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The Future of E-Health: Blockchain Solutions with Hyperledger Fabric and IPFS

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ABSTRACT

The electronic representation of a patient's medical information is called an electronic health record, or EHR. Normally, these records are kept on cloud-based or central servers. Blockchain technology is a new technology used to solve security and privacy problems of EHR data in a decentralized way. Hence, they are accessible to authorized health providers for better management of patient care. Building secure e-health systems with public blockchains such as Ethereum faces several problems. The main issue is that these blockchains are permissionless; everybody can join in and obtain access to the data, which becomes a cause of significant privacy concerns. This research proposes a private and decentralized e-healthcare system using Hyperledger Fabric and the Interplanetary File System (IPFS) for securely and effectively storing and retrieving EHRs. Privacy and security are guaranteed with Hyperledger Fabric in ensuring that only authorized parties can access sensitive medical information. The system is further enhanced to include decentralized storage based on IPFS for the storage of medical images and files that cannot be directly stored in the blockchain.

1. INTRODUCTION

In blockchain technology, data is maintained in a decentralized ledger. Blockchain technology ensures integrity and availability, enabling members in the network to create, read, and verify transactions recorded in a distributed ledger. It prevents the deletion and alteration of any information in its ledger, including transactions. Digital signatures, hash functions, and other cryptographic primitives and protocols support and safeguard the blockchain system. These primitives ensure that the transactions entered into the ledger are legitimate, integrity-protected, and non-repudiated. Furthermore, blockchain technology requires a consensus protocol, which is a set of guidelines that each member must accept in a distributed network. This is necessary for all participants to agree on a single record and create a globally unified perspective [1].

With the increased interest in blockchain technology and its applications in different businesses and organizations, healthcare represents an essential field where many use cases have been recognized for blockchain applications [2-4]. In healthcare, a blockchain network stores and exchanges patient data among hospitals, doctors, drug companies, and diagnostic labs. Using blockchain in healthcare improves security, efficiency, and transparency during medical data sharing [5-7].

Blockchain technology is a great fit for many applications, including virtual currencies, e-government, e-healthcare, and food and drug monitoring, in agreement with the General Data Protection Regulation [8, 9]. There are three types of blockchains: private or permissioned, public or permissionless, and consortium.

The public blockchain, such as the Ethereum blockchain, is proposed in many studies in the healthcare sector [10, 11]. However, Ethereum has several drawbacks when it is used to design healthcare apps. The main drawbacks are high transaction costs, poor transaction throughput, and slow efficiency [12, 13]. The Hyperledger Fabric open-source platform is a private blockchain network used to establish a distributed ledger network. The modular architecture of Hyperledger Fabric provides high-security levels, scalability, adaptability, and resilience. Fabric-based systems may therefore be customized to fit different sectors. This secure and private blockchain framework is managed by the Linux Foundation [5].

The benefits of the Hyperledger Fabric platform, including its high performance, modular architecture, open-source nature, and high-quality code, increase its profitability. The key feature of Hyperledger Fabric is that it is permissioned. In contrast to the public blockchain, the private blockchain is not accessible to everyone. Everyone who requests access must first obtain permission. Another key benefit is the multichain support to restrict data access to private members and organizations, where data can be stored in private ledgers accessible only by chaincode on authenticated peers [12]. The Hyperledger Fabric network is proposed in various sectors such as the e-government system [14], health insurance system [15], and student certificate system [16]. One of the main challenges facing the healthcare sector is safely and effectively exchanging patient data throughout various providers and institutions. Many e-health systems have depended on public, paid platforms like Ethereum, which may be expensive and not completely suit healthcare data management's specialized demands. The suggested e-health system uses Hyperledger blockchain technology to provide an interoperable, transparent, and safe platform for exchanging health information. Data encryption, access controls, and audit trails in Hyperledger Fabric help meet Health Insurance Portability and Accountability's (HIPAA) strict requirements for confidentiality, integrity, and availability of patient data. The remaining sections of the document are arranged as follows: Section 2 displays some related works, Section 3 presents an overview of the Hyperledger Fabric architecture, Section 4 introduces the proposed blockchain-based e-healthcare system, Section 5 displays the study's findings and performance evaluation, and Section 6 concludes with recommendations for future work.

2. RELATED WORKS

Arunkumar and Kousalya [17] suggest a decentralized secure cloud-based medical blockchain to maintain the traceability, interoperability, and anonymity of patients' electronic health record (EHR) data between various organizations. To attain better performance, the lightweight authentication encryption algorithm AES_256_GCM encrypts the data before uploading it to the cloud-based blockchain. Access to EHR data on the cloud is restricted by an Ethereum-based solidity smart contract.

Khatoon [18] explores the use of the Ethereum platform to facilitate data management in the healthcare system. They design and implement various medical workflows like surgery and clinical trials to manage large amounts of medical data. The paper estimates the associated costs of implementing these medical smart contract systems.

Kayastha et al. [19] introduce a decentralized application that utilizes Ethereum private blockchain, Interplanetary File System (IPFS), and other internet technology tools to support healthcare providers, research organizations, and policymakers in Nepal. The paper concludes that blockchain technologies can offer a better alternative for public and private health institutions and practitioners in storing safe patient records, thus improving the timely delivery of quality healthcare services in a resource-constrained country like Nepal.

Rupa and Chakkaravarthy [20] suggest an Ethereum framework for authenticating medical documents using unique IDs based on blockchain. These digital IDs can substitute physical documents to reduce the risks related to hacking or forgery. The framework recommended in this paper exploits the immutable nature, decentralized nature, and transparency and security of blockchain technology. The proposed framework uses Remix Ethereum IDE, Solidity programming, and MetaMask.

Haddad et al. [21] propose an EHR management system that is patient-centered and blockchain-based so that patients can manage their data with many stakeholders, ensuring privacy and control without centralization. It stores data in a distributed and unchangeable manner using the Ethereum blockchain and IPFS. Access control is secured through an Ethereum smart contract. They test and evaluate the framework in Windows using Truffle and Web3 networks for its data storage costs and execution time.

While Ethereum is a strong public blockchain, it is not well suited for e-health systems because of its issues with scalability, privacy, governance, and high operating costs. In contrast, Hyperledger Fabric offers a more private, governed, and customized environment that better fits the demands of organizations and industries needing scalability, privacy, and flexibility.

3. HYPERLEDGER FABRIC ARCHITECTURE

Distributed applications built in general-purpose programming languages (e.g., Node.js, Go, and Java) are executed by Hyperledger Fabric, a distributed operating system for permissioned blockchains. its execution history in a duplicated ledger data structure that is appended securely. Hyperledger Fabric departs from the conventional order-execute design and presents the execute-order-validate blockchain architecture as shown in Figure 1 [22].

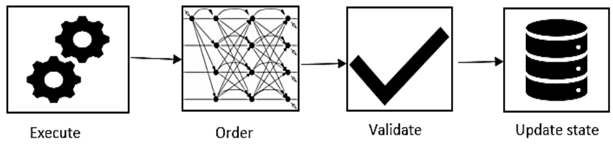

Figure 1. Execute-order-validate architecture of Hyperledger Fabric [21]

3.1 Execution phase

Clients sign and send the proposal for the transaction to one or more endorsers for implementation at the execution step. With the endorsement policy, each chaincode inherently designates a group of endorsers. A proposal includes the following: the MSP- determined identity of the submitting client, the transaction payload, a nonce that each client will use only once (random value or a counter), and a transaction identifier that is created from both the nonce and client.

By implementing the operation on the specific chaincode installed on the blockchain, the endorsers simulate the proposal. The simulation generates a writing set (a state update) and a reading set (version dependencies), which endorsers sign and return to the clients as endorsements. Clients gather these endorsements to meet the chaincode endorsement policy before creating and submitting the transaction for ordering service [22].

3.2 Ordering phase

A transaction is put together and sent to the ordering service by the client once it has gathered sufficient endorsements for a proposal. The transaction consists of a collection of endorsements, transaction information, and the transaction payload—that is, the chaincode procedures with all of its parameters. Ordering, despite faulty orderers, broadcasts endorsements atomically and begins consensus on transactions. Additionally, the ordering service batches several transactions into blocks, creating a hash-chained sequence containing transactions. to increase the broadcast protocol throughput [22, 23].

3.3 Validation phase

In Hyperledger Fabric, blocks are forwarded directly to peers from the ordering service. Thereafter, they follow a three-phase validation process. In the first phase, there is the validation of the endorsement policy. The second phase is the sequential version check of all the transactions. In the third phase, the state of the blockchain is updated in the local ledger by appending the block [22].

A smart contract in Hyperledger Fabric is called chaincode, a computer code that executes throughout the execution phase and implements the application logic. The chaincode is the core component of a distributed application in Hyperledger Fabric. System chaincodes are special chaincodes that exist to manage the blockchain system and control parameters [22, 24].

4. THE PROPOSED METHODOLOGY

This paper proposes the Hyperledger Fabric to serve as the blockchain network that provides secure and immutable storage to manage e-health records. The proposed design of the Hyperledger network-based e-health system involves three organizations: Hospital1, Hospital2, and Patient. The Patient organization is used to record patients' data and retrieve all their EHRs. It uses a single channel to connect the three organizations and maintains a single ledger to store and retrieve the Patient, Hospital1, and Hospital2 records. Figure 2 shows the proposed Hyperledger-based e-health system with a single channel and three organizations.

It is impossible to directly store images on a blockchain such as Hyperledger Fabric because of their size, cost, inefficiency, and scalability problems. Instead, these issues are tackled through the use of the IPFS, which offers decentralized storage for large files efficiently and at a low cost. IPFS employs content-addressing to ascertain the file's integrity and fast retrieval. Therefore, the proposed solution is to offload image storage to IPFS while storing metadata and file references (hashes) only on the blockchain. The suggested approach is made to work with three different types of web apps (Patient application, Hospital1 application, and Hospital2 application). Figure 3 shows the interaction between the entities: Application Interface, Hyperledger SDK, Peer organization, and Orderer organizations to add new blocks to the ledger.

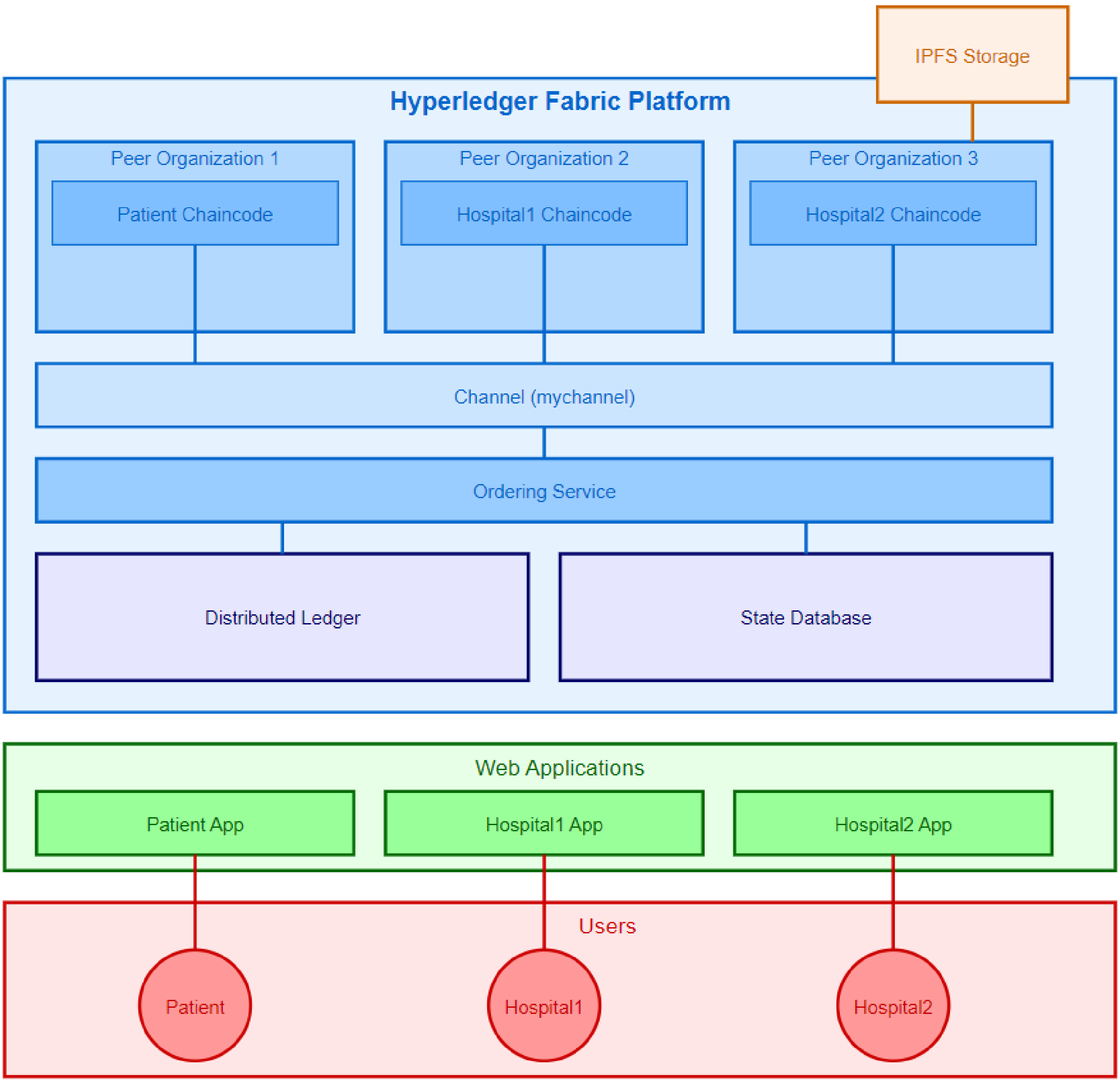

Figure 2. The proposed Hyperledger-based e-health system with a single ledger

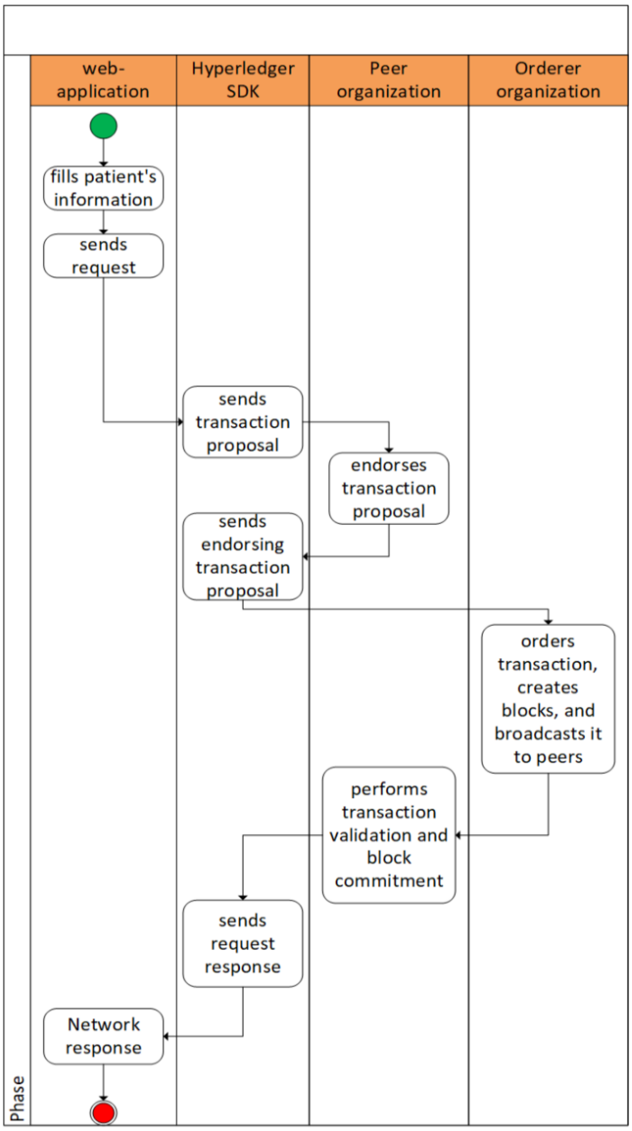

Figure 3. Activity diagram of the proposed e-health-based Hyperledger Fabric system

4.1 Patient application

Patients can register and create an account in the first one (*Patient chaincode*) by providing their details, including name, age, gender, username, and password for sign-in. Every patient receives an automatic ID from the system. This ID is essential since it makes the patient's EHRs easier to store and retrieve, as shown in Algorithm 1. The patient can retrieve his medical records from any hospital using his ID. The channel (mychannel) acts as the main channel used to retrieve data from other ledgers.

The main steps of this chaincode are:

• Add new patients including (name, age, gender, username, and password).

• Retrieve the patient's unique ID.

• Get patient data using his ID.

• Define the count key to retrieve the last count index stored in the ledger to increase it for new patients.

• Generate a unique patient ID based on the count key, patient name, and age.

Algorithm 1: Patient chaincode

```
Define constant patient_count_key as "patientCount"

Define structure Patient:
    ID: string
    Name: string
    Gender: string
    Age: integer
    Username: string
    Password: string

Define function GenerateID(name, age, count):
    shortName = first 4 characters of
    return lowercase (shortName + age + count)

Define function AddPatient(name, gender, age, username, password):
    count = GetPatientCount()
    id = GenerateID(name, age, count + 1)

    patient = new Patient with:
        ID = id
        Name = name
        Gender = gender
        Age = age
        Username = username
        Password = password

    Save patient to blockchain
    SetPatientCount(count + 1)

Define function GetPatient(id):
    patientData = Retrieve data from the blockchain using id
    if patientData doesn't exist:
        return "Patient not found"
    return patientData as a Patient object

Define function GetPatientCount():
    count = Retrieve patient_count_key from blockchain
    if count doesn't exist:
        SetPatientCount(0)
        return 0
    return count as integer

Define function SetPatientCount(count):
    Save count to the blockchain using patient_count_key

Main function:
    Initialize PatientContract
    Start the blockchain application
```

4.2 Hospital1 application

Hospital1 uses the second application, *Hospital1 chaincode*, to store the patient's medical record indexed by their ID. The medical record that makes up this chain code contains many pieces of information, including the patient's name, ID, gender, age, blood type, medical conditions, date of admission, treating physician, and any related insurance information. It saves and retrieves data from the Hyperledger blockchain using functions in Algorithm 2.

The main steps of this application are:

• Add new medical records including medical data (ID, Name, Age, Gender, BloodType, MedicalCondition, AdmissionDate, Doctor, Insurance, BillingAmount).

• Retrieve the medical record using ID.

Algorithm 2: Hospital1 chaincode

```
Define structure MedicalRecord:
    ID: string
    Name: string
```

```
    Age: integer
    Gender: string
    BloodType: string
    MedicalCondition: string
    AdmissionDate: string
    Doctor: string
    Insurance: string
    BillingAmount: float
    RoomNumber: integer
    AdmissionType: string
    DischargeDate: string
    Medication: string
    TestResults: string

Define function SetRecord(all fields of MedicalRecord):
    Create a new MedicalRecord with the provided fields
    Save MedicalRecord to the blockchain using ID as a key

Define function GetRecord(id):
    Retrieve data from the blockchain using id
    if data doesn't exist:
        return "Record not found"
    return MedicalRecord object

Main function:
    Initialize MedicalRecordContract
    Start the blockchain application
```

4.3 Hospital2 application

Hospital2 manages patient medical records using the *Hospital2 chaincode* and IPFS. Since Blockchain technology cannot store files directly in its blocks, we use another storage system such as IPFS or the cloud to store the files. We then take the hash value or the URL of the files (if the cloud is used) and store it in the blockchain to ensure the integrity of the medical record. Hospital2 chaincode involves storing patient medical data and the hash value of the IPFS-generated medical images, guaranteeing effective and safe storage and retrieval of both data and images, as shown in Algorithm 3.

The main steps of the Hospital2 application:

• Store the medical files such as medical images in the IPFS and take the hash values of the file.

• Add new medical record including (ID, Name, Age, ImageHash).

• Retrieve the medical record using ID.

Algorithm 3: Hospital2 chaincode

```
Define structure Record:
    ID: string
    Name: string
    Age: integer
    ImageHash: string

Define function CreateRecord(id, name, age, imageHash):
    Create a new Record with:
        ID = id
        Name = name
        Age = age
        ImageHash = imageHash

    Save Record to the blockchain using ID as a key

Define function RetrieveRecord(id):
    Retrieve data from the blockchain using the ID
    if data doesn't exist:
        return "Record not found"
    return Record object

Main function:
    Initialize RecordContract
    Start the blockchain application
```

5. EXPERIMENTAL RESULTS AND ANALYSIS

The following features are included in the ASUS laptop that was used to carry out the suggested methodology: i7-12700H, a 2.30 GHz 12th generation Intel(R) Core (TM) processor, with 16.0 GB of RAM added. The machine was running Ubuntu 22.04 64-bit. The Hyperledger Explorer dashboard is seen in Figure 4, with the three operational organizations linked to "mychannel" enabling safe and effective cooperation; these institutions serve as the backbone of a private e-health network. Figure 5 shows the three chaincodes that are deployed on "mychannel" (Patient chaincode, Hospital1 chaincode, and Hospital2 chaincode).

				Ledger Height		
Peer Name	Request Url	Peer Type	MSPID	High	Low	Unsigned
peer0.org2.example.co...	peer0.org2.example.co...	PEER	Org2MSP	0	59974	true
peer0.org3.example.co...	peer0.org3.example.co...	PEER	Org3MSP	0	59974	true
peer0.org1.example.co...	peer0.org1.example.co...	PEER	Org1MSP	0	59974	true
orderer.example.com:7...	orderer.example.com:7...	ORDERER	OrdererMSP	-	-	-

Figure 4. Three organizations connected to "mychannel" in the private e-health network

Chaincode Name	Channel Name	Path	Transaction Count	Version
reg-patient	mychannel	-	199564	1713527971
hospital1-chaincode	mychannel	-	200000	1713528012
hospital2-chaincode	mychannel	-	200000	1713528030

Figure 5. Three chaincodes that are deployed to "mychannel" in the private e-health network

5.1 Performance metrics

The performance metrics used in the experimental result are achieved using Hyperledger Explorer and (Prometheus& Grafana) reports. Also, the Average response time is computed. Hyperledger Explorer metrics are:

- Blocks per hour
- Blocks per minute
- Transactions per hour
- Transactions per minute

Grafana is an open-source analytics and visualization platform that connects with Prometheus and many data sources to provide interactive, customized dashboards, facilitating the viewing and analysis of metrics. Together, they offer a comprehensive monitoring solution. Grafana provides the following metrics:

- Docker containers metrics (CPU usage, and Memory usage)
- Chaincode metrics (Request duration, Request received, Request completed)
- Endoreser metrics (Successful Proposal duration, Proposal received, Successful proposals)
- Ledger metrics (Block processing time, Block storage commit time, StateDB commit time).

5.2 Experimental results

In this section, the proposed system's outcomes are displayed using the mentioned metrics, and a comparison with the Ethereum platform is conducted. Figures 6-9 show the network's performance in terms of blocks/hour, blocks/minute, transactions/hour, and transactions/minute, respectively.

The same chaincodes were written in solidity to be run on the Ethereum platform using Truffle and Ganache techniques.

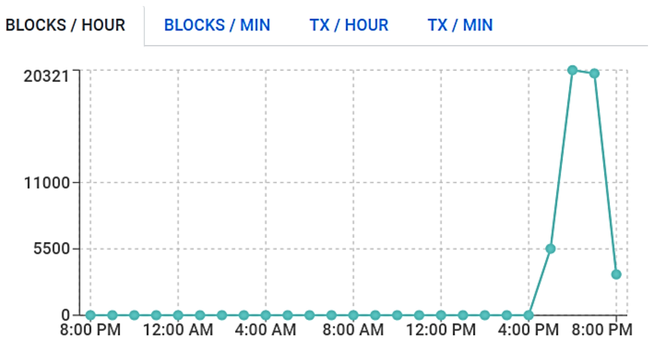

Figure 6. Blocks/hour generated in the Hyperledger-based e-health system

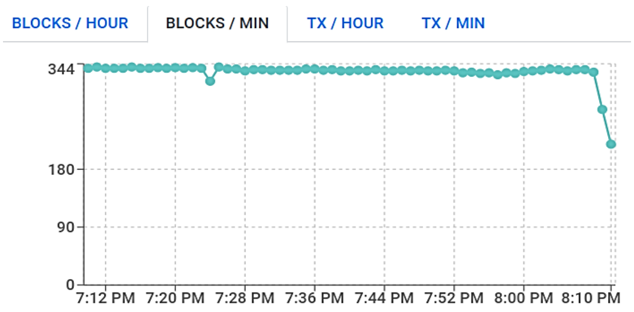

Figure 7. Blocks/min generated in the Hyperledger-based e-health system

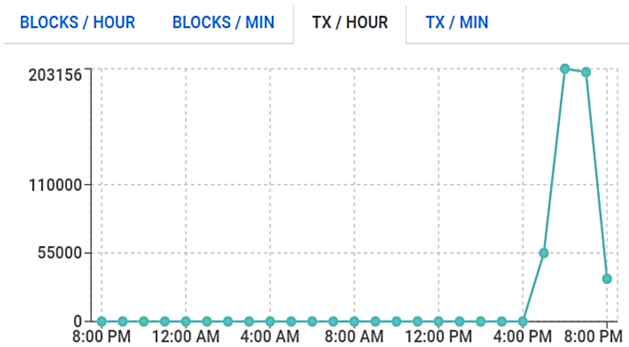

Figure 8. Transactions/hour generated in the Hyperledger-based e-health system

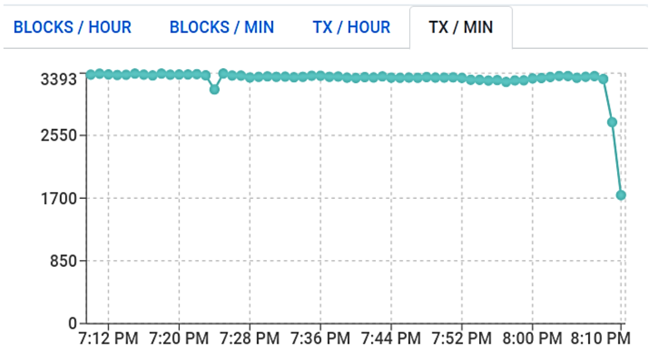

Figure 9. Transactions/min generated in the Hyperledger-based e-health system

Hyperledger Fabric uses Docker containers to manage organizations. Each organization includes peers, orderers, and certificate authorities, all operating within isolated Docker containers. This configuration facilitates scalability, modularity, and flexibility, enabling organizations to execute chaincodes, manage their ledgers, and process transactions within their containerized environments. The CPU and memory usage by each container are shown in Figures 10 and 11. The complexity of the chaincode affects the performance metrics for each peer.

Figures 12-14 show the Endoreser metric. successful proposal duration implies the amount of time in (milli second) for the proposal to be processed by the peer, proposal received indicates the number of proposals received by the peer in time unit, and successful proposals which indicate the number of proposals that are successfully processed and endorsed by the peer.

Figures 15-17 display Chaincode metrics. Request duration indicates the time taken to process a request, request received indicates the number of received requests time unit, and request completed indicates the number of completed requests. Figures 18-20 display the Ledger metrics. Block processing time, block storage commit time, and StateDB commit time, respectively. Figures 21-23 show the screenshots from the Ganache display, which presents the gas price of adding blocks when running the three chaincodes on Ethereum.

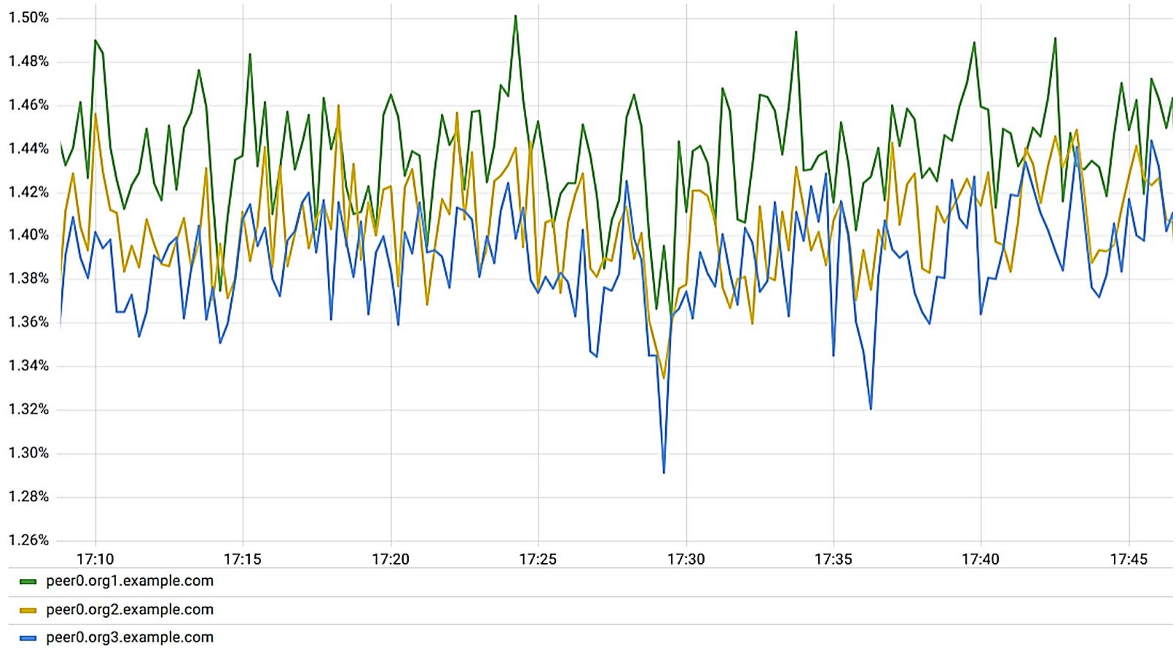

Figure 10. Total CPU usage per container

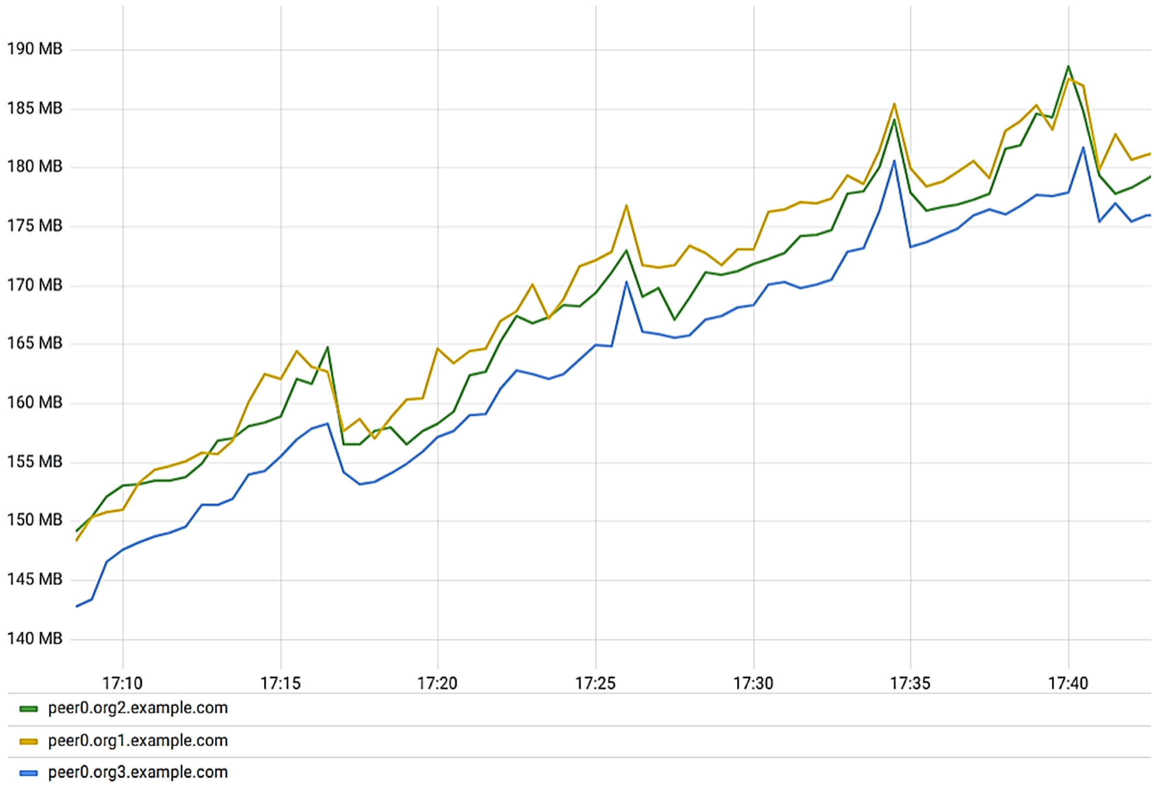

Figure 11. Total memory usage per container

Figure 12. Successful proposal duration

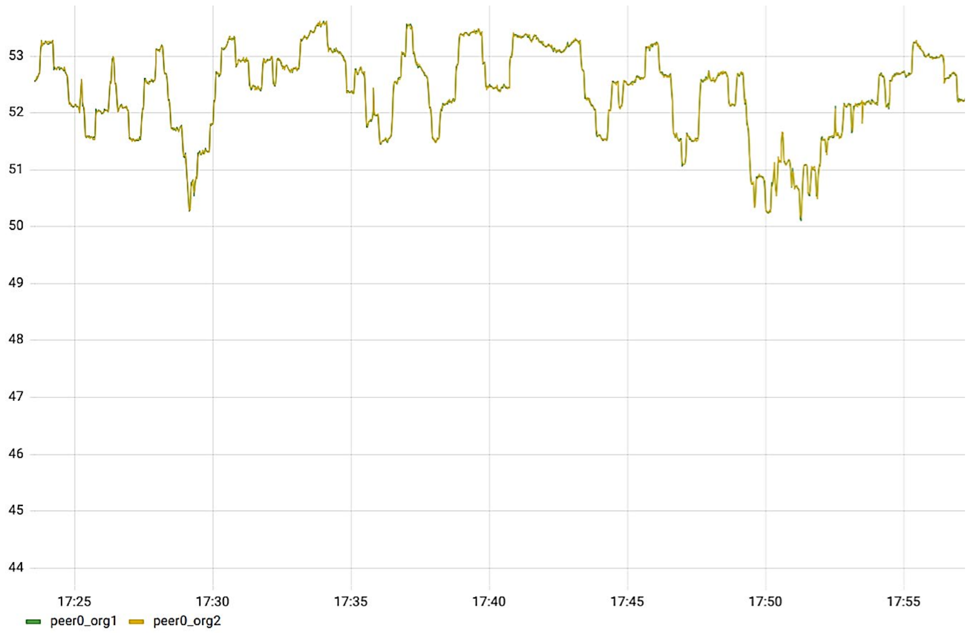

Figure 13. Proposal received

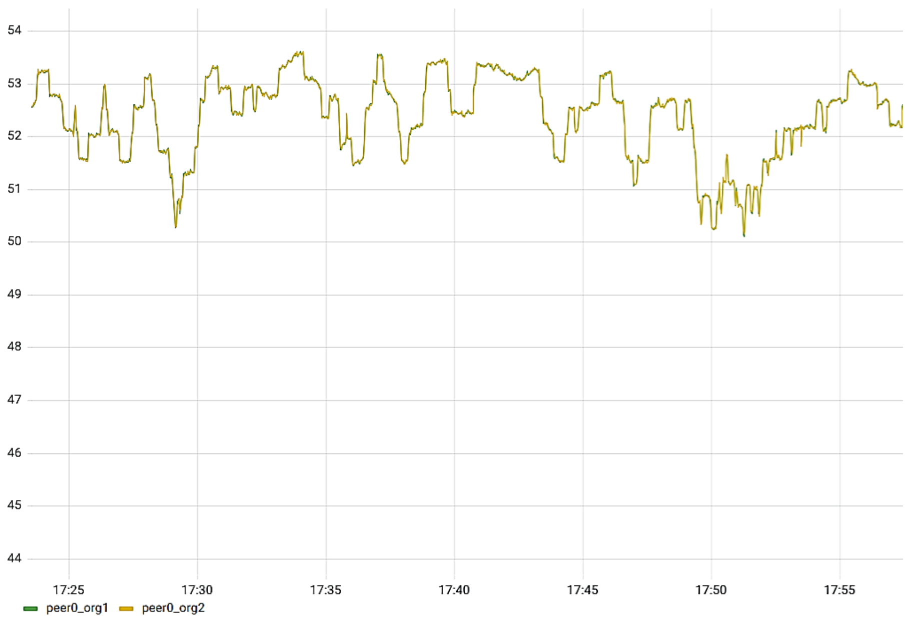

Figure 14. Successful proposals

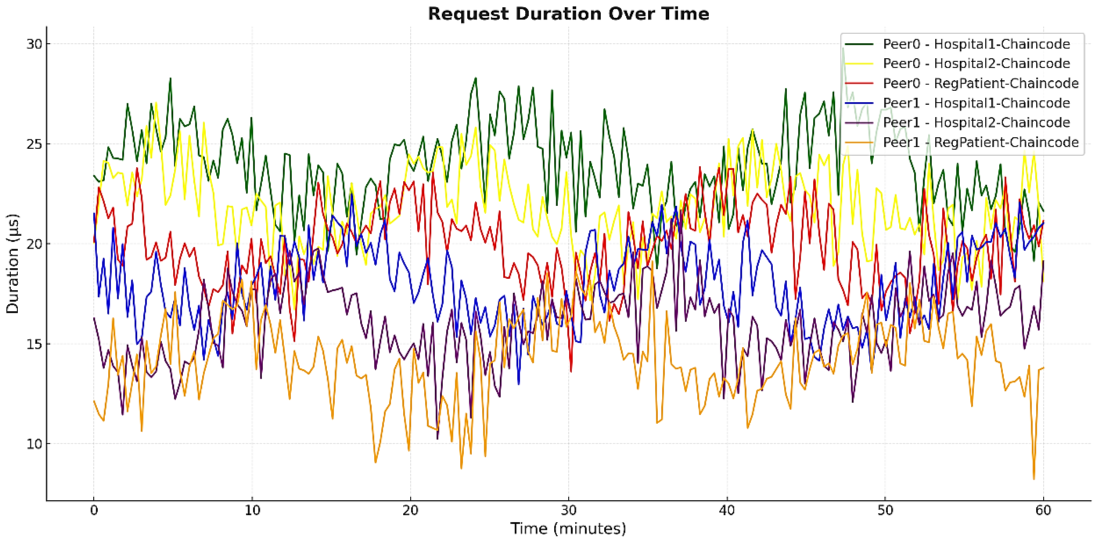

Figure 15. Request duration

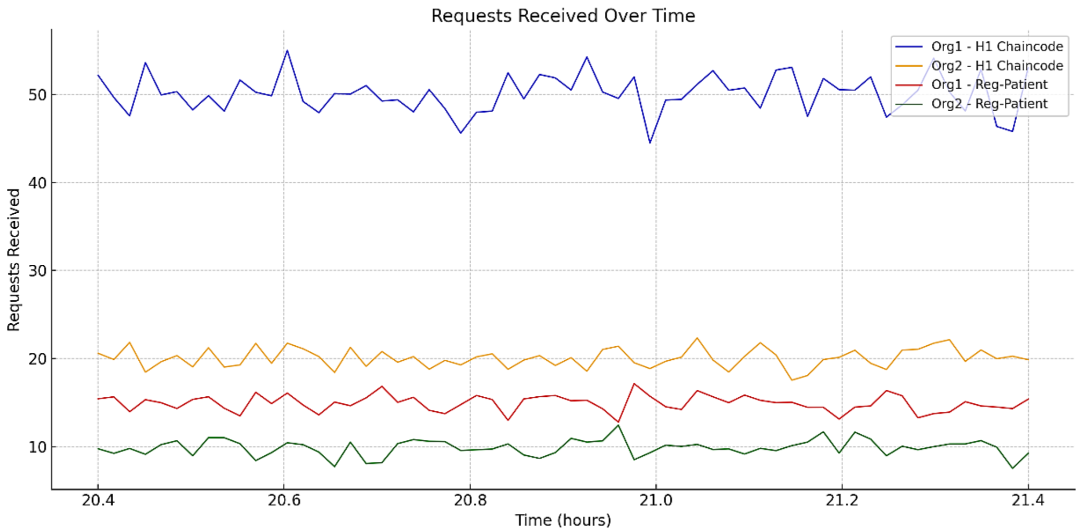

Figure 16. Request received

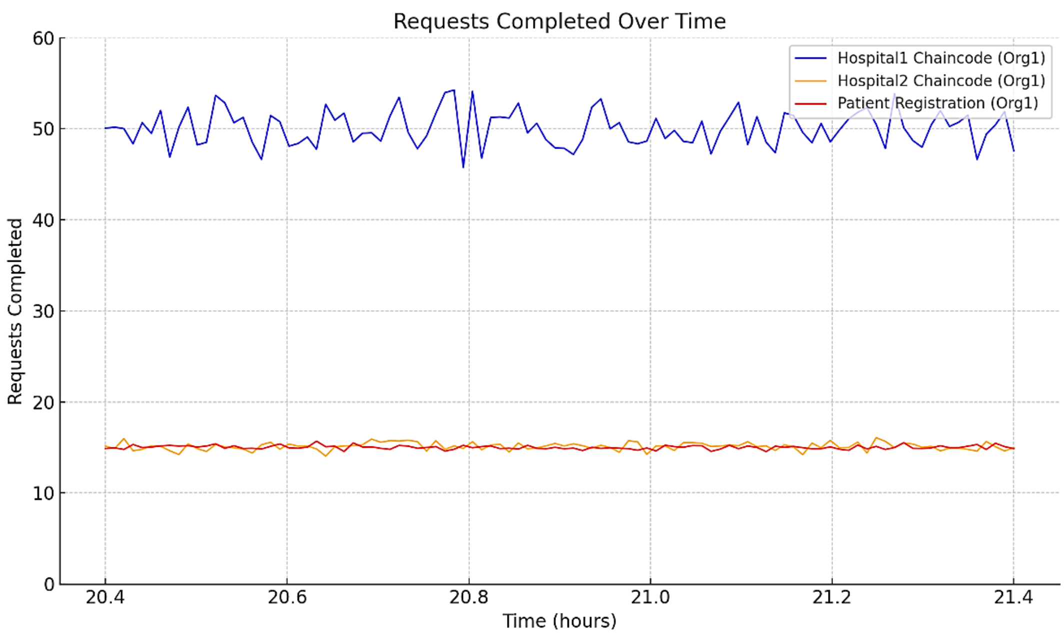

Figure 17. Request completed

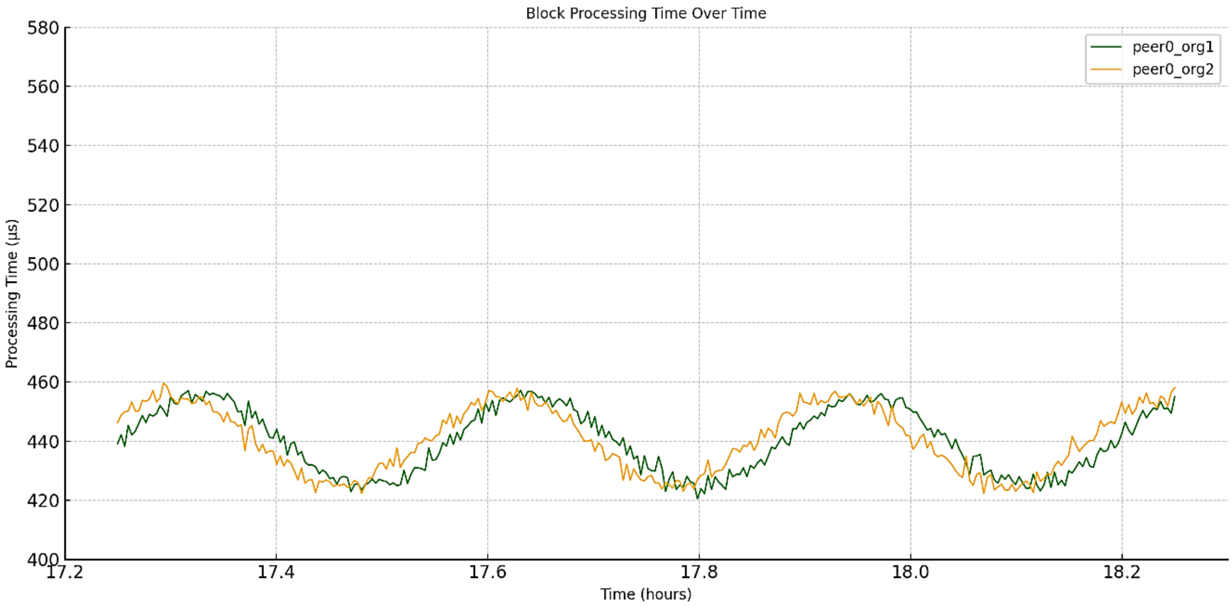

Figure 18. Block processing time

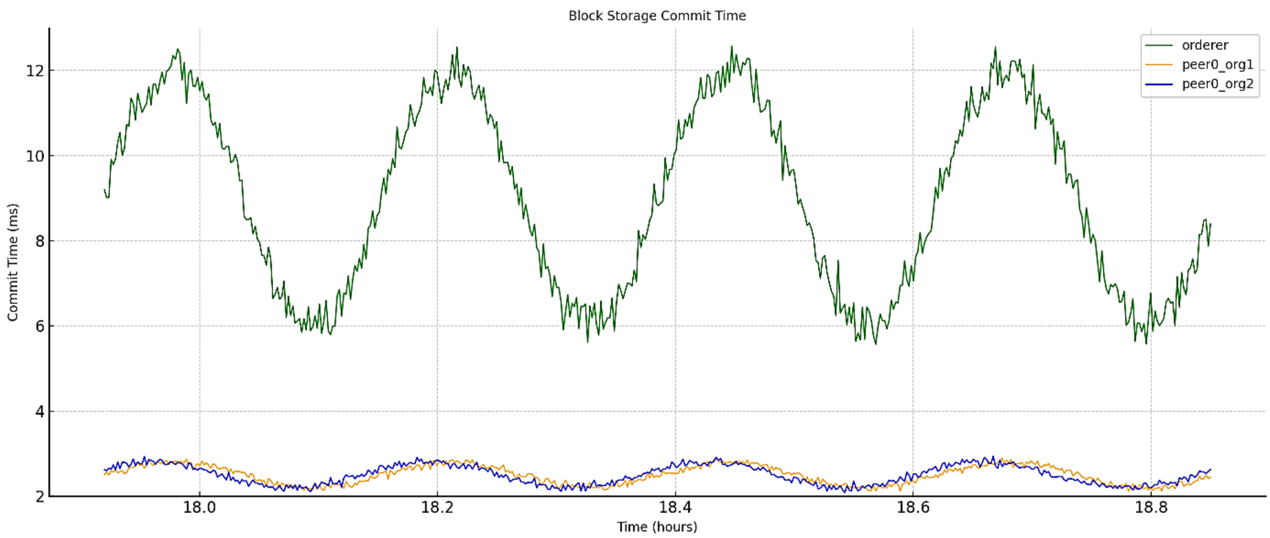

Figure 19. Block storage commit time

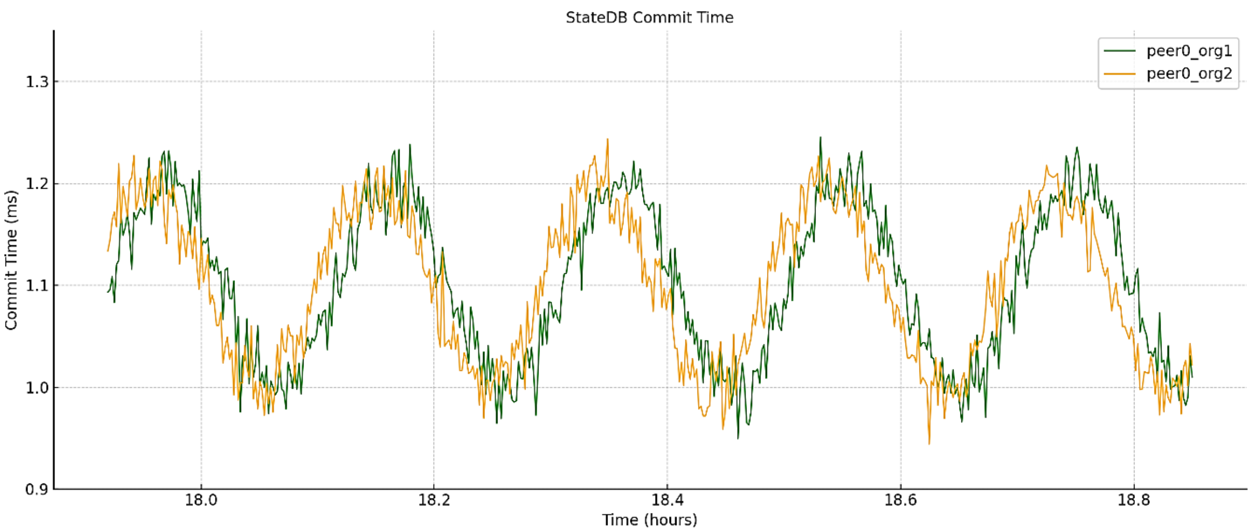

Figure 20. StateDB commit time

Figure 21. Gas amount used for adding blocks of the Patient smart contract

Figure 22. Gas used for adding blocks of the Hospital1 smart contract

Figure 23. Gas used for adding blocks of the Hospital2 smart contract

Table 1. A comparison of Ethereum and Hyperledger metrics for the three Chaincodes

Chaincode Name	Ethereum Time	Ethereum Gas	Hyperledger Time	Hyperledger Gas
Patient Chaincode	24295	201602573	150	0
Hospital1 Chaincode	15237	167365360	138	0
Hospital2 Chaincode	12671	118476040	136	0

Table 1 shows a comparison between the Hyperledger Fabric platform and the Ethereum platform in terms of total execution time (ms) and total gas used for 1,000 transactions from the three organizations. Hyperledger Fabric is a blockchain platform for non-currency purposes designed to serve businesses. In contrast, Ethereum utilizes fees or gas prices for transactions to incentivize miners and secure the network.

5.3 Result discussion

The performance metrics for the Hyperledger Fabric network indicate generally stable operation with efficient request processing and balanced resource usage. All three of the peers' memory consumption trends indicate an overall upward tendency, peaking at 190–195 MB from initial values of 145–150 MB. The CPU utilization remains consistent, primarily varying between 1.32% and 1.52%. The successful proposal duration fluctuates between 1.75ms and 2.20ms over the monitored period. The proposal received metric ranges from about 44 to 54 proposals. The proposal Received graph shows that almost all proposals received were successful. Request processing is generally stable, with occasional spikes in duration. The network shows high efficiency, with nearly all received requests being completed. The block processing time mostly ranges between 400µs and 500µs, with occasional spikes up to about 560µs. The peers have much lower and more consistent commit times, mostly between 2ms and 3ms. Furthermore, when comparing the chaincode performance of Ethereum to Hyperledger, Hyperledger exceeds Ethereum in terms of execution time and resource efficiency. For example, the Patient chaincode takes only 150ms on Hyperledger against 24,295ms in Ethereum, and Hyperledger consumes no gas versus Ethereum's 201,602,573 gas units.

6. CONCLUSION AND FUTURE WORKS

This paper suggests a private and decentralized e-healthcare system that can store and retrieve electronic health records securely and efficiently using Hyperledger Fabric and IPFS. The monitoring of the peers shows stable performance with a gradual increase in memory usage, consistent CPU utilization, and efficient proposal processing times. Network efficiency is high, with nearly all requests completed, and block processing times remain low. Commit times are stable. Unlike Ethereum, which uses fees or gas prices to reward miners to secure the network, Hyperledger Fabric is a blockchain platform for non-currency applications developed to support businesses. This is because Hyperledger Fabric operates on the premise of a permissioned blockchain, where known participants are responsible for running consensus processes. Therefore, transactions are faster and cheaper in Hyperledger Fabric, making it an ideal choice for those companies that need robust, scalable, and private solutions without any transaction costs or overheads. In future work, a multichain e-health-based Hyperledger Fabric with multiple channels can be used to maintain multiple ledgers instead of uploading all records in one ledger to increase network scalability. To further enhance data management, cloud storage might also take the role of IPFS.

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