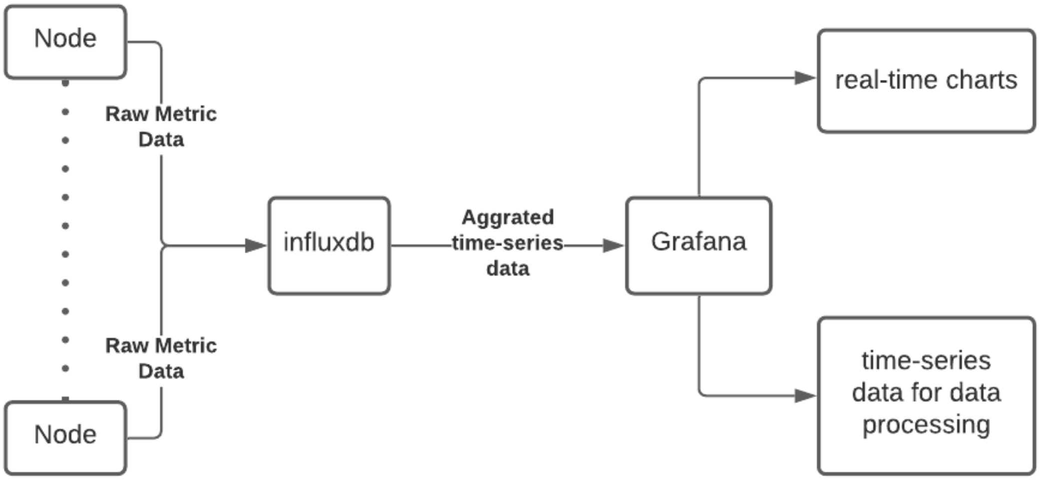

**Figure 3.** Diagram of the information flow of the metrics data

refers to the ability to protect the communication system from unauthorized access. The unit can be time-based (the time it takes to breach the security), probability-based (probability of an attacker to gain access), or cost-based (amount invested resources needed to defeat the security) depending on the type of security measures implemented. For this study, security tests were not performed due to its high complexity nature and the rapidly changing security landscape. The evaluation solely focused more on the other three parameters. Additionally, the established communication system requirements in microgrid settings in Table 2 was adopted.

*Simulations*

Three Raspberry Pi 4B microcomputers were used to create simulated nodes. Each microcomputer can run 20 simulated nodes at a time. A network switch was also used to establish connection between the microcomputers. This is illustrated in Figure 4.

Random network topology was generated based on the real-world rural characteristics. The nodes used rural load profiles defined in Figure 2. The number of nodes used, 60, was based on the number of households in an isolated rural area. Specifically, barangay Convento (Pob.), Cagayancillo, Palawan. As of 2015, the population is 310 and the number of households is 59 (Philippines Statistics Authority, 2016). The municipality is located 330 km east of Puerto Princesa City, near the middle of the Sulu Sea. Geographically, the municipality is composed of islands spanning 26.39 km$^2$ surrounded by low reefs (Philippine Statistics Authority, 2016).

Networks were represented by an adjacency list. In this case, from an initial list of nodes, a random network was randomly generated by adding random neighbors to each node. The nodes were initialized so that only connections from neighbors were accepted. Additionally, the nodes were assigned the roles of consumers and prosumers randomly, where the only difference between them is that prosumers gained tokens at the start of each cycle. For each test, a random network was generated, and 10 cycles were simulated where each node tried to trade energy until it had enough energy for the day as indicated in the optimized rural load profile in Figure 2. For simplicity, all the prosumers were considered to have solar RES so that sunlight data from National Renewable Energy Laboratory's RE explorer tool can be used to simulate power generation. The scale and size of the solar RES for each prosumer were randomized as well but limited to residential size. Metrics were recorded

**Table 2.** Summary of the metric standards for energy applications.

| APPLICATION | LATENCY | THROUGHPUT (kbps) | RELIABILITY (%) | SECURITY |
|---|---|---|---|---|
| DER and Storage | <1 ms – 1.5s<br>15s (E2E) | 9.6 – 56 | 99-99.9 | High |
| EV Charging | 2 s – 5 m | 9.6 – 56 | 99-99.9 | High |
| Smart Meter | Variable | 10/m | >98 | High |
| Home Energy Management | 300 ms – 2 s | 9.6 – 56 | >98 | High |
| Demand Response | <1 m | 14 – 100/node | >99.5 | High |
| DCS | <5 s | 120 - 144 | >99.5 | High |
| Meter data Management | 2s | 56 | 99 | High |
| Asset Management | 2 s | 56 | 99 | High |
| Home/Building Automation | Seconds | 4.8 – 48 | >98 | High |

*Source:* (Jogunola, et al., 2018)

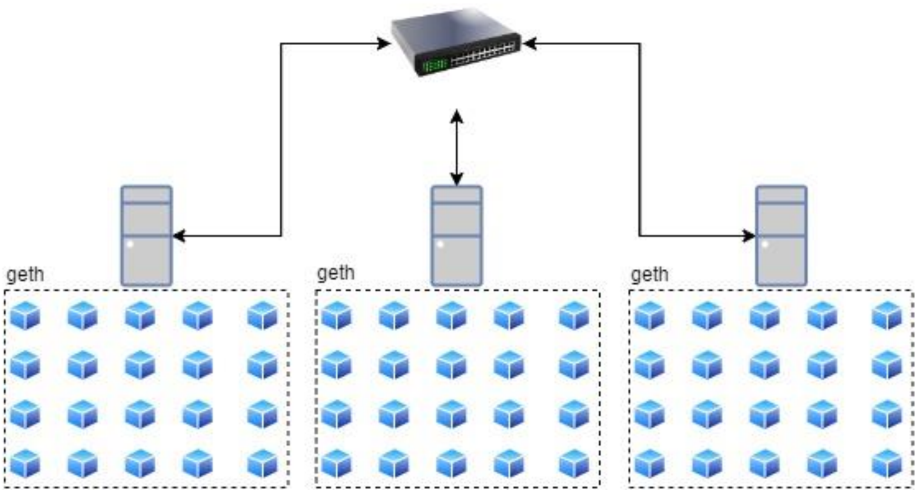

**Figure 4.** Interconnection of the devices used.

and compared to the standards defined in Table 2. For throughput, the network traffic data was used while for the latency, block propagation data was used. 10 test runs of 10 cycles each were simulated so a variety of the networks were considered as well as see the performance of the nodes through multiple cycles.

One-sample Wilcoxon signed-rank test was used to test the network latency and throughput to ensure that the developed P2P energy system is within the standards. To test the reliability of the data generated, a static network configuration was generated and 10 repeated tests of 10 cycles are done on that static network. Spearman's rank correlation coefficient was used to determine the reliability of the system.

## Results and Discussion

### *Network Throughput*

Figure 5 shows the aggregate network traffic data of all the nodes during the simulations

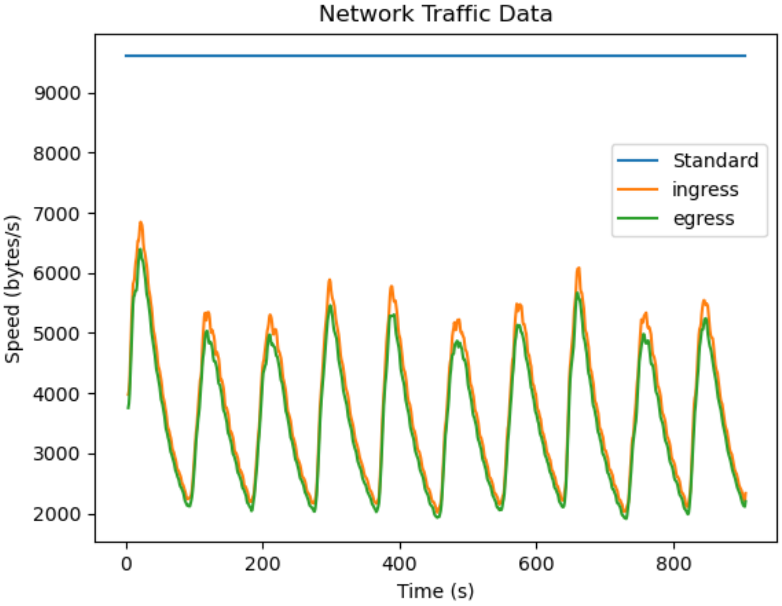

**Figure 5.** Time series data for network throughput

**Table 3.** Result of the one-sample Wilcoxon signed-rank test for the network throughput in reference to the standard

| | STATISTIC | P-VALUE | DECISION |
|---|---|---|---|
| ingress | << 0.05 | 1.00 | Fail to reject Ho |
| egress | << 0.05 | 1.00 | Fail to reject Ho |

including the standard defined in Table 2. Ingress is the rate of data entering the node while egress is the rate of data going out of the node. For this metric, a one-sample Wilcoxon signed ranked test is used to determine if the given data is higher or lower against a standard. The null hypothesis for the one-sample Wilcoxon signed ranked test used is that the target data's median is lower than the standard while the alternative hypothesis is that the target data's median is higher than the standard. Table 3 shows the result of the one-sample Wilcoxon signed ranked test for both ingress and egress. Both test results accept the null hypothesis signifying that the network throughput data of the simulated network is below the standard.

Based on Table 2, the standard for network throughput is 9.6 kbps while the mean of the gathered data for network throughput is 3.75 kbps for the ingress and 3.52 kbps and average peaks of 5.99 kbps and 5.46 kbps for ingress and egress, respectively. Although the resulting network throughput data is below the standard, it does not mean that the developed P2P energy trading system process data slower than the standard. It is mostly attributed to the lack of network traffic on the network itself. Additionally, the number of nodes is on the lower side and the information transferred over the network is also on the smaller side since the transmitted data mainly consists of transaction data. Based on Figure 5, there is still a noticeable increase and decrease in the speed of ingress and egress. This coincides with the cycles of the system. The bulk of the transactions was submitted during the transaction period which increased the data transmitted, which resulted in the increased ingress and egress. On the other hand, the decrease in speed is attributed to the solving and execution phase. During these phases, there is not much data transferred so the ingress and egress fall.

### *Network Latency*

Figure 6 shows the aggregate network latency of the network during the simulations. Receive to announce and receive to broadcast are under the block forwarding category while execution, validation, and commit are under the block processing category. The block forwarding category involves the sending and receiving blocks. On the other hand, execution, validation, and commit are internal processes involving the blocks themselves. In this case, execution is the time needed to execute transactions and smart contracts, validation is the time needed to check if the block is valid, and finally, commit is the time needed to store the block on the blockchain. Based on Table 2, there are two standards for latency involving DERs and storage. The standard for energy-to-energy (E2E) communication is much higher as this involves relatively slow equipment. For this metric, one sample signed Wilcoxon signed ranked test is used to determine if the target data is higher or lower than the standard. The null hypothesis for the one-sample Wilcoxon signed ranked test use is that the target data's median is lower than the standard while the alternative hypothesis is that the target data's media is higher than the standard. Table 4 shows the results of the one-sample Wilcoxon signed ranked test for the network latency data against the two standards. Both test results accept the null hypothesis signifying that the network latency of the simulated network is below the given standard.

Based on Table 4, the network latency of the simulated network is below both the normal and E2E standards. Table 2 shows the normal standard for latency is between 1 ms and 1.5 s and the E2E standard is 15 s; meanwhile the mean of the gathered data for latency is 405 ms. The lack of network latency is also attributed to the low node count as well as the minimal data

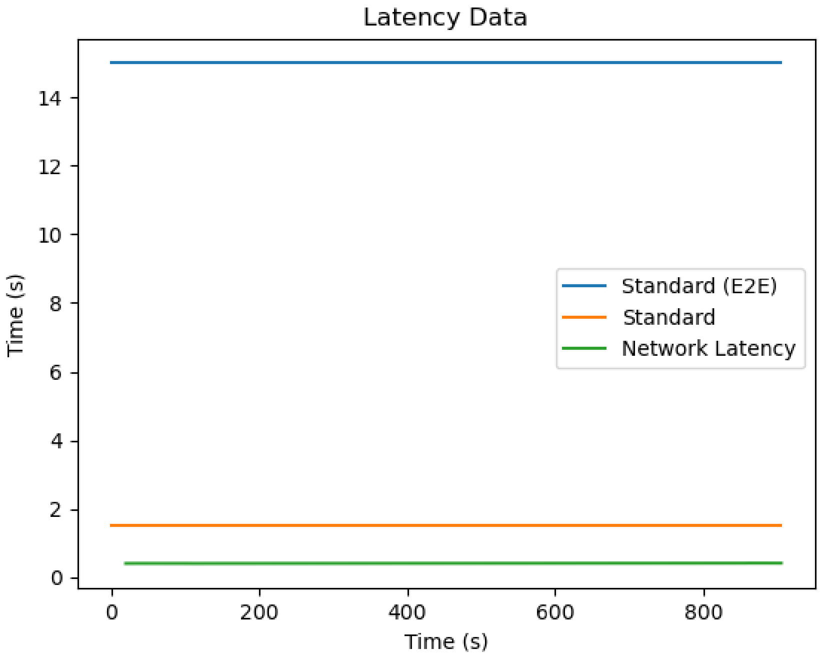

**Figure 6.** Time series data of the network latency

**Table 4.** Results of the one-sample Wilcoxon signed-rank test for network latency data in reference to the standard.

| | STATISTIC | P-VALUE | DECISION |
|---|---|---|---|
| Against standard | << 0.05 | 1.00 | Fail to reject Ho |
| Against E2E standard | << 0.05 | 1.00 | Fail to reject Ho |

transferred over the network. Note that this low latency data refers to the time needed for the node to process the incoming block and store it on the blockchain as well as announce and share it to other nodes. Essentially the network latency data gathered just refers to adjacent node-to-node latency, which means that for nodes not connected and far apart, the network latency stacks up. This is the reason why increasing the number of nodes and increasing peer-to-peer connections results in much lower total network latency.

### *Reliability*

For the reliability metric, 10 tests are run on the same network with the same random seed so that all the random choices will be the same for every test. Spearman's rank correlation coefficient is used to determine if there is a correlation between the tests. The null hypothesis is that there is zero correlation between the datasets while the alternative hypothesis is that there is a correlation between the datasets. Table 5 shows the result of Spearman's rank correlation coefficient on the static network. All test results reject the null hypothesis, signifying that there is some form of correlation across the tests.

**Table 5.** Summary of the Spearman's rank correlation coefficient

| | STATISTIC | P-VALUE | DECISION |
|---|---|---|---|
| Network Latency | -0.2362 | << 0.05 | Reject Ho |
| Ingress | 0.86301 | << 0.05 | Reject Ho |
| Egress | 0.8686 | << 0.05 | Reject Ho |

Table 5 shows the results of the reliability test using Spearman's rank correlation coefficient. While all test results signify that there are correlations between the tests, all statistic values are below the standards defined in Table 2. The reliability statistic for the network throughput data ingress and egress is on the higher side just below the standard which is 99.9%. Since the network configuration and all random choices will return the same result in every test, the main reason for the loss of reliability is the block processing timing of the miners. Due to the limited processing capacity of the microcomputers used on the simulated network, only a select few nodes are miners. In ideal conditions, all the nodes should also be a miner which should reduce the downtime of miner nodes. This further increases the block processing power of the whole network, reducing or eliminating the queuing of transactions to be processed.

On the other hand, the network latency data has a negative statistic which means that there is a negative correlation between the tests. The most likely reason for the negative correlation of the network latency data is that the network latency data have a narrow range of values of about 402 ms to 412 ms, which makes a slight variation of the data heavily affect the overall test result of the network latency data.

## Conclusion

This study developed a blockchain-based P2P energy trading system and assessed this against the three parameters stipulated in IEEE Std 1547.3 – throughput, latency, and reliability. Due to the small node count and minimal data used by the system, the network throughput of the system is below the standard. This is not to say that the system is not performing badly, it only means that the system does not have enough network activity to push above the standard for network throughput. In the same vein, the minimal data used by the system resulted in very low network latency.

With regards to the reliability of the system, the network throughput has a reliability statistic of 86.31%, which is below the 99.9% standard. On the other hand, the range of the values of the network latency is very small, that is, between 402 ms and 410 ms, way below the 15-second latency specified in the standard. This resulted in slight fluctuations having significant effects on the overall statistic. Overall, the developed system, which is not dependent on an active internet connection, allowed local energy trades in the simulated networks and still did not use all network resources when simulated on a 60-node isolated rural area network model. Theoretically, these results will be true also for a rural area with the same load profile and number of nodes considered in the study. The results may be different for a network model with a greater number of nodes. Future works may consider other load profiles wherein more transactions are needed to fully test the capability of a blockchain for P2P energy trading system based on IEEE Std 1547.3.

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