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# Blockchain at the Edge: Performance of Resource-Constrained IoT Networks

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**Abstract**—The proliferation of IoT in various technological realms has resulted in the massive spurt of unsecured data. The use of complex security mechanisms for securing these data is highly restricted owing to the low-power and low-resource nature of most of the IoT devices, especially at the Edge. In this work, we propose to use blockchains for extending security to such IoT implementations. We deploy a private Ethereum blockchain consisting of both regular and constrained devices connecting to the blockchain through wired and wireless heterogeneous networks. We additionally implement a secure and encrypted networked clock mechanism to synchronize the non-real-time IoT Edge nodes within the blockchain. Further, we experimentally study the feasibility of such a deployment and the bottlenecks associated with it. We study the effects of network latency, increase in constrained blockchain nodes, data size, Ether, and blockchain node mobility during transaction and mining of data within our deployed blockchain. This study serves as a guideline for designing secured solutions for IoT implementations under various operating conditions such as those encountered for static IoT nodes and mobile IoT devices.

**Index Terms**—Internet of Things, blockchain, Edge nodes, Ethereum, Constrained-networks

## 1 Introduction

The major challenge associated with IoT-based systems is the issue of ensuring the security of data being handled by such systems, besides the regular challenges of connectivity, address reuse, energy efficiency, and mobility. Typically, due to the challenging issues of massive deployments, the presence of constrained networks, and often characteristically constrained nature, IoT devices themselves, the ensuing IoT ecosystem has inherent vulnerabilities. A majority of the present-day IoT solutions are plagued by vulnerabilities, which are challenging and which make them prone to easy manipulation and disruption. Some of the common vulnerabilities are weak or hardcoded passwords, insecure network segments, poorly protected interfaces and data access mechanisms, insecure data transfer mechanisms, and others. Furthermore, the massive deployments of IoT devices often make it impossible for a network administrator to track-down malicious or compromised devices amongst the deployed devices.

The issue of designing practical solutions for securing IoT data, especially in terms of speed-

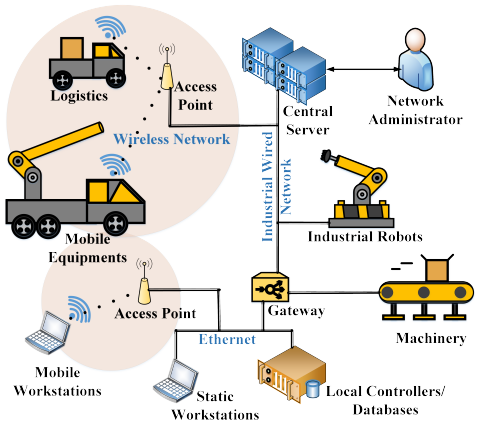


Fig. 1: An outline of a typical IoT-based Industrial ecosystem.

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ily ensuring trust, integrity, and non-repudiation, hinges on the nature of the devices, its energy efficiency, and mobility associated with it. The nature of the devices in IoT, especially at the Edge is vastly heterogeneous. As the Edge IoT devices mainly focus on ensuring low-power connectivity and basic computation, a significant chunk of these Edge devices making up this paradigm does not possess sufficient processing power or resources to host conventional network security mechanisms. Typically, IoT Gateways are popularly associated with providing security to the IoT devices/nodes under its operational purview. The current state-of-the-art IoT infrastructure relies on a centralized Gateway to process and aggregate data from IoT devices [1]. The centralized Gateway plays a vital role in ensuring the security of the sensed data.

However, the next generation of mobile communication technology is enabling device-to-device communication where billions of IoT devices are expected to exchange sensed data with each other in cities, industries, homes, and other ecosystems. These devices not only sense and transmit data but also perform actuation based on the data received from other IoT devices. This trend clearly shows that the existing centralized approach cannot be scalable and will soon become a bottleneck. Therefore it is inevitable to use distributed technologies to replace the role of the Gateway as this approach often leaves the IoT nodes under the domain of a Gateway, quite open to security breaches such as unauthorized access to data directly from the Edge devices. Additionally, the dilution of hard requirements for devices to be static or mobile in an IoT ecosystem, further complicates issues as customized solutions for one cannot be used for the other. Rather than focusing on traditional security solutions, which rely majorly on remotely hosted security mechanisms such as at Cloud or centralized Gateways, the requirements of IoT-based systems necessitate distributed solutions [2]. These distributed solutions primarily focus on the IoT devices at the Edge [3] or even utilize hardware-based security [4].

Towards this objective, we analyze the performance and feasibility of using blockchains – a promising distributed security paradigm for ensuring data security for IoT-based systems [5]. To secure the data generated and exchanged between IoT devices in a distributed manner, we propose the use of low-power IoT Edge nodes as the blockchain nodes. These nodes are not only capable of continuing their regular sensing and actuation tasks, but also perform necessary blockchain functions such as verification, mining, and transactions. In this work, we deploy a private Ethereum blockchain consisting of IoT Edge devices as its nodes and experimentally verify the performance of this approach to usher-in a low-power and mobile blockchain-based IoT ecosystem. Architecting a blockchain-based solution for IoT systems at the Edge requires addressing the following challenges:

- More the number of Edge devices in the IoT ecosystem that is part of the blockchain, more is the work-load of each of these blockchain nodes. The generally constrained nature of the network associated with the IoT systems/devices further makes it challenging for the devices to partake in network-based blockchain operations reliably.
- Blockchains require real-time synchronization between its nodes. Most of the constrained IoT Edge devices do not have an internal clock for time synchronization, making it necessary to come up with solutions to address this lacuna.
- The resource-constrained nature of most of the Edge IoT devices require mechanisms to handle processing-heavy blockchain-based operations.

### 1.1 An IoT-based Industrial Ecosystem Application Scenario

We envision a real-life use case of an IoT-based industrial ecosystem for motivating the applicability of this work. Fig. 1 shows the significant physical and infrastructural components of an industrial complex. We choose an industrial complex primarily because of the massive density of deployed Edge devices, and the constrained nature of the network arising due to the high density of these devices and challenging areas of implementation – prone to interference and noise from the environment. Furthermore, industrial complexes are an excellent example of the use of heterogeneous networks, which take care of functions starting from process monitoring, security, tracking, logistics, to even regular communication with the outside world.

The networks on the factory floors are typically wired and resource-constrained. Constraints to network and device capabilities are automatically induced in such ecosystems due to the presence of dedicated automation and control systems working with new as well as legacy infrastructures. It is common to see both wireless and many variants

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of wired connections for communication in industrial ecosystems. In continuation, the heterogeneity in devices in terms of their mobility, processing abilities, and energy consumption also makes it a challenging environment for implementing secure IoT systems.

The amounts of data generated and flowing through the network in an IoT-enabled industrial ecosystem are quite massive. However, most of the data and systems – typically Edge devices – are insecure and open to unauthorized access and manipulation. Here, we envision the use of blockchain to provide a layer of security to the connection and communication between all the devices within an industrial setting. The use of blockchain introduces the features of transparency and traceability to the IoT data generated within the industrial ecosystem. Additionally, the distributed nature of Blockchains prevents single-point-of-failures for the whole network under severe working conditions, typically associated with industries. Both constrained IoT Edge nodes, as well as regular computing stations, can be incorporated within this setting. In our experimental evaluation, we fashion the blockchain nodes as such that they consist of both regular computing platforms such as PCs as well as constrained IoT Edge nodes consisting of Raspberry Pi boards (refer to Table 1). In such scenarios, our proposed evaluation provides critical insights into the challenges and limitations of deploying a decentralized blockchain-based provision of security for the IoT-based systems and devices.

### 1.2 Contributions

The constrained nature of the devices at the Edge is the main reason for the lack of decisive security schemes and measures for protecting communication integrity at the Edge or within the operational range of IoT gateways. The nature of the data plays a decisive role in evaluating the requirements of security and privacy to be used at the IoT devices. For example, the requirements of security and privacy are very high for healthcare IoT data. In contrast, the requirements are moderate to low for data originating from general sources, say, agriculture or traffic. However, the integrity of data is an irrefutable need for all IoT data types and needs, which is ensured by the private blockchain.

In this work, we incorporate the heterogeneity of IoT devices by including both small nodes – constrained, with fewer resources and processing power – and large nodes – nodes with abundant resources and processing power. Further, we incorporate network heterogeneity in our implementation by making use of both fixed Ethernet-based network connections as well as including WiFi-based connections. The inclusion of network heterogeneity allows us to include the feature of mobility in some of the IoT Edge nodes, while the rest of the nodes in the blockchain remain static. The static nodes are connected to an Ethernet-based network, whereas the mobile nodes connect to the blockchain through WiFi, as outlined in Fig. 2. We undertook this work to fill in this gap by evaluating the various interactions of constrained IoT devices with blockchain networks, even when they have heterogeneity in their connection and/or are mobile. Besides, typical device and blockchain performance measures, we also evaluate the performance of various encryption algorithms such as the RSA and 256-bit AES along with the blockchain to secure our implemented IoT network further.

### 1.3 Related Work

There have been several efforts in the past to use blockchain with IoT devices. Wu *et al.* demonstrate a system comprising of private and public blockchain for secure and efficient storage of data [6]. The private blockchain ensures the accuracy of a transaction, whereas the public blockchain ensures its data integrity. Similarly, Wu *et al.* propose the inclusion of an additional device to check for certain characteristic features in the received messages [7]. The results of the verification are saved on the blockchain, which ensures that even in the case of loss of key to unscrupulous entities, the unauthorized hijacking of IoT devices is prevented.

TABLE 1: blockchain node specifications for our implementation

| Features | Node-1 | Node-2 | Node-3 | Node-4 |
|---|---|---|---|---|
| Device | Raspberry Pi3-B+ | Raspberry Pi3-B+ | Dell Power Edge T410 server | Raspberry Pi3-B+ |
| Processor | Quad Core 64 bit ARM cortex at 1.2 GHz | Quad Core 64 bit ARM cortex at 1.2 GHz | 16x4 Core 64 bit at 2.67 GHz | Quad Core 64 bit ARM cortex at 1.2 GHz |
| RAM | 1 GB | 1 GB | 32 GB | 1 GB |
| Network connection | Ethernet | Ethernet | Ethernet | WiFi |

Dorri *et al.* demonstrate the efficient use of Blockchains in IoT systems by replacing the proof-of-work (POW) by a distributed trust algorithm

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[8]. This effort has resulted in substantial energy savings during the process of mining within the blockchain. Another work, by Fan *et al.* proposes the use of a delegated proof-of-stake (DPOS) instead of POW to ensure adequate provision of privacy in Blockchains [9]. Other approaches use proof-of-authority (POA) such as the one demonstrated by Angelis *et al.* [10]. Similarly, the extra use of smart contracts in large IoT Blockchains requiring time synchronization has been proposed by Huh *et al.* [11], whereas Cha *et al.* demonstrate the use of smart contracts with blockchain hosted in an IoT Gateway for enabling IoT Blockchains [12]. Rahulamathavan *et al.* proposed an advanced encryption technique for IoT networks to enable fine-grained access and verification necessary for ensuring privacy in the blockchain [13].

Blockchains have found beneficial use in several application areas such as smart cities [14], healthcare [15], crowd-sourcing [16], and others. Blockchain-based solutions to extremely critical domains such as healthcare are making use of Blockchains to store patient's data securely and privately [17], and through smart contracts, the need for seeing the data is also done away with [15].

## 2 System Model

In this work, we implement an Ethereum-based blockchain on heterogeneous IoT nodes, some of which connect to the blockchain over an Ethernet-based connection, whereas the others connect through a WiFi-based connection, forming a hybrid network connection as shown in Fig. 2. Further, adding to the device heterogeneity, the devices themselves have different specifications and processing capabilities, as outlined in Table 1.

IoT nodes have unique "ENODE" values and connect using these values. The "ENODE" value consists of a public key, an IPv4 address, and a port number. Simulating a real-life IoT implementation, we have incorporated heterogeneous IoT nodes, some with low processing power and reduced energy requirements (i.e., Raspberry Pi) and some with high processing power and more significant energy requirements (i.e., server, PC). The Raspberry Pi-based nodes connecting over WiFi are considered as mobile and treated as such during the performance evaluation of our setup. However, these IoT nodes in our blockchain are capable of independently handling their transactions as well as mining.

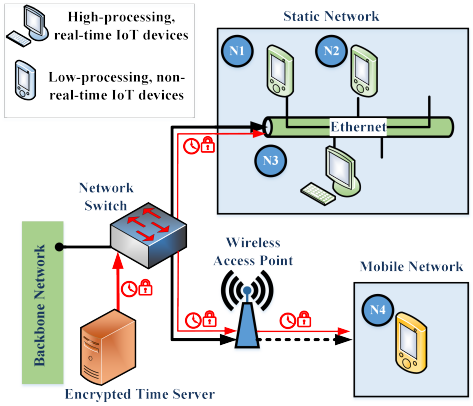


Fig. 2: The representative network architecture of our implemented IoT blockchain.

### 2.1 Incorporating blockchain for IoT

Fig. 2 outlines the representative network architecture of our implemented IoT blockchain. The network can be considered to consist of heterogeneous nodes (N1-N4). These nodes may consist of large static devices such as servers and PCs, or they may be small and portable consisting of Raspberry Pi boards. All these devices act as nodes in the blockchain. A switch connects an external backbone network to the internally formed network. The network connections from the switch may be either used for connecting physically to the IoT nodes through Ethernet or wirelessly through a wireless access point. An external encrypted time server is also used to provide network time synchronization to the IoT devices, which are mostly non-real-time.

TABLE 2: Specifications of our private blockchain

| blockchain specifications | Values |
|---|---|
| Gas limit (in Hexadecimal) | 0x47b760 |
| Gas limit (in Decimal) | 0x4700000 |
| Difficulty | 0x1 |
| Consensus Engine used | Clique - proof of authority |
| Time (in sec) each block takes | 5 seconds |
| Number of accounts on each node | 1 |
| Accounts which are allowed to seal | Accounts of all the nodes |
| HomesteadBlock | 1 |
| EIP150 Block | 2 |
| EIP155 Block | 3 |
| EIP158 Block | 3 |
| Gasprice for node 1 | $3 \times 10^{55}$ wei |
| Gasprice for nodes 2, 3, 4 | $3 \times 10^{28}$ wei |
| Syncmode | full |

We implement a private blockchain to account for the low-processing capabilities of the implemented IoT nodes, as well as keeping the data and

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transactions localized within an application area. Each of these nodes runs an Ethereum framework, the specifications of which are outlined in Table 2. Each of these nodes has an account associated with it over the Ethereum framework and uses a "CLIQUE- Proof of Authority (PoA)", instead of regular "ETHASH- Proof of Work (PoW)" to reduce mining times and reduce the average energy consumed by the nodes. The transaction of Ethers and data are performed based on the "ENODE" values of each node, which are subsequently mined by intended nodes. Post successful completion of a transaction, Ether balance is updated to a receiver node's account by the same amount it gets deducted from the sender's account. The Ether balance with the sender node was initially logged at $7.5^{19}wei$, the whole of which gets transferred to the receiver upon completion of a transaction. Unlike public blockchains, which deal with unknown and trustless systems, the private blockchains do not need an incentive-based mechanism to work.

We automate the process of an IoT node joining the blockchain, generating data, and performing transaction and mining operations. Algorithm 1 highlights this automation process. On power-up, each IoT node boots into a startup file containing the multi-threaded instructions and commands for time synchronization using the encrypted network-broadcasted time string and initialization of the node's Genesis file. Subsequently, each of the activated nodes checks for transaction data (to send or receive), which is then mined and submitted accordingly. Blockchain contracts can also be deployed similarly. Irrespective of a node's processing capabilities, the nodes are self-sufficient to carry out mining operations on their own. It is prudent to mention that in the absence of proper time synchronization, the connection between nodes is interrupted, resulting in association and disassociation with the blockchain. This drop in connection results in a significant increase in mining times at the affected nodes.

**Algorithm 1** Node automation

```
while DEVICE POWER ON do
    Locate node blockchain automation file
    Initialize Genesis file
    Start mining
    if (Transaction Data == TRUE) then
        Submit the transaction and generate receipt
    end if
end while
```

### 2.2 Encrypted Time Synchronization

A significant part of our private blockchain consists of non-real-time systems such as Raspberry Pi, which necessitates the need for a centralized time synchronization mechanism. Operations such as mining rely heavily on the synchronization of time and its maintenance between the nodes of the blockchain. Our implementation requires the communication of an encrypted time string to a node joining the blockchain for the first time or every time it is powered on. This provision has been kept mainly because of the absence of Real-Time Clocks (RTC) in the resource-constrained IoT devices. Every time these devices power-up, the internal clock resets to the default value, which is unlike personal computers or machines with RTCs. Further, unless the sender and receiver nodes have a common system time, network security provisions prevent them from communicating reliably, especially for blockchains.

Additionally, any external efforts to include a network-based time synchronization should be secure enough to ensure long-lasting and interference-free membership of the IoT nodes to the blockchain. In case the time server or any message generated from it is compromised or altered, the IoT nodes forming the blockchain will get dissociated, resulting in the breakdown of the blockchain. To avoid any such eventuality, we additionally implement the use of an encrypted time string from a centralized time server (refer Fig. 2), which can be read only by the member nodes of the implemented blockchain as outlined in Algorithm 2. The time server has a record of all the member nodes of the blockchain along with their "ENODE" values. The IP of each node corresponding to its "ENODE" value gets periodically updated at this time server. For our encryption, we adopt a *different node – different encryption* policy [13], which adds an additional level of security to our IoT blockchain. The synchronizing encrypted time string is customized according to each of the registered member nodes, which can only be decrypted by the target IoT node using its "ENODE" value as the private key. Any attempts to falsify or manipulate the IP address of the node or the ENODE address will result in a clash in the records at the server, alerting the network administrator of this attempt. As the server broadcasts the time strings over the blockchain network, all the nodes can see the encrypted message, but only the designated node with the proper "ENODE" value can decrypt it. The mapping of IP addresses and ENODE values also prevents the duplication of

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ENODE values by malicious nodes. Further, the encrypted time string meant for a node will be relayed multiple times, similar to a typical networking scenario, if the time server is not directly connected to the target node.

**Algorithm 2** Time Synchronization

**SERVER**
$n \leftarrow$ number of nodes
$message \leftarrow$ time string
Replicate $ENODE$ and $IP$ of all the nodes in the time server
**for** $i = 1$ to $n$ **do**
  $IP[i] \leftarrow IP$ of $i^{th}$ node
**end for**
**for** $i = 1$ to $n$ **do**
  $key[i] \leftarrow ENODE$
  Encrypt time string using $ENODE \rightarrow ENODE(message)[i]$
  **for** *all* $i$ **do**
    send $IP[i] \leftarrow ENODE(message)[i]$
  **end for**
**end for**
**RECEIVER (intended node)**
$TIME \leftarrow$ original time of the node
During node startup **DO**
Copy $ENODE \rightarrow$ file.txt
Receive encrypted time $T_{ep}$
Auto decrypt using $ENODE$ of the node $T_{dp}$
Set $TIME = T_{dp}$

This mechanism additionally implies that the nodes in the blockchain do not need to depend on each other for maintaining trust, which is quite useful as the nodes (IoT nodes) are typically low-resource ones and are susceptible to hijacking or alterations. In the event one of the nodes in our blockchain is somehow compromised, its effect would not flow over to the other nodes of the blockchain. Elaborating this scenario, consider all IoT nodes in the blockchain network receive a common encrypted/open time synchronization signal. If the synchronization signal is open, it is effortless to modify it and take down the blockchain, potentially resulting in severe economic and operational losses. Similarly, if the same encrypted time signal is used for all the nodes in the blockchain, and in the event that one of the nodes is compromised, the infected node might be used to forward wrong time signals to the nodes in the blockchain, again interrupting its operation. Therefore, our approach of using a node-specific encryption key for sending time synchronizing signals avoids both of the above scenarios.

Further, now, if someone outside our blockchain tries to receive the encrypted string and try to extract the information out of the encrypted string, our algorithm has ensured that even if they receive the encrypted string by forcefully setting their IP same as that of the IP of the true node of our blockchain, it can receive the encrypted string but not been able to decrypt it.

Concerning a Man-in-the-Middle Attack for modifying the time, the encrypted time server (refer Fig. 2) is tasked with periodically updating the mapping of ENODE and IP addresses of the participants in the private blockchain. As the ENODE values are unique to each blockchain node, these ENODE values can be uniquely mapped to the nodes' IP addresses. Even if there is a change in the node's IP address, the periodic check by the time server ensures its update in the mapping repository. Once a node with the proper IP address receives the encrypted time string meant for it, only it can decode it using its unique ENODE value. The mapping of IP addresses and ENODE values also prevents the duplication of ENODE values by malicious nodes.

In the event of a faulty time server sending different timestamps to different nodes, there can be two cases – 1) all nodes will receive different timestamps, 2) some targeted nodes will keep on receiving faulty time stamps. In the first case, if all the nodes in the blockchain receive different timestamps, which are not similar to each other, the nodes will not be able to join the blockchain. This will be easily flagged as an error to the network administrator. Further, in the second case, if some of the nodes are sent different times in the blockchain, they will not be able to take part in the blockchain, which will again be flagged as an error to the network administrator. Although, our implementation of the time server may seem like a good candidate for the Byzantine failure, but the problem mentioned above (if occurring) can be easily localized during the initial phase itself.

## 3 Performance Evaluation

In this work, we establish a private Ethereum blockchain with four nodes, following the architecture outlined in Fig. 2, the exact specifications of which are briefly outlined in Table 1. Two of these nodes (nodes 1 and 2 in Table 1) are non-real time, static systems with constrained processing power and energy, and which join the blockchain network through the Ethernet. The third node (node

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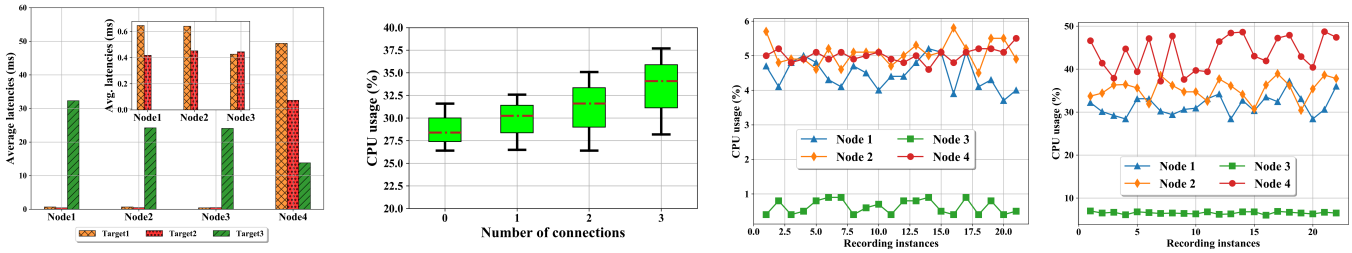


(a) Average network latencies across nodes (b) Average CPU usage vs. number of connecting nodes (c) CPU usage before mining (d) CPU usage during mining

Fig. 3: Network and node performance characteristics for our implemented IoT blockchain.

3) has significant processing resources and does not have any energy constraints as it draws power directly from the grid. This node also takes part in the blockchain through a dedicated Ethernet-based connection and is deemed a static node. Finally, the last node is yet another non-real-time, resource, and energy-constrained node similar to nodes 1 and 2, but takes part in the blockchain through a wireless connection (WiFi) as it is mainly mobile. It is to be noted that both the Ethernet and WiFi-based networks are not established dedicatedly for this evaluation, but are part of a single institutional network over which a significant number of users communicate simultaneously at any time of the day.

To establish the quality of the network, we estimate the latencies encountered by each of these different nodes connecting to the network through heterogeneous means. We observe an average latency of 0.4 ms to 0.7 ms on each of the nodes 1, 2, and 4 while they receive information/ connection requests from other nodes. However, node 3 connecting to the network through a WiFi-based connection encountered average latencies of around 13 ms to 50 ms when receiving messages from the other nodes. Similarly, nodes 1, 2, and 4 observe average network latencies of up to 24ms to 33ms, when receiving messages from node 3.

### 3.1 Effect of Network Latency

Considering the network architecture discussed previously, Fig. 3(a) shows the comparison between network latencies while sending *ping* packets from each node to every other node (designated as Targets 1 -3) in the network. We observe that for *ping* queries over the Ethernet-connected nodes, the response time is significantly lower than that of the one connected over WiFi. Additionally, we observe that the response time for *ping* from Node-3 (server) is relatively lower than the responses from the resource-constrained nodes (Nodes- 1 and 2), even when connected over the same Ethernet-based connection. These relatively higher latencies incurred due to the resource-constrained nodes (Nodes-1 and 2) is attributed to the time taken by them to process the packets. In continuation, the significantly higher latencies at Node-4 can be attributed both to its resource-constrained nature, requiring more time to process the packets, as well as its mobility, which causes it to have unstable network characteristics. These latencies are crucial in estimating the performance of our implemented IoT blockchain and act as the network performance baseline.

### 3.2 Effect of Increase of Node on CPU Usage

Fig. 3(b) shows the average CPU usage (denoted in %) for a randomly selected constrained node in our blockchain network. We observe that as the number of network connections to that node increases, the nodes' average CPU usage goes up to maintain the connections to and from it. An important takeaway from this observation is that resource-constrained nodes support only a limited number of simultaneous network connections, which necessitates the use of distributed security solutions for reliable use of such nodes.

Further, Fig. 3(c) represents the CPU usage at each of the four implemented nodes before joining the blockchain, whereas Fig. 3(d) represents the CPU usage in the same nodes during mining in the blockchain. From Figs. 3(c) and 3(d), we observe that the three constrained nodes (Raspberry Pi) incur almost 5-8 times the CPU usage as compared to the regular node (server). Additionally, the mobile constrained node (connected to the WiFi), incurs further resource usage (CPU usage) as compared to the constrained nodes connected to the Ethernet.

We further observe that being part of the blockchain and performing its operations induces a massive increase in CPU usage of the devices by

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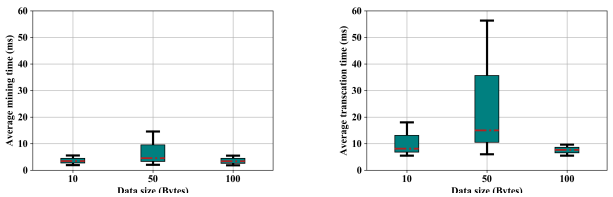
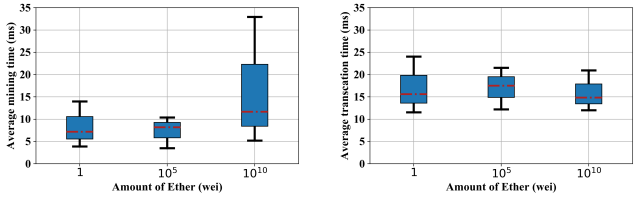



(a) Average mining time (b) Average transaction time

Fig. 4: Variation in blockchain performance with the variation in data size.




(a) Average mining time (b) Average transaction time

Fig. 5: Variation in blockchain performance with the amount of Ethers transferred.

almost 10 times as compared to when the devices are operating on their own (refer Figs. 3(c) and 3(d)). For resource-constrained nodes, the percentage CPU usage is about 5 to 7 times more as compared to that for the node with ample storage and high processing power. As in our implemented blockchain, nodes 1, 2 and 4 are resource-constrained, we observe their average CPU usage to be around 31.686%, 35.323%, 43.704% respectively, while node 3 which is a server accounts for about 6.536% of CPU usage during blockchain mining operations.

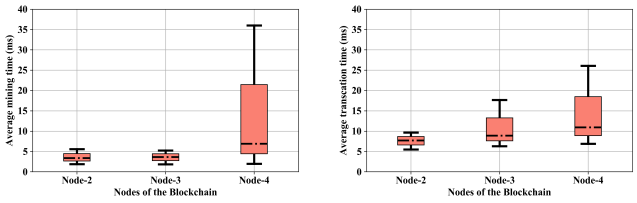
### 3.3 Effect of Data Size

Fig. 4 shows the effect of data size on the IoT blockchain operations of our implemented system from the perspective of the static nodes. Fig.4(a) shows the variation in mining time when the size of the data used for transacting over the blockchain is varied while the amount of Ethers transacted is kept fixed at 750 wei. The sender and receivers involved in the transaction are also kept fixed. We evaluate the performance of mining in our implemented IoT blockchain by using transaction data packets of size 10 bytes, 50 bytes, and 100 bytes. We observe the same variation in mining time for different data sizes over 30 repetitions of this exercise for each data size. Except for some random cases where mining time may show an increased deviation from the norm (as can be seen for the 50 byte data packet in Fig. 4(a)), the mining time for all these data sizes remains reasonably consistent. We attribute these random unexpected values to unstable and congested network behavior and the induced latency thereof.

Similarly, Fig. 4(b) shows the variation in transaction time for the same repeat of the exercise outlined above. Similar to the observed behavior in mining time, the transaction operation also reports some unaccounted-for surge in transaction time, which we again attribute to fluctuating network conditions. As the plot in Fig. 4(b) shows the average behavior, considerable fluctuations in network conditions tend to disturb the norm, which for most of the cases, is reasonably consistent.

### 3.4 Effect of Ether

Fig. 5 shows the effect of Ethers on the IoT blockchain operations of our implemented system from the perspective of the static nodes transacting a data of 100 bytes over the blockchain. Fig. 5(a) shows the variation in mining time on varying the number of Ethers transacted while keeping the data size fixed to 10 bytes, between pre-determined senders and receivers. We transact 1 wei, $10^5$ wei, and $10^{10}$ wei in our blockchain for over 30 times in each case. We observe that the variations in mining time remain almost the same for all cases except for some unexpected random fluctuations because of varying network conditions, which is evidenced from the apparently high error bar in the plots.




(a) Average mining time (b) Average transaction time

Fig. 6: Variation in blockchain operation times with respct to various nodes

Similarly, Fig. 5(b) shows the variation in transaction time for the same exercise as described above. For each of the three cases, i.e., for 1 wei, $10^5$wei, and $10^{10}$ wei, we observe almost the same type of variations as reported previously. We attribute this randomness in behavior to unstable network conditions. The randomness distorts the norm of

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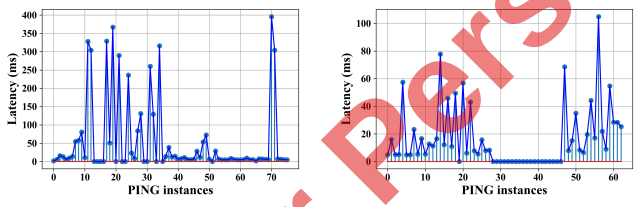
the readings for all three cases, as is evident from the significantly larger error bar in the plots.

### 3.5 Effect of Node Characteristics

Fig. 6(a) shows the variation in mining time at node-1 with the change of receiver nodes while keeping the data size fixed at 100 bytes and the number of Ethers at 750 wei. The make of the nodes is described in Table 1. We observe that there is almost no difference in mining time when nodes 2 and 3 – connected to the blockchain over an Ethernet-based connection – act as receivers of the data. However, there is a significant rise in mining time when node-4, which connects to the blockchain over WiFi, is made the receiver of data from node-1. The error bar for the plot of mining time at node-4 indicates a massive fluctuation of values, indicating unstable network connection.

Similarly, Fig. 6(b) shows the variation in transaction time for transactions between node-1 and the other three nodes under the same operating conditions, as mentioned earlier. Here we observe that there is an increase in the average transaction times at node-1 when the transactions are performed between it and nodes 2-4. The increase in transaction time at nodes 3 and 4 are caused due to random variations in network latencies due to intermittent network connections, as evidenced by the relatively higher error bars in the plots for these two nodes.




(a) Mobile node to a static node (b) Static node to a mobile node

Fig. 7: Network latency encountered during *ping* operation.

### 3.6 Effect of Node Mobility

In contrast to the static node analysis until Section 3.5, in this section, we evaluate the performance of the network as well as the implemented blockchain from the perspective of a mobile node. The mobile node under consideration is node-4, which connects to the blockchain through a WiFi-based connection, which gives it the ability to relocate without changing any physical configurations quickly. To estimate the network quality available to this node when it is mobile, we perform two network-based tests – 1) check the network response time when the mobile node queries an address over the network during mining operation, and 2) check the network response time when a static node queries the mobile node's address during mining operation.

Fig. 7(a) shows the network latencies witnessed by node-4 during the first test. Whereas, Fig. 7(b) shows the network latencies witnessed by a static node during the second test. It is to be noted that the static node connects to the network through a fixed Ethernet-based connection. We observe that there is a considerable variation in the recorded network latencies as node-4 moves through regions of weak and strong WiFi signal strengths. This mobility and fluctuations in signal strength further give rise to intermittent connectivity issues such as the unavailability of the network (as seen in Fig. 7(a) between instances from 33 to 46). The network stays unreachable until the mobile node enters into a zone of good signal strength. As a result of this behavior, there is an induced lag in mining times whenever mobile nodes connect to the blockchain over constrained networks.

Fig. 8(a) shows the variation in mining time for two different data sizes, i.e., 10 bytes and 100 bytes while transacting between a static and a mobile node in our implemented blockchain. The considerable variations in mining times, as evidenced by the error bars, are a result of unstable network connections when the mobile node traverses through zones of good and bad signal strengths. Considering equal network variations during the transference of the two data blocks, we observe that the norm for 100 bytes is higher than that for 10 bytes of data, indicating higher mining time incurred for more significant data sizes.

Similarly, Fig. 8(b) shows the variation in transaction time for the two selected data sizes, i.e., 10 bytes and 100 bytes while transacting between a static and a mobile node in the network. We again observe the average transaction time of 100 bytes data packet to be slightly higher than that for 10 bytes data packets, which is due to the increase in time required to transmit and process the data. The variations and increased values of the error bars signify intermittent network connectivity, resulting in higher transaction times for the mobile node.

Further, Fig. 8(c) shows the variation in mining time for three different amounts of transacted Ether, viz. 1 wei, $10^5$ wei, and $10^{10}$ wei while transacting from the static node to the mobile node in the

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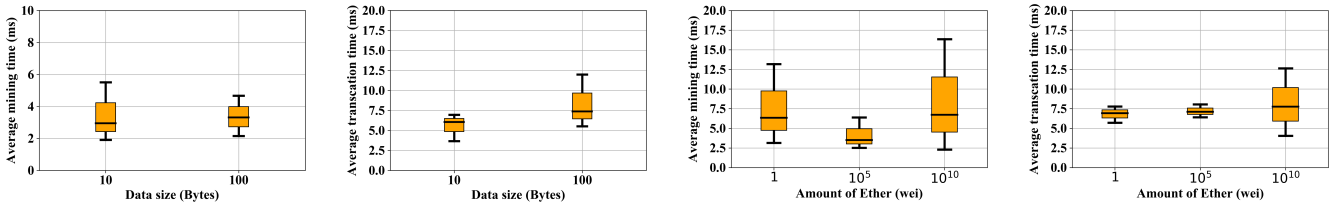



(a) Average mining time vs data size (b) Average transaction time vs data size (c) Average mining time vs Ethers used (d) Average transaction time vs Ethers used

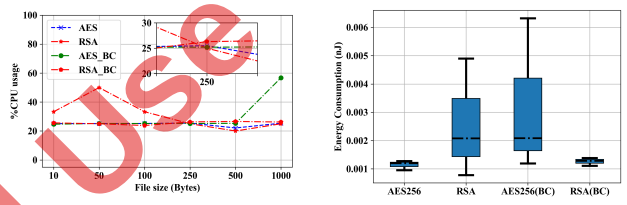
Fig. 8: Evaluation of parameters during transmission of data from static to mobile IoT nodes.

blockchain. Here, we consider the bar for $10^5$ wei to be the standard baseline as its error bars are relatively much lesser than that of the other two bars. The increased error bars for 1 and $10^{10}$ wei indicate an increase in network-based disturbance, which affects the mining operation, even for increased Gas prices.

Similarly, Fig. 8(d) shows the variation in transaction time for the three different amounts of transacted Ether, viz. 1 wei, $10^5$ wei and $10^{10}$ wei, when they transfer from a static node to a mobile node of our blockchain. As compared to the mining time, the transaction time experiment witnesses relatively lesser network disturbances, as evidenced by the smaller error bars for 1 wei and $10^5$ wei.

### 3.7 Effect of Encryption Algorithms

We evaluate the effect of additional security and privacy measures, which are integrated on the same constrained IoT nodes, which are part of the blockchain operations. The data being forwarded on the blockchain is encrypted using two algorithms – RSA and the 256-bit AES. We analyze the standalone effect of these algorithms on the CPU usage and energy consumption of the resource-constrained devices, as shown in Fig. 9. We have first used AES and RSA in a standalone mode to encrypt data on the IoT node. Thereafter, both of these encryption algorithms are used to encrypt data before it is put to the blockchain – the IoT node simultaneously runs one of these algorithms along with blockchain operations, which are denoted as AES256(BC) and RSA(BC) in Fig. 9(a). From the same figure, we observe that for varying data sizes, the four algorithms have comparable CPU usage (neglecting the intermittent outlier behavior observed in some of the readings). We calculate the processing energy required for these security measures from the CPU utilization of each type of IoT device [18]. From Fig. 9(b), we observe that although the energy consumed for executing each of the four algorithms (AES, RSA, AES256(BC), and RSA(BC)) is significantly small, the RSA and AES256(BC) have a high variance for data sizes ranging from $10B$ to $1000B$.




(a) Percentage of CPU usage (b) Energy consumed (in nJ)

Fig. 9: Performance of various security measures on a resource-constrained IoT node.

### 3.8 Discussion

In our evaluation, we observe that the blockchain performance is significantly dependent on the network quality – more unstable the network more is the time taken for mining and transaction operations over it. This effect becomes more pronounced when the blockchain nodes are both constrained as well as mobile. The mining and transaction times are relatively consistent for data sizes up to 100 bytes for both static and mobile nodes. We observe a similar trend for the effect of Ethers, for the fixed number of nodes in our evaluation. The Ether balance with the sender node was initially logged at $7.5^{19}wei$, the whole of which gets transferred to the receiver upon completion of a transaction. Unlike public blockchains, which deal with unknown and trustless systems, the private blockchains do not need an incentive-based mechanism to work. We also note that the blockchain operations cause the constrained Edge nodes to incur additional processing overheads due to the blockchain operations,

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which restricts the applicability of the Edge nodes to regular sensing and actuation operations.

Applications incurring heavy processing, such as computer vision and processing-intensive learning-based tasks, might induce significant overheads if used at the Edge blockchain nodes. Similarly, tasks generating voluminous data such as those associated with multimedia data are also detrimental to our present implementation's performance.

## 4 Conclusion

As a significant majority of IoT Edge devices and IoT networks are resource-constrained, the provision for incorporating reliable security measures is often not available for these devices. These restrictions have resulted in an abundant presence of unsecured data propagating through IoT networks and make the Edge devices susceptible to unauthorized access and tampering. In this work, we have proposed and analyzed the feasibility of incorporating heterogeneous IoT Edge devices as functional blockchain nodes to extend the feature of decentralized security to resource-constrained IoT deployments. We also implement an encrypted network-based time-synchronization mechanism to enable the non-real-time IoT Edge nodes to co-exist in the blockchain.

We conclude that the feasibility of utilizing a blockchain-based decentralized security cover at the IoT Edge devices itself is significantly high in terms of restricting data repudiation and enforcing trust in the constrained deployment, which were previously susceptible to manipulation. However, the underlying connectivity of the network and the minimum processing capabilities of the blockchain nodes control the blockchain performance, which further restricts the nature of the sensing and actuation tasks that the Edge node can accommodate. In the future, we plan to design and develop methodologies to incorporate processing-intensive tasks such as computer vision with our implemented blockchain at the Edge.

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