FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING
DEGREE PROGRAMME IN WIRELESS COMMUNICATIONS ENGINEERING

# MASTER'S THESIS

## BLOCKCHAIN-BASED ROAMING AND OFFLOAD SERVICE PLATFORM FOR LOCAL 5G OPERATORS

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# ABSTRACT

**5G is the latest generation of mobile networks which will be deployed based on network softwarization concept. It will enable Local 5G Operator (L5GO) concept which is one of the most prominent versatile applications of the 5G in the near future. The unique locality features of L5GOs will be useful in many use cases such as smart cities, industrial internet and healthcare. The popularity of L5GOs will trigger more and more number of roaming and offloading opportunities between mobile users. However, existing static and the operator-assisted roaming and offloading procedures are inefficient for L5GO ecosystem. To address these challenges, we propose a blockchain / Distributed Ledger Technology (DLT) based service platform for the L5GOs to facilitate efficient roaming and offload services. We introduce several novel features, namely, universal wallet for subscribers, service quality based L5GO rating system, user-initiated roaming process and the roaming fraud prevention system. Blockchain-based smart contract scheme is proposed to establish dynamic and automated agreements between operators. A prototype of the proposed platform is emulated with the Ethereum blockchain platform and Rinkeby Testnet to evaluate the performance and justify the feasibility of the proposal.**

**Keywords: Roaming, Offload, 5G, Local 5G Operators, Blockchain, Distributed Ledger Technology, Smart Contracts**

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# FOREWORD

The primary focus of this thesis is to develop a blockchain based platform to carry out roaming and offloading services for Local 5G Operators. This work is partly supported by European Union in RESPONSE 5G (Grant No: 789658) and Academy of Finland in 6Genesis (grant no. 318927) and SecureConnect projects. I express my sincere gratitude to my supervisor and mentor Associate Prof. Mika Ylianttila for his valuable support and guidance throughout the period of the research. I would like to extend my gratitude to my technical supervisor Dr. Madhusanka Liyanage for his continuous supervision and encouragement. I express my deep gratitude to my external supervisor Dr. Maheshi Dissanayake from University of Peradeniya for her assistance and providing valuable ideas for my research. My sincere appreciation also goes to Mr. Tharaka Hewa for guiding me to realize the thesis objectives successfully. I would also like to thank Prof. Nandana Rajatheva for his guidance throughout this master program and also double degree coordinator Matti Isohookana for his immense support during the master's studies. My thank also goes to the lectures from University of Oulu University of Peradeniya for their contribution in making my double degree master's program a success.

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Nisita Weerasinghe

# LIST OF ABBREVIATIONS AND SYMBOLS[1]

| | |
|---|---|
| 3GPP | 3rd Generation Partnership Project |
| API | Application Programming Interface |
| BaaS | Blockchain As A Service |
| CDR | Call Detail Record |
| DApp | Decentralized Application |
| DCH | Data Clearing House |
| DCM | Digital Currency and Minting |
| DLT | Distributed Ledger Technology |
| EVM | Ethereum Virtual Machine |
| HMNO | Home Mobile Network Operator |
| HPMN | Home Public Mobile Network |
| ID | Identity |
| IDE | Integrated Development Environment |
| IoT | Internet of Things |
| IMSI | International Mobile Subscriber Identity |
| L5GO | Local 5G Operator |
| MNO | Mobile Network Operator |
| NFV | Network function virtualization |
| NPM | Node Package Manager |
| PBFT | Practical Byzantine Fault Tolerance |
| PoB | Proof of Burn |
| PoC | Proof of Capacity |
| PoET | Proof of Elapsed Time |
| PoS | Proof of Stake |
| PoW | Proof of Work |
| QoE | Quality of Experience |
| QoS | Quality of Service |
| RPC | Remote Procedure Call |
| SMS | Short Message Service |
| VNF | Virtual Network Function |
| VPMN | Visited Public Mobile Network |

| | |
|---|---|
| AC | Available Capacity |
| B | Network Bandwidth |
| $C_{Data}$ | Data Cost |
| $C_{SMS}$ | SMS Cost |
| $C_{Voice}$ | Voice Cost |
| $J_A$ | Allowed Jitter |
| $J_D$ | Jitter Deviation |
| $J_S$ | Session Jitter |
| $L_A$ | Allowed Latency |
| $L_D$ | Latency Deviation |
| $L_S$ | Session Latency |
| $P_{B_A}$ | Allowed Blocking Probability |
| $P_{B_D}$ | Blocking Probability Deviation |
| $P_{B_S}$ | Session Blocking Probability |
| $PL_A$ | Allowed Packet Loss |
| $PL_D$ | Packet Loss Deviation |
| $PL_S$ | Session Packet Loss |
| $S_C$ | Cost Score |
| $S_O$ | Offload Score |
| $S_R$ | Reputation Score |
| $S_{RO}$ | Roaming Score |
| SS | Signal strength |
| $W_{AC}$ | Capacity Weight |
| $W_B$ | Bandwidth Weight |
| $W_C$ | Cost Weight |
| $W_{Data}$ | Data Cost Weight |
| $W_J$ | Jitter Weight |
| $W_L$ | Latency Weight |
| $W_{P_B}$ | Blocking Probability Weight |
| $W_{PL}$ | Packet Loss Weight |
| $W_R$ | Reputation Score Weight |
| $W_{SMS}$ | SMS Cost Weight |
| $W_{SS}$ | Signal Strength Weight |
| $W_{Voice}$ | Voice Cost Weight |

# 1 INTRODUCTION

The emerging 5G technology revolutionize the mobile communication. 5G is a promising technology which has the potential to provide disruptive connectivity, supports millions of devices, low latency and high reliability. These characteristics of 5G give rises to various applications. Mainly, industrial Internet of Things (IoT), smart cities, autonomous vehicles, remote surgeries, virtual and augmented reality and so on. Hence, 5G delivers services to fulfill the requirements of numerous vertical sectors. The adaptation of network softwarization in 5G allows to operate local 5G networks or the Local 5G operators (L5GOs). The concept L5GO is to establish local small cell networks for tailored service delivery. Blockchain technology is able to contribute in diverse ways to achieve the potential challenges arise with the implementation of L5GO models. Exploitation of blockchain features will ensure availability, low cost service, no intermediary intervention, secure transfer payments and to gain many more advantages.

## 1.1 Background and Motivation

The L5GOs will be a disruptive innovation of 5G networks to cater a diverse set of emerging applications [1]. The decentralization and locality oriented design of L5GOs will facilitate high reliability, context awareness and in-premise security and privacy management. The L5GOs are expected to serve wide range vertical sectors including smart manufacturing, entertainment, healthcare and so on. The distinguishing features of the L5GOs include the customized serving capability to the tenants as per the requirement [2]. The real world use cases may include the ultra-high speed internet connectivity with free data on the convention centres. Furthermore, the local 5G operators are applicable to many use cases including smart healthcare, entertainment, and manufacturing [3].

The roaming and offloading procedures allow subscribers to roam on different networks with persistent connectivity. The current system faces critical issues and has made researchers dive deep in to problems and to come up with solutions. Telecommunication industry lost over USD 38 billion annually due to roaming frauds [4], for most of which, preventive measures have not been taken yet. Roaming/offloading requires collaboration between network operators to deliver indispensable service. Hence, elevated level of interoperability is essential [5]. Visitor network operators must have the capability to leverage on this technology to improve roaming user's quality of experience and should guarantee to serve the subscriber as similarly or better as the way subscriber's home network serves. Additionally, there is potential for a partner operator to access the user's information unlawfully and to charge roaming users unfairly which might generate bill-shocks to users [6]. Therefore, the trust between operators must be maintained.

The popularity of L5GOs will trigger more and more number of roaming and offloading instances. Especially, MNOs (Mobile Network Operators) can offload their subscribers to L5GOs to offer better services without stressing their networks. However, above issues need to be addressed before enabling reliable roaming and offloading services.

The blockchain / Distributed Ledger Technology (DLT) is another disruptive technology which is distributed and decentralized in the operational perspectives. Researches are now urged to apply blockchain technology to overcome this situation

[7], [8], [9]. However, none of these proposals offer a complete roaming and offloading platform for L5GOs. Most of the proposals lack of the real implementations of their proposed systems.

Network Load Balancing is another key technology that have been addressed in this thesis. This concept basically discusses the distribution of traffic load among available entities (eg: Base stations) in specific geographical locations. In our approach, the load balancing functionality is implemented intending to boost the network efficiency of the system, minimize power consumption of base stations, achieve expected quality of service and maximize throughput. This concept executed in our model by establishing a dynamic agreement between MNO and L5GOs through smart contract on the blockchain.

## 1.2 Research Problem

Currently, L5GO is an emerging concept and still evolving. Therefore, this thesis developed addressing key drawbacks related to L5GOs and then to enhance its service delivery in both buying and selling aspects. The L5GOs can be deployed in two different ways. First scenario, L5GOs purchase the spectrum band from distinct MNOs and operate locally. Second scenario, L5GO owns their spectrum and they can re-sell their services to MNOs who are lacking in coverage within L5GO's territory. In both cases, blockchain can be useful to enable proper spectrum and services sharing between MNO and L5GOs. The research aims at developing a DLT based platform to enable secure, efficient and automatic sharing or selling spectrum and services between MNOs and L5GOs. Intermediate communication, transactions between these two parties are cryptographically secured within the blockchain. Also, faster settlements and transparency assured with the integration of blockchain. In other words, blockchain will enable MNO to L5GO and vice versa transactions in a decentralized network establishing trust among by recording transactions in an immutable distributed ledger.

## 1.3 Selected Scope

The thesis predominately evaluates the L5GO's selling service out of the two cases suggested in research problem. There are many research work promoted buying service, which is defined as the spectrum sharing mechanism. However, only a few research studies focused on selling service of the L5GO, which is expressed as the roaming service. Therefore, the scope of the thesis confined to the roaming service offerings. With this regards, an extensive research required to carry out to investigate the current problems in the roaming process. As expected in the research problem, involvement of blockchain technology is essential to address the explored issues. Thus, we decided to propose a blockchain-based platform to cater roaming and offload services for L5GOs. Moreover, other potential challenges within L5GO ecosystem are also intended to address in the thesis with the contribution of blockchain technology.

## 1.4 Contribution of the Thesis

To realize the goals of the thesis, blockchain opportunities in L5GOs are analyzed. Then it is important to comprehend challenges in each opportunities and to suggest methods to overcome them. Once all the approaches are identified, a blockchain as a service architecture is proposed by combining each and every suggestions.

To address the limitations of roaming service offering, the master's thesis proposes a novel blockchain based architecture for L5GOs to enable the offload and roaming services. The high level overview of the proposed platform is depicted in Figure 1.1. Our solution facilitates unique features explicitly, a universal wallet for each registered subscriber, the secure log of user details, a reputation management system to ensure the quality of service, automatic selection of the best-rated network for a subscriber, the supervision of traffic load across network operators and automatic execution of load balancing techniques and a system to avoid over-utilization. These service offerings are delivered with the establishment of dynamic smart contracts between stakeholders. A prototype of the proposed approach is implemented using Ethereum-based Decentralized Application (DApp). Finally, the performance evaluation is carried on the Rinkeby test network [10].

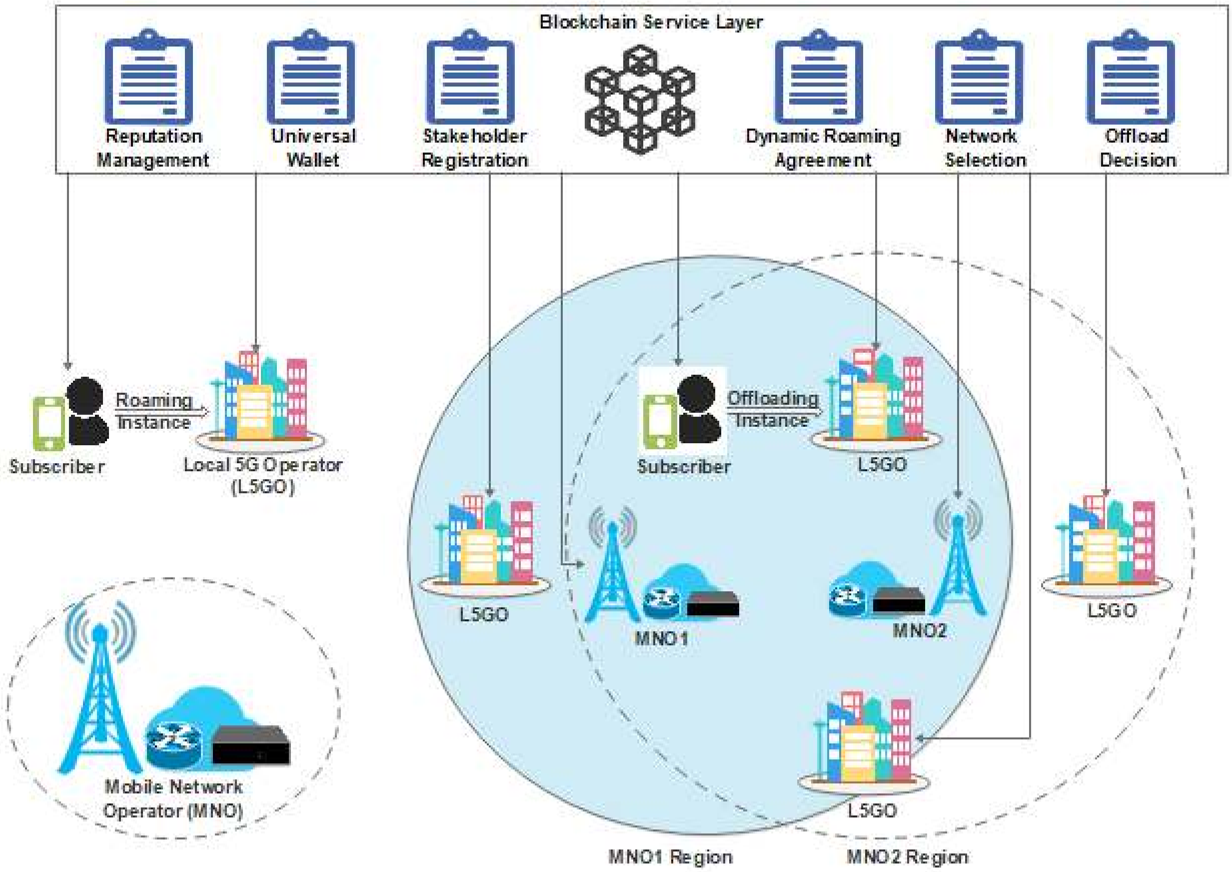



Figure 1.1. The high-level view of the proposed model

## 1.5 Structure of the Thesis

The rest of the master's thesis is organized as follows:

Chapter 2 basically discusses the existing research works carried out and related concepts on L5GOs and related works. Literature review consists of five sections. Initially, it concentrates on the progress of the current 5G networks and expected implementations in near future. Then the L5GO concept is defined briefly while explaining the roaming and offloading processes in L5GO. Next, key enabling blockchain features such as decentralized technology, immutability, distributed ledger technology, consensus, enhanced security, faster settlements, Digital Currency and Minting (DCM) and smart contracts are considered. It then elaborates the blockchain opportunities in L5GOs. Finally, it elucidates the problems in blockchain based L5GOs.

Chapter 4 explains the implementation procedures followed to execute the proposed model. Firstly, it provides brief descriptions of the utilized experimental environments such as Metamask, Web3.js, Remix IDE, Node Package Manager (NPM) and the Ethereum. Next, the architecture of the application is demonstrated with explanations. Then all the captures from the user interfaces of the DApp are depicted. Finally, the various functionalities of smart contracts and their interactions between each other are manifested.

Chapter 5 elaborates the experimental results obtained from testing the model on Rinkeby Testnet. This section provides latency measurements for various proposed operations. Further, it has recorded the transaction and execution costs consumed by each smart contracts. Moreover, proposed model's performance is evaluated in this chapter by carrying out a critical analysis based on the acquired results.

Chapter 6 comprises three sections. Firstly, it presents a comparative analysis between thesis work and the existing similar research works. Next, it evaluates whether the thesis work has achieved the defined objectives. Finally, it includes potential future research directions.

Chapter 7 manifests a summary of the complete thesis including research goals, proposed model and end results.

# 2 LITERATURE REVIEW

The thesis addresses the potential challenges of L5GOs, which accommodates the forthcoming case specific communication requirements in a 5G ecosystem. Thus, the literature review initially focuses on the 5G networks and its current developments. The latest 3rd Generation Partnership Project (3GPP) standards are also discussed. Next, a brief introduction on blockchain is provided with highlighting its vital features. Then, this chapter covers the study that has carried on key applications of L5GOs where the exploitation of blockchain features has become prominent. Further, the current drawbacks in a L5GO network are discussed. Moreover, our investigation on blockchain opportunities in L5GO narrow down to roaming application. Hence, a research study is carried out to explore the blockchain based previous works, related to international and national roaming. Finally, the potential challenges in blockchain based L5GOs are discussed with providing innovative solutions to eliminate them effectively.

## 2.1 5G networks

Currently, 5G networks are being embraced in diverse industrial contexts anticipating the unparalleled connectivity around the globe. These services of 5G primarily focused on delivering next generation mobile broadband using existing mobile frequencies. Furthermore, new millimeter wave frequencies will open up broader new bandwidth range. However, these networks are only the beginning of the revolution. The 5G 3GPP which is the standardization partnership that produces the specifications for 5G and already working on the next phase of 5G known as release 16 [11]. The specifications are scheduled to be completeed in June 2020. This will dramatically broaden the ecosystem and the diversity of use cases that can benefit from 5G. It adds a set of features enabling ultra-reliable low latency and time sensitive communications. These features are the key to supporting industrial IoT connectivity requirements which in turn is the foundation of the fourth Industrial Revolution where all processes and machines in a production environment are controlled with wireless connectivity. Among other features, release 16 will also focus on introducing support for private network deployments including corresponding security features as well as enabling 5G to be deployed in unlicensed spectrum. This opens new opportunities for enterprises and campuses to avail themselves of the benefits of 5G.

Continuing evolution of 5G is coming to fruition in early planning for release 17 targeted at the first half of 2021. This will include enhanced support of industrial IoT with wider support for highly synchronous communications between devices [12]. Engineers expect a light version of 5G to be provided which will enable 5G devices to be built at lower cost with longer battery life while simultaneously providing higher data rates and reliability and lower latency than existing IoT technologies as the 5G ecosystem continues to expand non terrestrial connectivity will be integrated into the networks providing coverage even in the remotest of areas by means of high-altitude platforms and low-earth orbit satellites and release 17 will provide enhancements to network edge computing as well as further evolution of the all-important security features looking even further ahead the range of radio frequencies that can be exploited by 5G will be expanded with new technological developments opening up new bandwidth beyond 52.6 GHz up to 71 GHz [12].

## 2.2 Local 5G Operators

Currently, the main visible trend in telecommunication industry is subscribers being hungry for data. In the future, the number of smart devices connected to a one person will increases with the beginning of 5G era [13]. With the exponential growth of IoT usages, the capacity requirement grows significantly and the network operators must deliver network services to end users with minimum latency, high speed and ultra-reliability [14], [15]. Network operators try to build up the data chain which could serve all of those hungry endpoints. This can be considered as one of the major pressures a network operator goes through. To fulfill this requirement, 5G architecture must include large number of base stations in it [16], [17]. As a solution for these consequences, researches have introduced the L5GO concept. L5GO is a small scale mobile network which spans across a limited geographical area such as university, hospital, factory or shopping mall. L5GOs allow companies or building owners to operate their own 5G communication ecosystem with a unique design depending upon the operation specific requirements [18]. Further,the contrastive features of L5GOs compared to MNO are exhibited in figure 2.1.

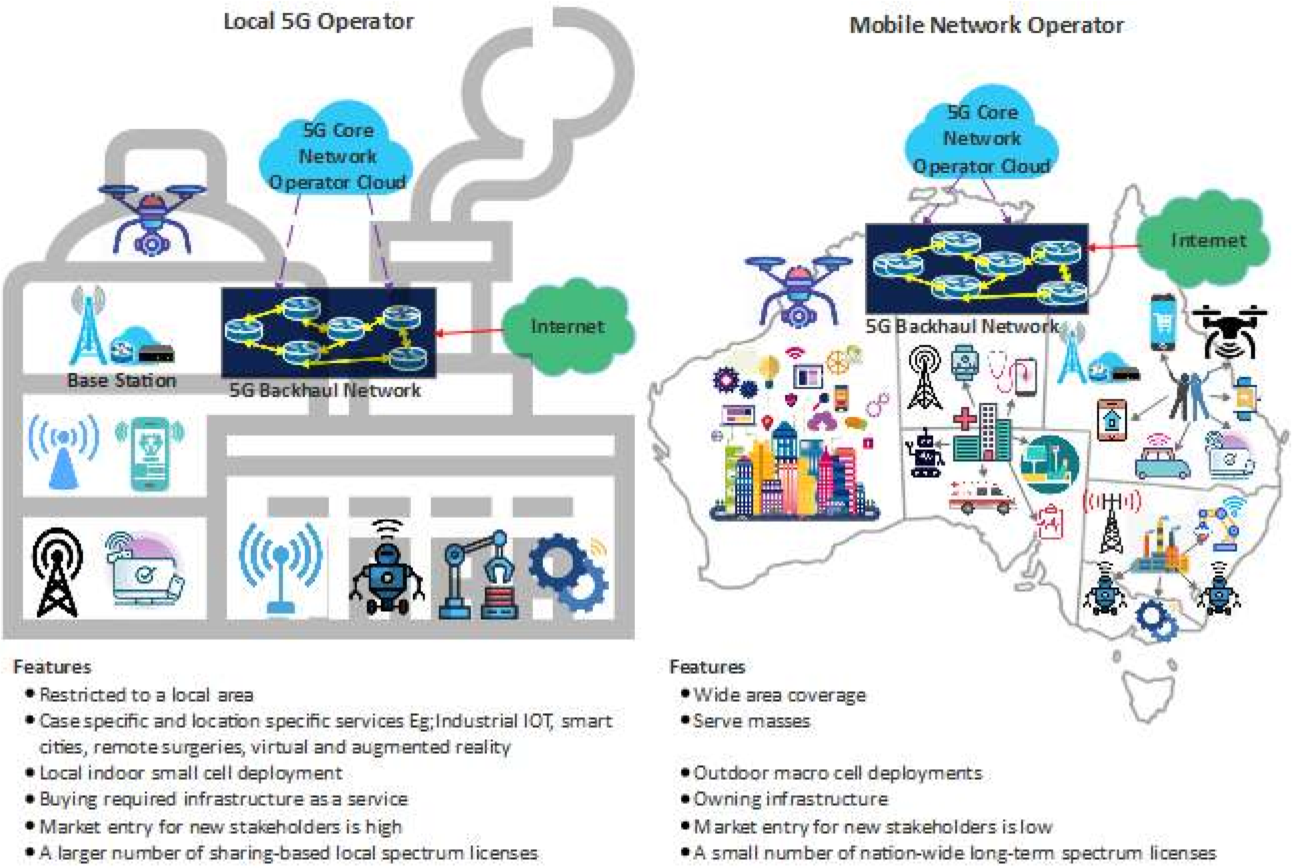



Figure 2.1. Comparison between MNO and L5GO

### *2.2.1 Roaming in L5GOs*

The roaming provides connectivity for a subscriber in a visitor network through the home network operator. This occurs when a subscriber's home operator does not have proper coverage within a specific geographical region [19]. As per present, home MNO should have pre-established agreement with visitor MNOs or L5GOs to enable the roaming services for its subscribers. However, such static and pre-established agreement procedures will not be practical when there are many L5GOs.

### *2.2.2 Offloading to L5GOs*

Offloading allows MNOs to handover the network traffic load to other networks to boost the network efficiency of the system, minimize power consumption of base stations, achieve expected quality of service and maximize throughput. Since L5GOs offer better coverage inside their premises, MNOs can use these L5GOs to serve their subscribers when they resides in L5GO's coverage area.

## 2.3 Blockchain Technology and its Key Features

Blockchain technology converts the traditional way of our work by allowing users to exclude the central authority from various services, cutting costs and uplifting productivity. Blockchain can also comprehended as a decentralized ledger. The technology adds transaction to the ledger after validated by thousands of miners in the public network rather than by a middle party. This part of the sub section provides a brief overview on blockchain with its key enabling features that can be used to cater the requirements of a L5GO ecosystem.

### *2.3.1 Decentralized Technology*

Blockchain technology provides a public decentralized database of the transactions committed, by creating a record for which the authenticity is verifiable by the connected community. A Decentralized Network essentially is a network that isn't controlled by any single central entity [20]. Such a network is formed by a large number of nodes connected to each other. This is the unique underlying feature, that makes the blockchain technology a reality. With that, users are given the full control and authority over what they share or store securely in the blockchain and are protected from unauthorized access using private key/public key pair. Moreover, third party centralized trust is eliminated with the distributed trust establishment of the core architecture of the blockchain.

### *2.3.2 Immutability*

Each block bundles an array of transaction records and the cryptographic chain links. Blockchain, like any other database, is technically prone to forgery [21]. However, thanks to the distributed core architecture of blockchain network, the mathematical puzzle to solve the forgery is extensive and unreachable with current computing infrastructure. To alter a chain, one would need to take control of more than fifty one percent of computers in the same distributed ledger and alter all of the transactional records within a very short period of time. To date, this has never happened. Network confirms the record and lists the blocks of transactions sequentially [22].

### *2.3.3 Distributed Ledger Technology*

Blockchain is known as the DLT with explicit the idea of digital databases where every member can supplement the data stored within the ledger [23]. It is decentralized and functioning as a peer-to-peer network. Moreover, blockchain records transactions in a distributed ledger of blocks.

### *2.3.4 Consensus*

Generated blocks pass through an approval process. Firstly, blockchain selects the next block that will be added to the chain. Next, the selected block is verified for the cryptographic trust chain, including Merkle tree, previous block signatures etc. Then, it will be added to the current chain after verification. Validation and the consensus process is carried out by special peer nodes called "miners". Furthermore, there are different types of consensus algorithms exists. They are Proof of Work (PoW), Proof of Stake(PoS), Practical Byzantine Fault Tolerance (PBFT), Proof of Burn (PoB), Proof of Capacity (PoC) and Proof of Elapsed Time (PoET) [24], [22], [25].

### *2.3.5 Enhanced Security*

All the blockchain data are hashed cryptographically using the hashing algorithm. That is a mathematical function which takes arbitrary length of numerical data and convert that into a fixed length numerical data. Though the size of the input data can be varied, length of the output data will be fixed. Based on the algorithm which we are using to do the hashing operation,the length of the output will be changed. For instance, SHA-256 algorithm returns a unique 256 bit hash [26]. A small modification in the dataset will change the entire hash value in a different manner. Therefore this process is irreversible since there is no possibility to obtain the actual input from the hash value though conversion of given data set into a hash is easier. In the blockchain, Public key cryptography mechanism is utilized where the private key is used for the data access while public key is used for transactions purposes. Anyone can use the public key but it is impossible to find out the private key from the pubic key. Moreover, every block in ledger has its own unique hash with the previous block's hash. Thus, to alter the data in the distributed ledger, one has to modify each and every hash value which is impossible. since all the nodes have a replica of the ledger. Therefore, blockchain enhances the security in the network [22], [25].

### *2.3.6 Faster Settlement*

Processing time of a transaction in the blockchain network is faster than the conventional banking models. Further, the processing fee is negligible with the disappearance of an intermediary party [27]. This will bring real benefits for people who maintain international rapports.

### *2.3.7 Digital Currency and Minting*

The most popular way of minting coins in blockchain network is the process of mining. The miners are the powerful computers executing the software defined by blockchain protocol and they are incentivized with a fee (eg: bitcoins or Wei) for the computational effort committed to the transaction verification in the blockchain [28]. Miners select the set of transactions from the pool of unconfirmed transactions to create a block. Then miners compete by solving a puzzle in order to determine which miner has earned the right to create the next block and the solved block is broadcasted. Finally, the other participants verify received block and adds it to the chain and to their local copy of blockchain.

### *2.3.8 Smart Contracts*

Smart contract is a piece of code deployed in blockchain node, bascially they are built for contracts and that resembles a class definition in an object oriented design [29]. The execution of smart contract initiated by a message embedded in a transaction. Every node in blockchain network should be able to execute the code irrespective of underlying type of operating system or hardware. We are able to trust smart contracts since they are stored on a blockchain and inherit some interesting properties of blockchain. They are immutable and they are distributed. Being immutable defines the fact that once a smart contract is created, it can never be changed again. Thus, no one can tamper with the contract code. Being distributed means that the output of your contract is validated by everyone on the network. Thus, a single person cannot force the contract to do unlawful things (eg: release the funds) because other participants on the network will spot this attempt and mark it as invalid tampering with smart contracts and becomes almost impossible. Now, there are a handful of blockchains who support smart contracts, but the biggest one is Ethereum. It was specifically created and designed to support smart contracts. They can be programmed in a special programming language called Solidity. This language was specifically created for Ethereum and uses a syntax that resembles Javascript.4

## 2.4 Blockchain Opportunities in L5GOs

An extensive research has been carried out to investigate the vital opportunities provided by blockchain in L5GO ecosystem. Such key applications of L5GOs are listed below along with their potential challenges.

### *2.4.1 Spectrum Sharing*

By default the mobile network spectrum is limited and the demand is expected to inflate with the future computing and networking demand. Hence, authorities lease the bands of the spectrum. In L5GO concept, there are three spectrum management options for a L5GO listed in the research study [30]. They are MNO centric, L5GO centric and collaboration centric spectrum management strategies. In this part of the section, we are addressing the challenges expected if the L5GO has selected the collaboration centric mode where the L5GO leases the local spectrum from MNO and operates locally. In a spectrum sharing process, a central authority exists to handle all the collaboration related operations and the agreements. This setup incurs an additional overhead to both the parties and the service subscribers have to pay extra fees. Therefore, we can apply blockchain concepts to eliminate the central authority and avoid excessive charges which is eventually beneficial for the parties intervene in the system.

### *2.4.2 Roaming*

Firstly, roaming fraud arises when a user attempts to utilize the Visited Public Mobile (VPMN)'s resources even after the end of a session. In such circumstances, it may take some time to synchronize and detect the fraud due to the existence of data transferring delay. Then, Home Public Mobile Network (HPMN) is incapable to charge the user but compelled to pay for the delivered service [4]. Secondly, roaming user experience is discouraging due to the poor service delivery and unexpected price discrepancies [5]. This is common due to the pre-selection of a local operating partner regardless of their quality of service. Thirdly, lack of transparency in the roaming processes. Due to the violation of static agreements and pre-agreements by network operators will provide bill-shocks to users [6]. Real-time network characteristics such as current load and bandwidth are not assessed in such agreements.

### *2.4.3 Offloading*

With the popularity of L5GOs, there will be more customers attracted towards its service. The smart city is a potential application for L5GO. A massive number of tenants expected to onboard with an extensive usage traffic. This phenomenon causes low network efficiency in the system and maximizes power consumption of base stations [31]. This will degrade the service quality and system's throughput. Therefore, offloading is an ideal technique to eradicate the significant drawbacks associated in terms of scaling up the usage. To achieve this functionality, L5GO selects the next optimal L5GO to achieve the maximum benefits of offload technique. Hence, we can use blockchain for the network selection process.

#### *2.4.4 Consortium*

Generally, L5GO contributes to the massive scaling requirements of subscribers and supports MNOs with customized demand varieties of their customers by providing cost-effective local service. To strengthen the service, L5GO required to have collaborations with small-scale or third party providers such as content providers, network infrastructure vendors, equipment vendors and facility owners [3]. For an efficient collaboration, existence of a middle organization is essential to handle the agreements and consequences where both the L5GO and third party providers must pay additional fees. This causes additional overheads, specially for smaller business entities. There will be an extra processing and transaction since all the agreements need to go through an intermediary party. Therefore, blockchain technology can be used as a tool to replace the role of a central authority.

#### *2.4.5 Identity Management and Data Access*

Current challenges in the identity management and data access includes the identity or subscription identity (ID) theft. A malicous node deliberately uses someone's identity credentials to obtain data or service access to their respective registered L5GO. In addition to that, the subscribers require to pass through a sequence of authenticating processes whenever they visit another L5GO which is a cumbersome experience to the customer.

#### *2.4.6 Virtual Network Function (VNF) Management*

Generally, several organizations operate the Network function virtualization (NFV) ecosystem. Consequently, challenges might triggered if any illegal organization uses VNF instances. This encounters massive damage to VNF and generic hardware provider. Further, more problems arise when the service delivered by different VNF vendors are not compatible as they have promised. Moreover, there can be challenges in the payment process between VNF provider and the L5GO [32]. For example: false details on VNF's consumption and payment policy disputes. Blockchain is a good solution to overcome illegal utilization and interoperability issues that might cause in the management process of VNF.

#### *2.4.7 IoT Data Management*

IoT has become an integral part of the current generation of information technology and it continues to grow at a rapid pace. As data generation, data analysis and data transportation are at the heart of IoT, it is equally important to secure them throughout their life-cycle. Due to the centralized nature of majority of IoT systems available today, they will not be able to cater the exponential growth of IoT technology which is expected in near future [33], [34], [35]. Data security will be at a risk, and devices will have to suffer from increased latencies due to network bottlenecks [36], [37].

## 2.5 Challenges in Blockchain Based L5GOs

Despite of all the benefits of blockchain in L5GOs, there are still crucial bottlenecks to be improved. All the potential drawbacks that can be arisen within the L5GO network are explicitly discussed below. Further, various techniques used in the industry to tackle each consequence are explained. With the execution of these methods will boost up the network efficiency of L5GOs.

### *2.5.1 Legal Issues*

The most significant legal hurdle in the blockchain based L5GOs arise when the personal data being stored on unknown nodes without data owners consent. Other type of legal issues are the ordinary suspects that we find on technology related applications. Mainly, the scope of the license, whether any open source software being used and they licensed under permissive or copyleft license terms, the warranties or indemnities are provided by the blockchain supplier, the scope of the support by the supplier service levels and service credits commitments to fix defects. All the problems occurred with the lack of regulatory in the blockchain technology achieved with the decentralization [38]. The regulatory authorities are still reluctant to enforce their legal system to facilitate the blockchain based L5GOs [39].

#### Possible Solutions

Government and regulatory bodies must take necessary actions to make sure that the blockchain applications of L5GOs are functioning within prevailing regulatory laws. For that, they should understand the influence of the blockchain in both commercial and customer segments of L5GOs. Further, to form new set of regulations specifically to blockchain based L5GOs.

### *2.5.2 Scalability*

Major scalability issue in L5GO arises with the the popularity of L5GOs. That is, with the growth of number of L5GOs will lead to more and more number of roaming and instances. Another significant limitation in blockchain based L5GOs is the scalability requirement of the ledger [40]. In blockchain, blocks are used to store the verified transactions. The maximum size of a block is limited [41]. For instance, Bitcoin has 1 MB size blocks. There is an increasing demand to process a large number of transactions in a short period. However, Bitcoin processes four transactions per second and Ethereum process is fifteen [42]. Even though, either the block size increased or time between the transaction changed, still the problem persists. In addition to that, the cryptographic operations incur significant overhead and eventually limit the scalability performance factors on lightweight computing nodes such as Raspberry Pi nodes which are functioning within L5GOs.

**Possible Solutions**

One of the solution to the above issues is offloading the subscribers of L5GOs to another L5GO to offer better services without overloading their own networks. Further, there are set of new techniques have been introduced to eliminate scalibility challenges. For instance, the Lightning Network, which is a second layer technology that function on top of blockchain to boost the speed of the transaction process. Additionally, the Sharding concept is another way to scale up the blockchain's performance. Data is shared among multiple shards; each shard is an independent node on the ledger that are responsible to process transactions parallel. Further, PoS and Segwit are other important models that have been initiated to overcome the scalability challenges.

### *2.5.3 Latency*

The time taken to process a complete transaction is increasing when the transaction ledger grows. Thus, the transaction cost goes higher than usual which limits the number of users in the network. This creates a problematic situation for whole blockchain network in the L5GO except for its instance of storing a value [43]. Moreover, blockchain is a candidate technology to replace banks and credit/debit cards by enabling the peer to peer payments. Visa card can handle thousands of transactions per seconds and millions of people doing transactions every day. In contrast, Bitcoin technology can only process around seven to ten transactions per second which is a significant drawback which makes the people reluctant to use Bitcoin for day to day retail transactions.

**Possible Solutions**

The latency challenges could be tackled with initiating ways to boost the processing speed. Further, the advancements in technology and processing speeds are required. Thus, more attention from researches and engineers in the field of L5GOs is vital at this stage.

### *2.5.4 Security and Privacy*

Blockchain is known to be a public blockchain. The term public refers to that the blockchain available to everyone where anyone can see the data. For instance, sensitive data stored in L5GO will be out there for anyone in the blockchain and will be no more confidential [44], [43]. This might cause damage to the reputation of L5GOs. In terms of security of L5GO, blockchain technology is not totally immune to hackers ,malicious attacks,frauds,..etc. To hack the blockchain network of L5GO, hacker should has the control over more than 51% of the total computing power of the complete blockchain network [22]. Therefore, there is a still a possibility for the blockchain network ulitized in L5GO to be hacked.

**Possible Solutions**

The Self-sovereign identity concept can be utilized to solve current challenges in security and privacy of blockchain based L5GOs. It facilitates any individual to own and manage their identity deprived of central directories.

### *2.5.5 Waste of Resources*

Energy consumption in the blockchain technology within L5GO is high since it utilizes a consensus algorithm to validate transactions [43]. For instance, Bitcoin follows the PoW concept. Accordingly, all the miners must solve the given complex mathematical puzzle which requires huge amount of computing power. Hence, this whole process consumes a great amount of energy and time, which is another problem to be solved.

**Possible Solutions**

Energy efficient consensus algorithms such as PoS are developed to address the above challenges. It reduces energy-intensive mining processes comparable to PoW. In PoS, the creator of new block is chosen randomly from pool of users that have staked a certain amount of cryptocurrency. Further, this process eliminates the process of rewarding when a contributor solves a complex mathematical puzzle. Thus, the PoS mechanism does not require massive energy.

### *2.5.6 Synchronization Network Overheads*

Synchronization of the nodes in the network is a core requirement in the blockchain based L5GO network. Each and every node will reach to consistency in blocks and transactions upon the block generation. The valid blocks disseminated within the nodes upon approval and eventually stored in the individual nodes after consensus [45], [37]. The block dissemination incurs a significant data overhead for the nodes. When the number of nodes increased, the network overheads also increased within the ecosystem.

**Possible Solutions**

A customization of consensus towards a data optimal synchronization is required to eliminate the network overheads incurred in the blockchain based L5GO network for synchronization. The elimination of data redundancy and re-designing of block and transaction data objects will reduce the size of individual data objects and eventually optimal transaction consistency.

### *2.5.7 Ledger Consistency Synchronization Delay*

Ledger consistency delay makes the entire blockchain network within L5GO inconsistent within a particular time frame after a transaction being committed. If any concurrent transactions committed from different nodes targeting a same data object, the inconsistency will make the transactional operation inaccurate within a specific time [37]. Thus, L5GO will have limitations when blockchain is incorporated in contrast with centralized systems.

**Possible Solutions**

Improvement of the consensus mechanism to minimize transaction approval time is the best solution to make the transaction process to complete with a minimal delay. In addition to that, the network level optimization will reduce the network delay in the consistency operation and eventually make the entire L5GO ecosystem consistent within a shorter period of time.

### *2.5.8 Ledger Growth*

Ledger growth is a significant challenge in blockchain based L5GOs. The core principle of the blockchain is the immutability of the shared ledger and L5GO networks should accept it. The growth of the ledger incurs storage overheads to the nodes corresponding to L5GOs [45], [46]. Further,the L5GO consists large number of resource restricted devices such as IoT nodes, the storage overheads will lead to performance limitations within the L5GO network.

**Possible Solutions**

Above challenges can be addressed by utilizing a software defined storage method which de-couples the storage from containers. Further, the total capacity of L5GO can be improved by adding storage devices to the pool. Also, by expanding the logical size of the container volume.

# 3 PROPOSED ARCHITECTURE

This chapter proposes two main architectures under two separate sections. One of the sections presents a blockchain based architecture which enables both roaming and offloading services for L5GO and discusses all the algorithms and functionalities used in the proposed model. The second model demonstrates numerous blockchain solutions to tackle challenges in L5GO network and discusses how blockchain service offerings can be managed by the Blockchain-as-a-Service (Baas) platform.

## 3.1 Architecture for Roaming and Offloading Service Platform

A novel architecture for delivering roaming and offloading services to L5GOs is illustrated in Figure 3.1. The architecture comprises of three major stakeholders, namely subscribers, MNOs and L5GOs.

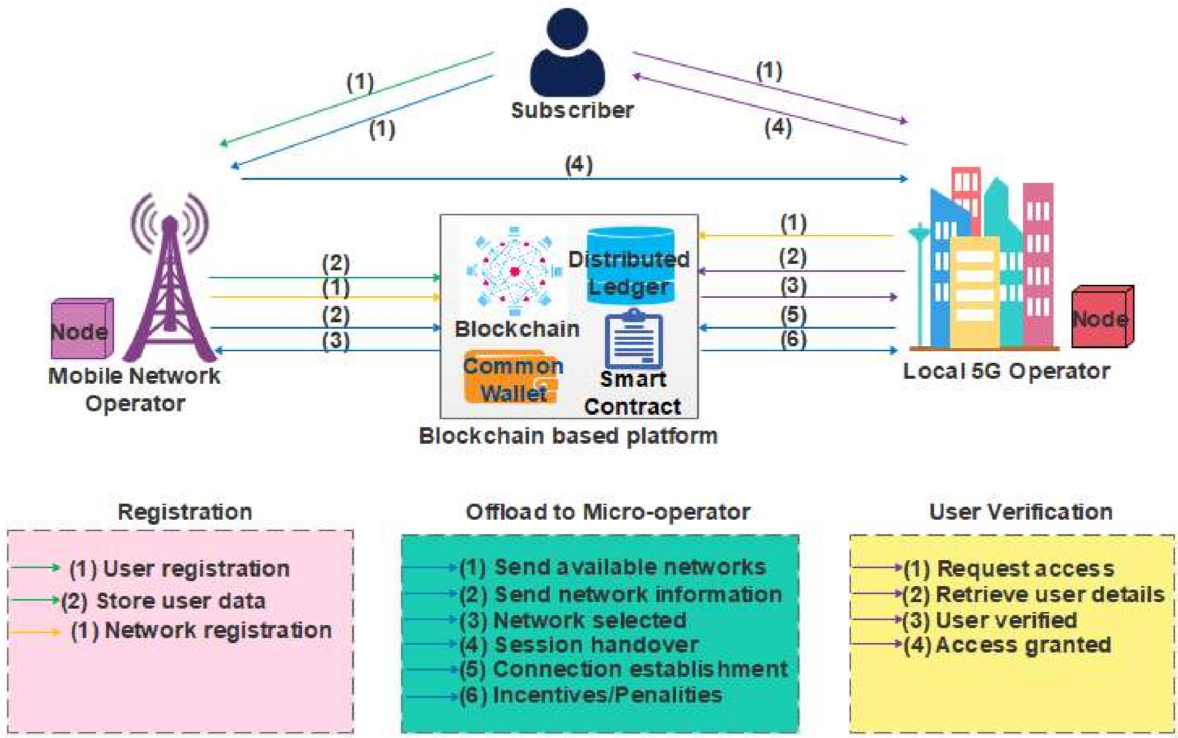



Figure 3.1. The proposed architecture

A blockchain based backend is proposed to offer various services to enable offloading and roaming between MNOs and L5GOs. Some of its services are described below; User, network and their related details are logged in the distributed ledger. Smart contracts are deployed to guarantee that the subscriber receives their desired connectivity experience throughout their stay at the L5GO region securely and efficiently. For example, enabling a cost efficient and transparent roaming service, selecting the best network provider based on their reputation and charging schemes, enforcing L5GO towards better quality of service by awarding incentives or incurring penalties through a reputation management system, verifying users and implementing a charging system are some of them. A universal wallet concept also enabled through Ethereum blockchain platform.

The basic functionalities of the proposed platform are discussed with the help of algorithms. The notations used in these algorithms are listed under the abbreviations and symbols section .

### *3.1.1 Registration of Stakeholders*

All three stakeholder i.e subscribers/users, MNOs and L5GOs are registered with blockchain.

**The user registration** process initiated whenever a new subscription is activated. During this procedure, the subscriber's details (i.e.name, the national identity card number, the home address) are uploaded to the blockchain by the MNO. MNO is responsible to store the user's details with their corresponding International Mobile Subscriber Identity (IMSI) number as the key, in the distributed ledger. Furthermore, a universal wallet will be assigned to each user.

In **the network registration process**, the information of MNOs and L5GOs will be recorded in the chain, including information relating to the network bandwidth, network capacity and their charging scheme. This process allows to create only one account per operator. Any of these details can be retrieved with operator's account address. Moreover, the initial reputation score of the operator is set to the system's average reputation score to maintain an equality among network providers. System's average reputation score is calculated by averaging all the reputation scores of the currently registered networks. Further, a cost rating is calculated for each network's pricing schemes by combining call, Short Message Service (SMS) and data costs with pre-defined weights for each parameter. The proposed cost score computation is given in (1).

$$S_{\mathrm{C_i}} = W_{\mathrm{Voice}} * C_{\mathrm{Voice_i}} + W_{\mathrm{SMS}} * C_{\mathrm{SMS_i}} + W_{\mathrm{Data}} * C_{\mathrm{Data_i}} \tag{1}$$

### *3.1.2 Universal Wallet*

During the registration, a universal wallet is created in the blockchain for each stakeholder. The usage charges are deducted directly from the subscriber's wallet based on their consumption and MNOs' pricing policies. Security is enhanced since all these operations function within the blockchain itself. These transactions between L5GO and subscriber will be recorded in the distributed ledger making it transparent to the user. Hence, the dispute resolution is also improved with transparency and non-repudiation is assured.

### *3.1.3 Offloading*

This functionality applies to the customers who have both the home operator coverage and the coverage of one or more L5GOs. Whenever the HMNO's capacity utilization exceeded a pre-defined threshold value of the total capacity, offload process will trigger. The MNO calls the offload decision contract after acquiring list of available networks for a selected subscriber. Among them, the best network for the user is selected by calculating a offload score for each detected network, as shown in (2).

$$S_{\mathrm{O_i}} = W_{\mathrm{AC}} * AC_{\mathrm{i}} + W_{\mathrm{B}} * B_{\mathrm{i}} + W_{\mathrm{C}} * S_{\mathrm{C_i}} + W_{\mathrm{R}} * S_{\mathrm{R_i}} \tag{2}$$

The network capacity and network bandwidth parameters are given a high dominance with weightages to ensure the load is balanced optimally. Then, a comparison is performed to find the highest rated operator among the "n" number of networks detected around the user.

Once the network with the highest rating is obtained, the deviation between the highest rating and the current network's rating is computed. The deviation is then compared against a pre-defined threshold and checked whether it is greater than the pre-defined threshold. Only if that condition is satisfied, a dynamic offloading agreement is established between the MNO and the selected L5GO by using a smart contract. Subsequently, the subscriber will be offloaded to the selected L5GO.Thereafter, the user receives the network services through the L5GO based on agreed policies.

The complete offloading strategy is expressed in the Figure 3.2.

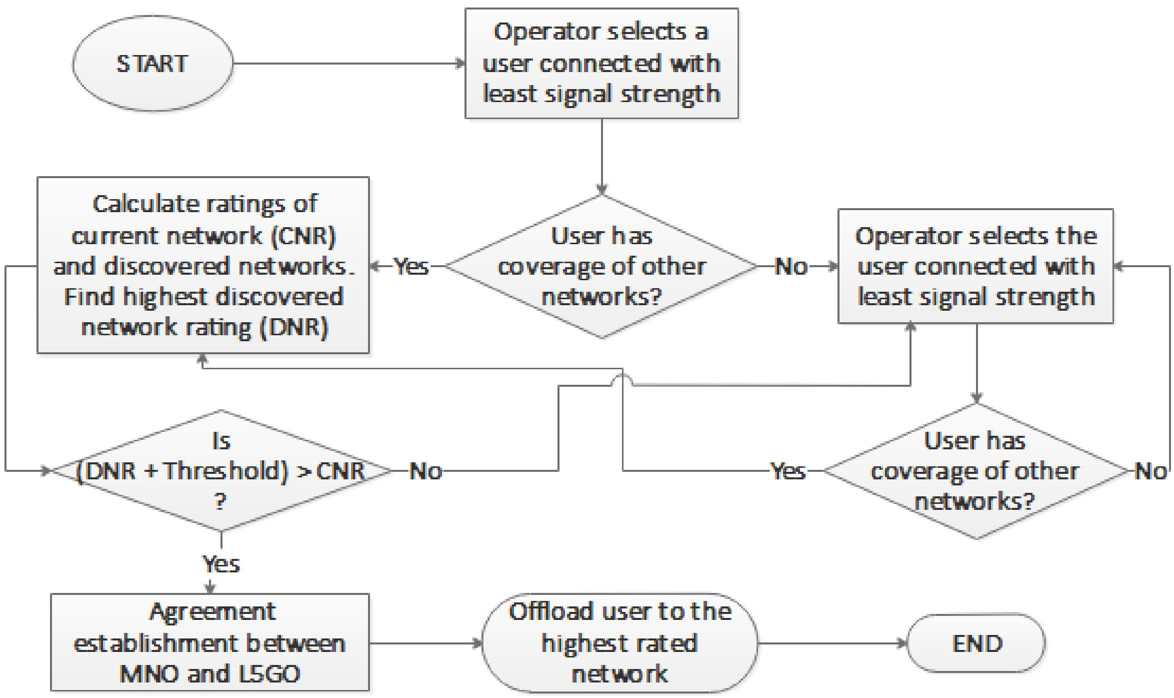



Figure 3.2. The flow of offloading procedure

### *3.1.4 Roaming*

This service is triggered when a user goes out from the home network coverage area. The user starts the process by sending details, including RSSI levels, of k number of nearby networks to a nearby L5GO. This data will then be processed on the blockchain via smart contracts, to find the best available L5GOs for the user. In the network selection algorithm, a roaming score for each network is computed by considering the service cost, reputation score and signal strength as per (3). Cost and reputation data are retrieved from the distributed ledger.

$$S_{\mathrm{RO_i}} = W_{\mathrm{SS}} * SS_{\mathrm{i}} + W_{\mathrm{C}} * S_{\mathrm{C_i}} + W_{\mathrm{R}} * S_{\mathrm{R_i}} \tag{3}$$

Once the roaming scores are calculated for each available L5GOs, the L5GO with the highest rating factor is selected for the user. Then, a dynamic roaming agreement is established between the selected L5GO and the MNO. Thereafter, the L5GO will offer roaming service to the subscriber. The roaming procedure is illustrated in the Figure 3.3.

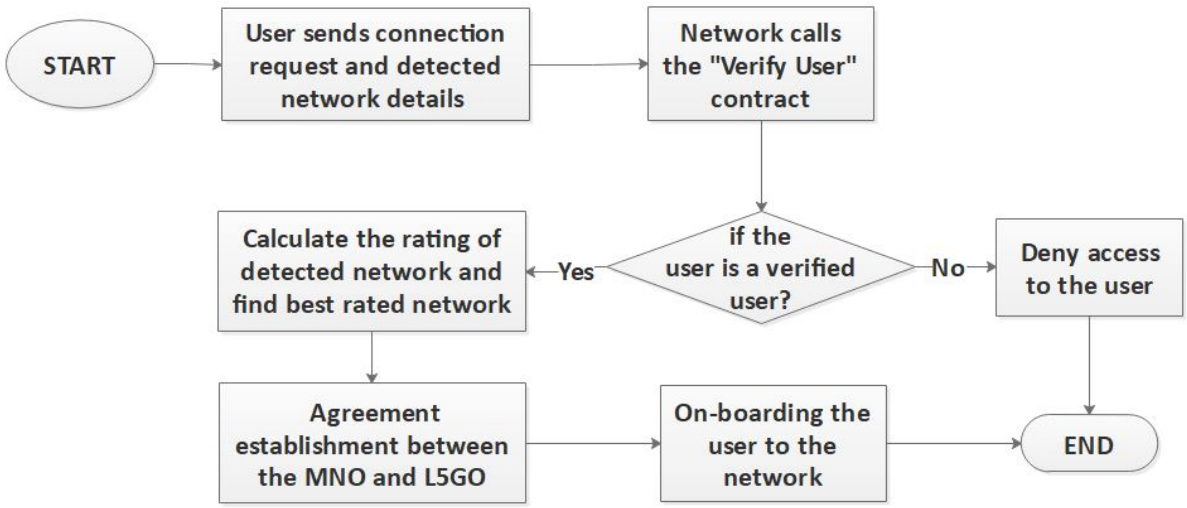



Figure 3.3. The flow of roaming procedure

### *3.1.5 Reputation Management System*

This system is responsible to maintain reputation score for each L5GO based on their performance as a service provider. Both incentives will be offered to operators with a good reputation while penalties will be incurred from the operators with an unsatisfactory track record. This essentially compels L5GO to offer high quality services and users will ultimately experience a high service quality. At the end of each successful session, the reputation management contract will be called to calculate the reputation score as demonstrated in the equations (4), (5), (6) and (7). The reputation score will be calculated based on several performance characteristics i.e. latency, packet loss, jitter and blocking probability.

$$L_{\mathrm{D}} = L_{\mathrm{A}} - L_{\mathrm{S}} \tag{4}$$

$$PL_{\mathrm{D}} = PL_{\mathrm{A}} - PL_{\mathrm{S}} \tag{5}$$

$$J_{\mathrm{D}} = J_{\mathrm{A}} - J_{\mathrm{S}} \tag{6}$$

$$P_{\mathrm{B_D}} = P_{\mathrm{B_A}} - P_{\mathrm{B_S}} \tag{7}$$

Next, to obtain a score value, a weighted sum will be calculated using above parameters as given in (8). Having an unique weight for each parameter allows prioritizing one or more factors over the others.

$$S_{\mathrm{R}} = W_{\mathrm{L}} * L_{\mathrm{D}} + W_{\mathrm{PL}} * PL_{\mathrm{D}} + W_{\mathrm{J}} * J_{\mathrm{D}} + W_{\mathrm{P_B}} * P_{\mathrm{B_D}} \tag{8}$$

Then, the moving average of the reputation score is calculated by considering both the previous average and current session scores.

$$S_{\mathrm{Rmoving}} = \alpha S_{\mathrm{Rcurrent}} + \beta S_{\mathrm{Rprevious}} \tag{9}$$

where $\alpha$ and $\beta$ are known to be the weight coefficients and addition of these two coefficients should be equal to 1. The network operator is allowed to set values for them depending upon their preference. Finally, the new moving average of the reputation score of the respective L5GO is updated and stored in the distributed ledger.

### *3.1.6 Fraud Prevention*

Fraud prevention measures are managed through usage limit smart contract. Whenever a service is requested by a subscriber from a L5GO, usage limit contract will be invoked to retrieve remaining account balance of the user. However, the user's account balance will not be directly shared with the L5GO, instead the contract will calculate the maximum cost for service that the L5GO can charge the customer. With this information, L5GO can determine when to terminate the service given to the user, even before the session is started, essentially avoiding over utilization problems.

## 3.2 Architecture for BaaS Platform

This section describes how blockchain technology can accommodate the previously discussed opportunities under chapter 2. The blockchain technology is exploited in L5GO networks to overcome the probable challenges of L5GOs and to ensure availability, low cost service, no intermediary intervention, secure transfer payments and to gain many more advantages.

### *3.2.1 Proposed Components in BaaS*

Novel strategies such as rating systems, bidding techniques are introduced along with blockchain to overcome the major challenges in a L5GO ecosystem. Each proposed solution is defined as components in this sub-part of the section. The Figure 3.4 depicts an overview of the innovative techniques that have suggested under BaaS for each service delivery.

#### Auctioning Component

A blockchain-based auctioning system provides a common bidding platform for all the nodes. All the available bidding resources and their prices of each MNOs are recorded

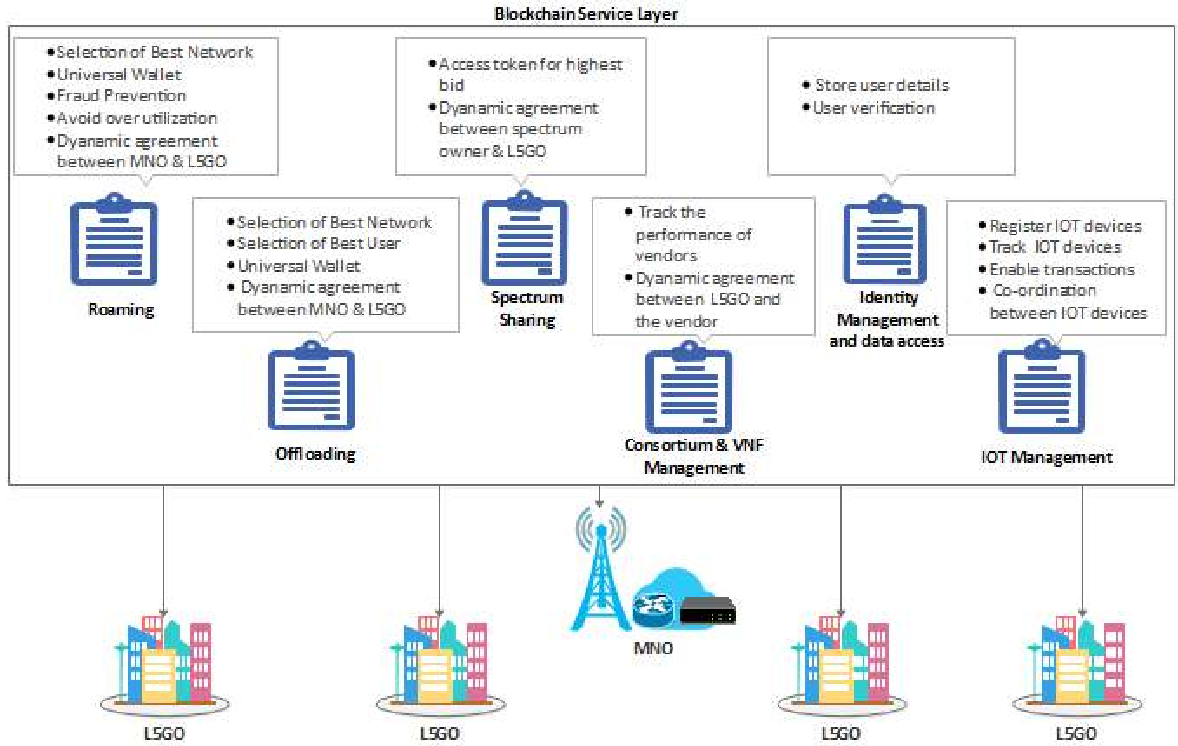



Figure 3.4. Services offered by Blockchain

in the smart contract. The bidding is implemented through a web-application. All the L5GOs bid for a resource. The access tokens are granted for each L5GO based on the highest bidding. The used auctioning criteria and conditions are recorded in the smart contract with the transaction record in the ledger. This is a one time operation. Next, the negotiation is made between each pair of MNO and L5GO while establishing an agreement via the smart contract.

### Network Selection Component

This mechanism keep track of each L5GO including information regarding their pricing, coverage, reputation etc., which are securely stored in the blockchain via smart contracts. The user initiate the process by sending details, containing RSSI levels of other networks nearby the L5GO. With the information gathered, the L5GO then calls a smart contract on the block chain, which calculates a score for each network detected by the subscriber, using details including signal strength, reputation, charging scheme etc. Among them, the best network for the user is selected as the network with highest score. Subsequently, the subscriber will be offloaded to the selected L5GO. Upon connecting, the stakeholders will negotiate on each other's pricing and other terms, and it will be recorded in the blockchain after the consent of each party. Thereafter, the user receives the network services through the new L5GO based on agreed policies. Payments will be then deducted automatically from universal wallet based on the consumption.

### Offload User Selection Component

Eligibility to offload will mainly depend on the signal strength of the connection between L5GO and subscriber. Whenever a particular L5GO's capacity utilization exceeded a threshold percentage value of the total capacity, the L5GO starts selecting the most eligible subscriber to offload. Then network selection process will be triggered.

### Fraud Prevention Component

The application of blockchain based smart contracts to the L5GO are beneficial to L5GO in different dimensions. The blockchain operates with decentralization. The decentralization leverages the decentralized and robust access control implementation to the user data, which is usable by malicious parties to commit frauds. The smart contract provides transparency in the execution logic, which enhances the trust between intervening parties. Furthermore, the integration of distributed ledger maintains a transparent log of footprints of the activities by each party. The transparency of logs are important in case of dispute resolution scenarios to ensure non-repudiation and trust between the resolving parties. Furthermore, the logs attached to the distributed ledger are immutable which guarantees that none of the party can change it. When comparing to the logs of centralized systems, the tenants can be reluctant to accept the logs provided by MNO in case of dispute resolution since the MNO has potential to change the logs in favor of themselves. These types of benefits make the application of distributed ledger to prevent and also identify the frauds. Furthermore, implementing robust access control mechanism to the user data, which should be protected to prevent identity frauds will also create performance bottlenecks when the number of tenants is increasing.

### Infrastructure Provider Selection Component

An edge node logs different infrastructure providers and their information on a smart contract and stores them in a distributed ledger. This information includes their charging rates, type of infrastructure, capacities, status and other important details. Next, the edge node distributes the list of data across all available L5GO. Subsequently, L5GO pick suitable investors depending on their requirements. Then the edge node invokes an agreement on blockchain between L5GO and the infrastructure provider through a smart contract. This will reduce disputes among parties since they need to follow each and every policy precisely. Payments will be then made automatically using crypto-currency based on the acquired services. Moreover, a rating-based algorithm is written in another smart contract to track the performance of investors. Then any new statistics of them will be added to the set of details created initially.This motivates the vendors which in turn builds up a competition among them to deliver efficient services. Additionally, to maintain their status. Furthermore, it allows L5GO to choose a suitable vendor from the pool of infrastructure providers depending upon their requirements. Furthermore, decentralization feature in the blockchain ensures the secure payment transfer from a L5GO to a infrastructure provider. Blockchain network will deduct charges from the L5GO based on the usage and consumption.

#### User Verification Component

Home Mobile Network Operator (HMNO) records each user details off chain and store the hash of the registry data structure in the distributed ledger. Next, blockchain assigns an unique id and a universal wallet to the respective user. Hence, whenever the user onboard to the L5GO network, user sends a request access along with the universal identity. Consequently, the edge node search for the stored hash value for the corresponding received id from the distributed ledger and hashes the received user information. Then, the edge node will grant the access if the stored and received hash values are the same. Hence, the proposed solution ensures the integrity of identity credentials. Furthermore, the authentication process becomes much more convenient for the subscribers.

#### IoT Component

With the blockchain technology, IoT devices will be able to offload major processor intensive tasks to the blockchain thereby increasing the resource efficiency, latency and the cost effectiveness of such devices. In this process, IoT devices are registered on the blockchain and then the services will be deployed closer to the devices with the use of L5GOs since they are capable of operating in a closed network to serve its own customers, which allows industries to maintain interconnected devices within their factory premises to make their processes smarter. While enabling registration of IoT devices, keeping track of billions of devices connected, it also enables secure message exchanges and co-ordination between IoT devices with the help of smart contracts. With decentralized communication infrastructure, concepts like smart cities, which demands a massive number of simultaneous connections, will become a reality without compromising on the latency or the quality of service levels.

### *3.2.2 Applications of Components in BaaS*

The potential challenges that can be evoked within L5GOs and blockchain based measures that can be taken to overcome are summarized in the table 3.1 while mapping each solution to the best matching component in the BaaS architecture.

### *3.2.3 Challenges in BaaS Components*

Despite of the improvements that L5GO will demonstrate, there are still issues that need to be addressed. Such consequences are tabulated with respect to each BaaS component. In addition, procedures to unravel the aforementioned circumstances are also listed in the table 3.2.

Table 3.1. Potential Challenges in L5GOs and Blockchain Based Solutions

| Issues in L5GOs | Potential blockchain based Solutions | Proposed Component in BaaS |
|---|---|---|
| Lack of transparency in the existing spectrum marketplace with the involvement of bribery and biased decisions | Development of a decentralized marketplace application which can verify the transparency of the system rules publicly | Auctioning |
| Exchange of roaming billing records between Home HPMN and VPMN through the Data Clearing House (DCH) causes extra charges which is a burden to the subscribers | Cost savings from carrying out all the DCH services through blockchain. i.e. the elimination of intermediary parties from the roaming instance | Network Selection |
| Generation of bill-shocks to roaming customers with the alteration of package prices occasionally | Selection of suitable network operator based on their signal strengths, charging scheme and reputation | Network Selection |
| Disagreements between L5GO and MNO in the roaming process | Establishment of dynamic agreements between MNO and L5GO via smart contracts | Network Selection |
| Presence of CDR (Call Detail Record) transfer delay between HPMN and VPMN might open up chances for frauds to over-utilize VPMN's resources. Change of transaction logs by MNO also leads to roaming frauds | Allow VPMN to deliver roaming services based on user's account balance. Further, storage of verifiable transactions between operators to enable quick dispute resolution | Fraud Prevention |
| User experience is negatively impacted due to the congestion within network. This is because of extensive usage traffic with the popularity of the L5GOs | Triggering a smart contract to find the most suitable subscriber to offload and the optimal L5GO to offload the selected user. This initiates the load sharing among L5GOs | Offload User Selection, Network Selection |
| Excessive charges for intermediary parties who handle agreements between L5GO and third-party providers | Cost savings from replacing the intermediary party and providing the services delivered by them using blockchain | Infrastructure Providers Selection |
| Delivery of low quality services by infrastructure providers | Track the performance of vendors by storing their each session information in the distributed ledger | Infrastructure Providers Selection |
| Subscription ID theft | Assign a unique ID for each subscriber and store it in in the distributed ledger. Then L5GO is able to retrieve user information whenever a user on-boards to the network | User Verification |
| Interoperability issues in VNF Management | Establishment of dynamic agreements between VNF provider and L5GO via smart contracts | Infrastructure Provider Selection |
| Data alteration of transaction logs in IoT devices | Enforcement of immutable decentralized transaction logs | IoT |

Table 3.2. Challenges of Proposed Components in BaaS and Possible Solutions

| BaaS Components | Related Challenges | Possible solutions |
|---|---|---|
| Auctioning | Reveal of bidders identity | Enforcement of security measures to protect bidders identity eg: Use of anonymous credentials |
| | Not able to hide all the bids during the auction | Enforcement of smart contract based privacy framework |
| Network Selection | Storage overhead in each nodes with a massive roaming customer base | Enforcement of storage offload mechanisms |
| | Transaction verification delay and computational delay | Utilization of a optimal consensus algorithm |
| Fraud Prevention | Reveal of sensitive information such as user account balance | Enforcement of smart contract based privacy framework |
| Offload User Selection | Possibility to involve with a malicious node | Requirement of robust authentication mechanisms to filter out legitimate users |
| Infrastructure Provider Selection | Availability of vendor information(eg: Reputation scores) publicly | Enforcement of privacy frameworks |
| User Verification | Synchronization delay when updating user credentials globally in the ledger | Execution of alternative authentication mechanisms |
| | Network overheads | Execution of network optimization techniques |
| IoT | High computational power consumption | Utilization of a optimal consensus algorithm |
| | Scalability issues, i.e database, Security and Privacy issues | Implementation of blockchain based IOTA project which is designed specifically IOT. It stores all the transactions in a distributed ledger named structure in the form of a Directed Acyclic Graph without use of blocks |

# 4 IMPLEMENTATION

Blockchain technology replaces the function of a central server, all the data will be decentralized and distributed across every device connected to the blockchain. Blockchain is a peer-to-peer network of nodes which share some of the same responsibilities. Every node will receive a copy of all the shared data across blockchain. All these set of nodes will have bunch of transactions known as blocks, that are chained through a digital data link to form the public ledger. All the blocks are validated and verified through a consensus process by a miner. All the nodes on the network work together to ensure that all the data on the public ledger remain secure and unchanged. This makes no intermediate parties or MNO to modify the user billing records. Further, blockchain acts as a network and a database. Code on the blockchain is shareable and unalterable. Moreover, Ethereum permits us to write the code, deploy to the blockchain network and then network nodes can run the code. Therefore, all the necessary dynamic agreements between MNO and L5GO are written in the smart contracts. These codes are known to be the decentralized part of the application. Further, a DApp was built on the Ethereum blockchain for the proposed model.

Initially, codes were written on smart contracts, then deployed them to the Ethereum blockchain, subsequently developed a client-side application which permits to carry out the various functions of the proposed approach. All these distinct procedures are discussed explicitly in this chapter.

## 4.1 Experimental Environment

There are mandatory dependency modules required to instantiate a DApp. Brief descriptions of these modules are given below.

### *4.1.1 MetaMask*

MetaMask is a web browser plugin which allows users to interact with Ethereum over web interface [47]. MetaMask offers a secure sign-in process along with a user interface to facilitate different activities including manage different accounts, sign transactions, send/receive Ether and interact with Ethereum based web applications. Accounts can be created for both users and network providers using the MetaMask with wallet instantiation for each account.

### *4.1.2 Web3.js*

Web3.js offers a set of javascript libraries to build client-side applications which interact with the Ethereum. Web3.js interacts with MetaMask via Remote Procedure Call (RPC) for the application integration. Libraries of Web3.js is exploited essentially to make a call to a smart contract, read data of an account, to deploy smart contracts, to send ether among accounts and so on [48].

#### *4.1.3 Remix IDE*

Remix IDE is used to write smart contract codes using solidity programming language. Remix also allows to deploy written smart contracts on to the Rinkeby private network. In addition to that, Remix facilitates debugging of the smart contracts.

#### *4.1.4 Node Package Manager*

The Node Package Manager also known as NPM, is considered to be the world's largest software registry which consists over 800,000 open source JavaScript software packages [49]. Software developers around the globe can either share the packages developed by them or borrow the packages shared by other developers using NPM. NPM also offers the ability to create organizations, which is a closed group of developers, and coordinate package maintenance, manage multiple versions of the code etc.

One of the key packages we used in implementing our blockchain network is the http server module, where we used to start up an http server at localhost.

#### *4.1.5 Ethereum*

Ethereum is often misinterpreted as just another cryptocurrency like Bitcoin. However, besides being a cryptocurrency, it also serves many other purposes.

Ethereum essentially is an open-source blockchain based platform. It allows users to build and run decentralized digital applications, which are also known as DApps [50]. DApps make it possible for users to perform highly secure transactions, such as paying for a service, within the nodes of the blockchain network. Thanks to the decentralized nature, any transaction get processed through the blockchain involves no middle parties.

Ethereum has a decentralized virtual machine, also known as Ethereum Virtual Machine (EVM) [51], powered by a large number of nodes connected to each other, which is capable of executing program scripts, which are known as smart contracts. Smart contracts can be built, deployed and executed by nodes connected to the blockchain.

### 4.2 Architecture of the Application

Front-end client application and the decentralized back-end server are the two main components of the prototype as depicted in the Figure 4.1. To run the front end client application, we deployed an http server at the localhost using the NPM. Stakeholders are able to interact with the DApp via a web browser with MetaMask plugin installed, that acts as the link between the application and the Ethereum blockchain. All the message transfers to and from the Ethereum blockchain are performed using the Remote Procedure Call (RPC) protocol. Web3.js contribute in the process of session establishment between DApp and the back-end server. Moreover, our front-end application run on the decentralized back end server which is known to be the Ethereum blockchain where all the smart contracts are deployed. All the transactions are managed by the deployed smart contracts. Therefore, complete roaming and offloading functionalities are controlled by the Ethereum blockchain platform.

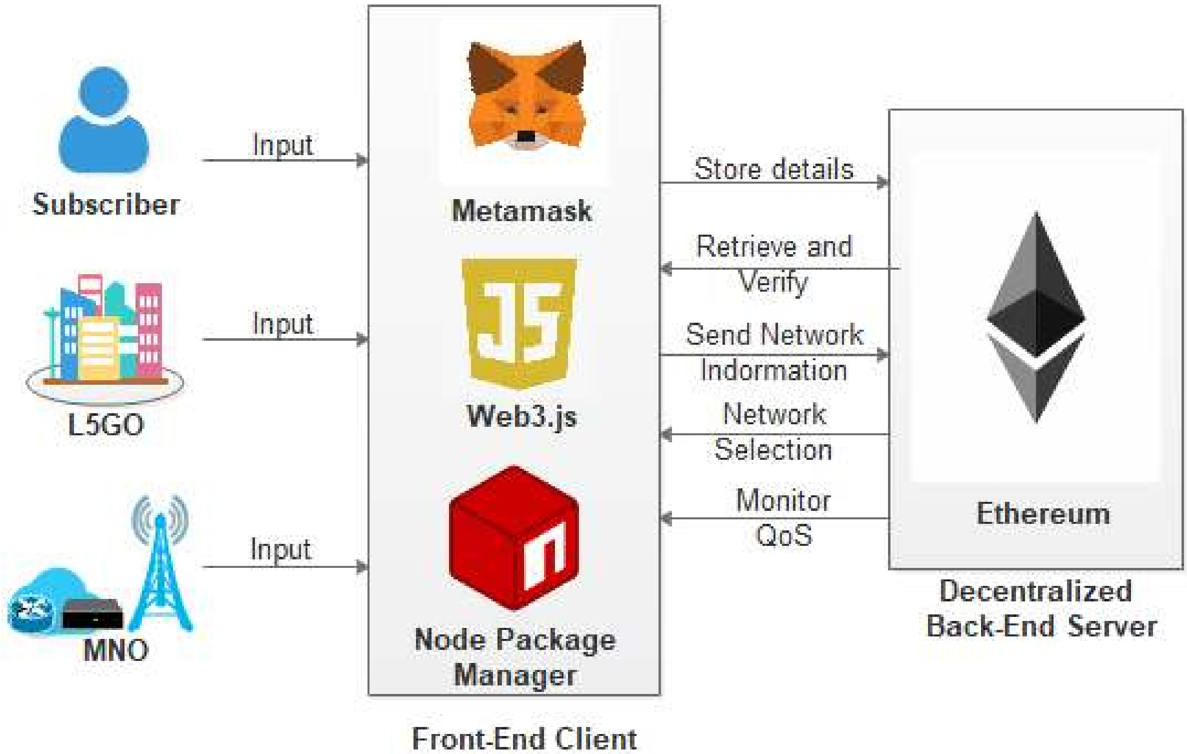


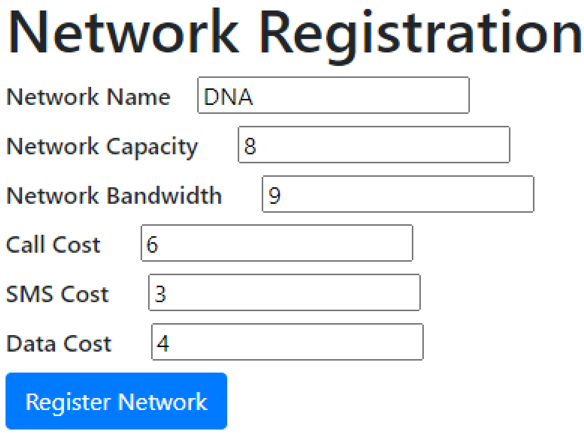

Figure 4.1. The Application Architecture of the Prototype

A front-end web application was built to test the proposed model. To achieve the purpose of sending data to the blockchain, various user interfaces were built per each smart contract as shown in Figure 4.2.

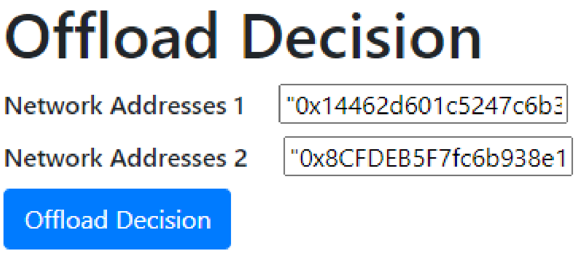
There were two key JavaScript libraries were used in developing the web interface, namely, jQuery and web3. jQuery is a lightweight JavaScript library which makes it easier to develop web content using JavaScript. In our prototype, jQuery was used to add input boxes and display labels of the web page.

Web3 is the Ethereum's javaScript Application Programming Interface (API), where we can use it to make our computers communicate with an Ethereum blockchain via RPC protocol. It offers various readily available methods, which can be used initiate transactions, listen to events, deploy smart contracts, invoking methods written in smart contracts etc.

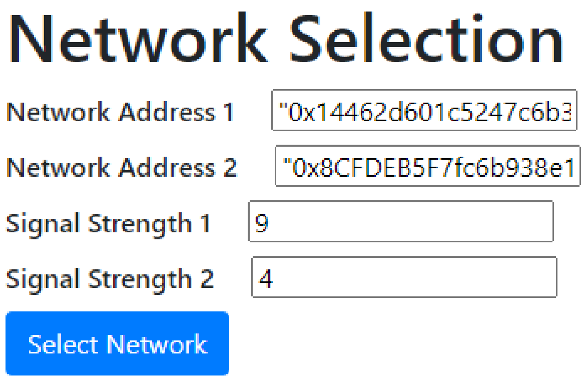

(a) User Registration



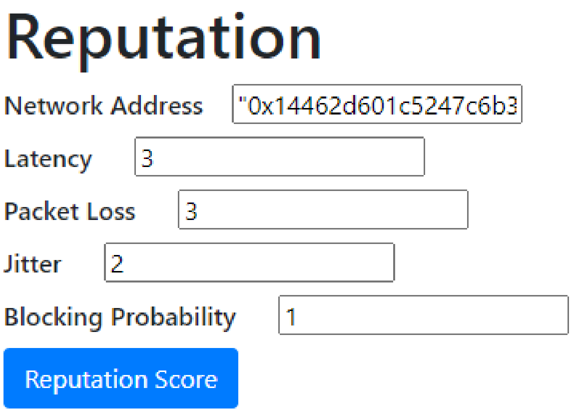

(b) Network Registration



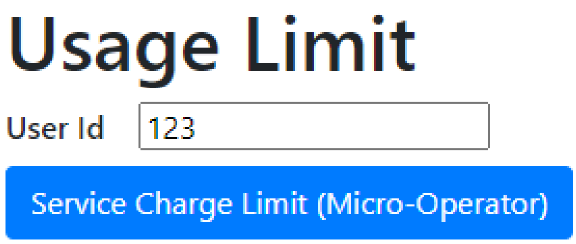

(c) Offload Decision



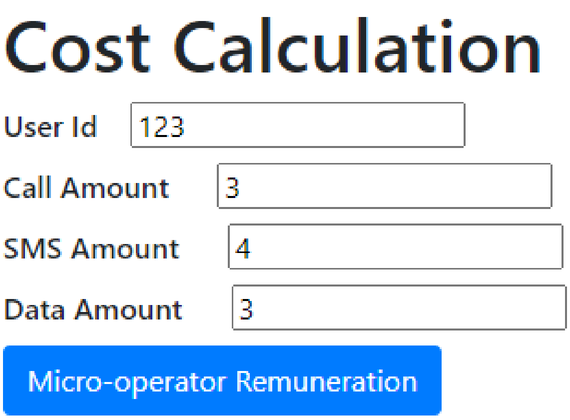

(d) Network Selection




(e) Reputation Management




(f) Usage Limit




(g) Cost Calculation

Figure 4.2. User Interfaces for Various Functions

## 4.3 Functions of Smart Contracts

A prototype of the proposed platform was implemented using Ethereum based smart contracts. The Fig. 4.3 represents the interaction between these smart contracts. Codes of smart contracts were written in solidity language by using Remix integrated development environment (IDE). Further, the written smart contracts were deployed on a Rinkeby private network.

### *4.3.1 User Registration Contract*

The main purpose of this contract is to register new tenants while avoiding duplicates. Also, its access is restricted to MNOs. All the user details will be stored in the distributed ledger and shared among the connected blockchain nodes. Thus, the user details can be retrieved at any given time by sending the IMSI to the blockchain, since all the user information are mapped with their IMSI. Further, a user verification function is implemented here. It checks whether the user has registered to avoid unauthorized accesses to the system.

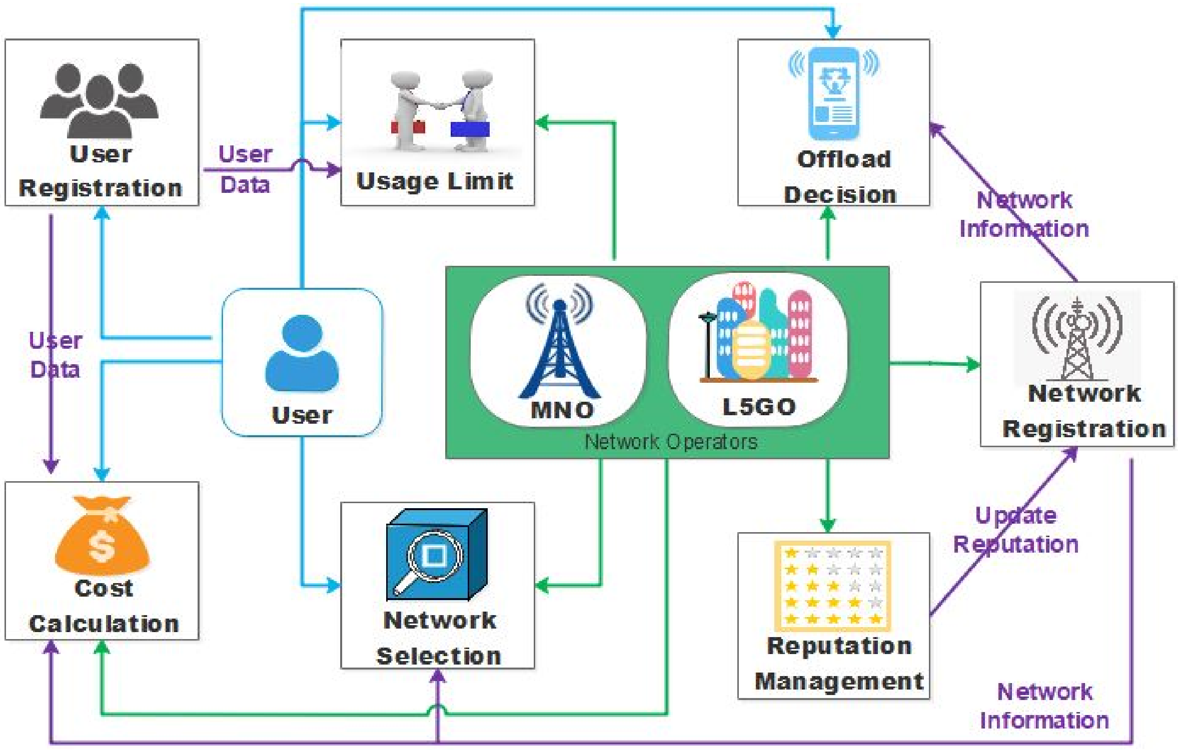



Figure 4.3. Interaction between smart contracts

### *4.3.2 Network Registration Contract*

The role of this contract is to register MNOs and L5GOs. For each network, their respective capacity, bandwidth, reputation and charging schemes are recorded at the registration. Additionally, the initial reputation score is set to system's average reputation score in order to ensure the fairness among network operators.

### *4.3.3 Offload Decision Contract*

This contract is executed to perform the offload process. It calculates the offload scores as describe in Section 3.1.3 and returns the L5GO with the highest score.

### *4.3.4 Network Selection Contract*

The main purpose of this contract is to find the best available network for a roaming user. It is initiated when a user starts to send details of all the available networks along with their signal strengths. Further, it calculates roaming scores for all the possible L5GOs as describe in Section 3.1.4, Then, L5GO with the highest score is returned.

### *4.3.5 Reputation Management Contract*

The contract is invoked whenever a session is ended. The functionality of this contract is to compute a reputation score for each connected network provider. Next, to calculate its moving average at each session and update the score to the blockchain as describe in Section 3.1.5.

### *4.3.6 Usage Limit Contract*

This smart contract acts as the dynamic agreement between MNO and the L5GO. L5GO is strictly responsible to deliver the network services based on the agreement. Additionally, usage limit contract prevents frauds by sharing the usage limits as describe in Section 3.1.6.

### *4.3.7 Cost Calculation Contract*

The main role of this smart contract is to provide billing information related to user consumption and reputation based incentives or penalties for L5GOs. Failing to maintain the minimum standard will result in penalties, while exceeding the satisfactory level will be rewarded with incentives. Penalties or incentives will be deducted from or added to the operator's commissions for the services they offered. It ensures the quality of service (QoS) and creates a competition between operators to provide better service.

# 5 EXPERIMENTAL RESULTS ANALYSIS

Rinkeby Testnet [10] is a platform utilized to run tests without paying any currencies. Rinkeby is a public Ethereum test network which is designed for carrying out experiments. We ran several tests in Rinkeby Testnet to validate the accuracy and to evaluate the performance of the DApp.

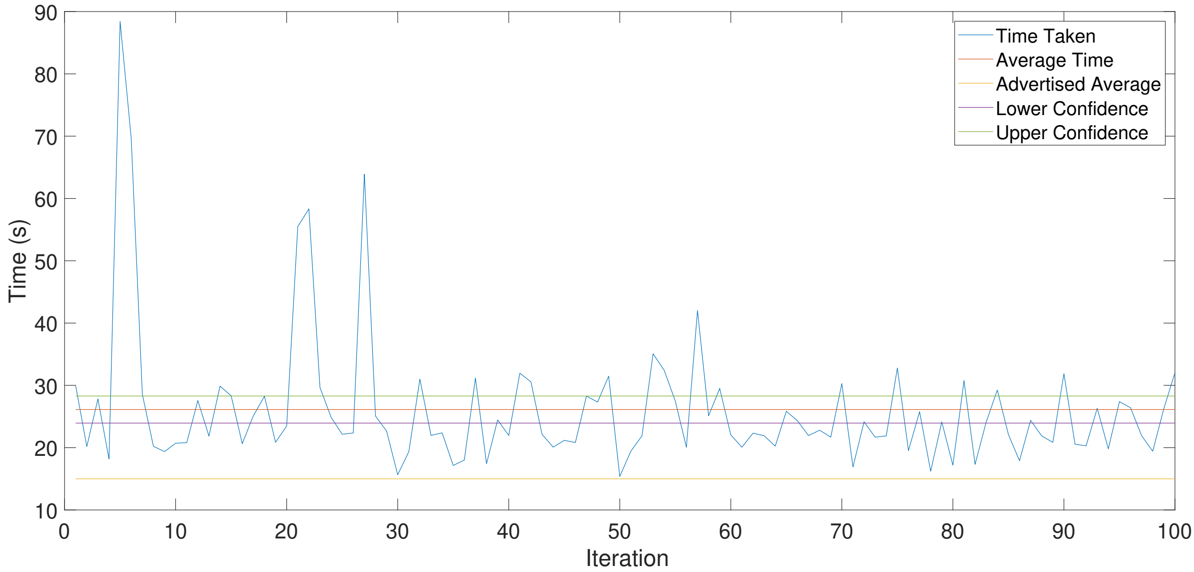
## 5.1 Latency Measurements for the Key Operations of the Proposed System

Connected users can retrieve, store or change data on the blockchain using smart contracts. Any request sent to the blockchain that does not need to change its state, get processed almost instantaneously, since they are not recorded in blocks as transactions. However, when new data is stored on the chain by invoking contracts, such operations will be logged in new blocks as transactions, which involve mining. Therefore, it not only takes more time to process the transaction, but also comes at a gas cost. According to [10], a new block is created every 15 seconds on Rinkeby Test network. However, to put it in a test, every smart contract was run for 100 times and the average latency was recorded with a 95% confidence interval, which are tabulated in table 5.1 and plotted in the Figure 5.3

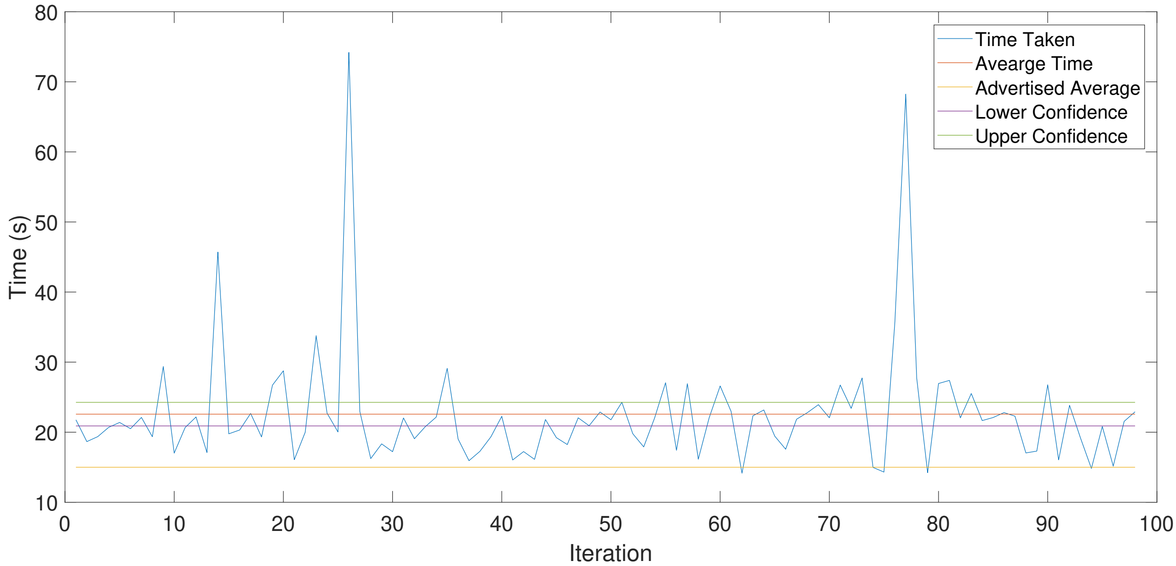
Table 5.1. Latency Measurements for the listed Operations

| Contract Name | Latency (seconds) |
|---|---|
| User Registration | $26.11597 \pm 2.17257$ |
| Network Registration | $24.13738 \pm 1.54385$ |
| Offload Decision | $25.48436 \pm 2.86953$ |
| Network Selection | $25.81101 \pm 2.95266$ |
| Usage Limit | $22.65481 \pm 1.11385$ |
| Reputation Management | $24.03633 \pm 2.10517$ |
| Cost Calculation | $22.57387 \pm 1.68210$ |

Based on the tabulated results, it is clearly visible that our tested average is approximately around 24 s. That is the process has experienced 9 s delay than the advertised time which is 15 s. The additional delay is caused due to the latency of the Internet service provider and the processing time.



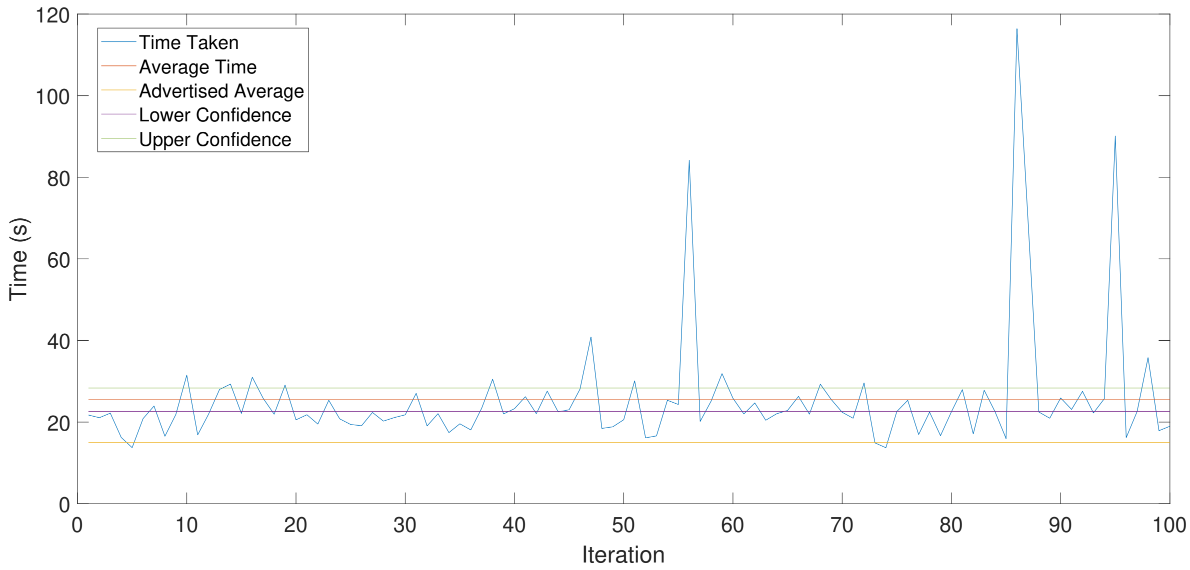

(a) User Registration



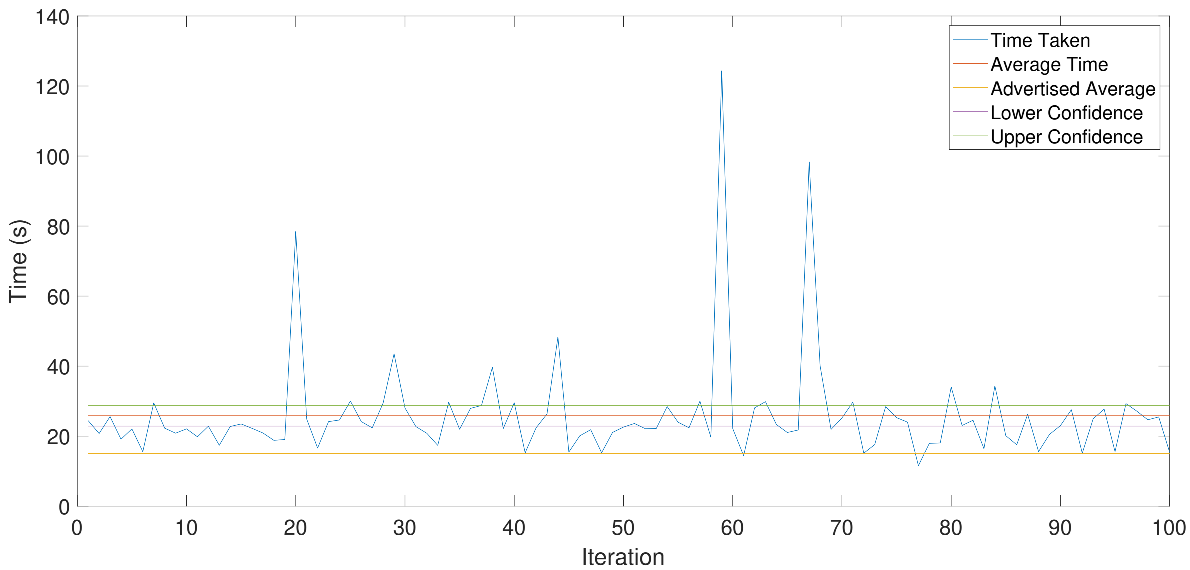

(b) Network Registration

Figure 5.1. Execution time for registration of stakeholders

Figure 5.1 depicts the execution time of smart contracts corresponding to subscriber, MNO and L5GO. Figure 5.1a demonstrates the time taken for MNO to register users on the blockchain network. Average time for this process is around 26.11 s with an expected deviation ranges from 23.94 s to 28.28 s. Further, Figure 5.1b provides the time taken to register network operators information and store on the distributed ledger. It has an average time of 24.14 s with a time interval of 1.54 s. It is clearly visible that, existence of a slight time difference between two procedures. That is because, they perform similar functions. However, network registration contract requires more computation time than user registration contract since it calculates the cost rating factor for each registered network at the initial stage of its process.



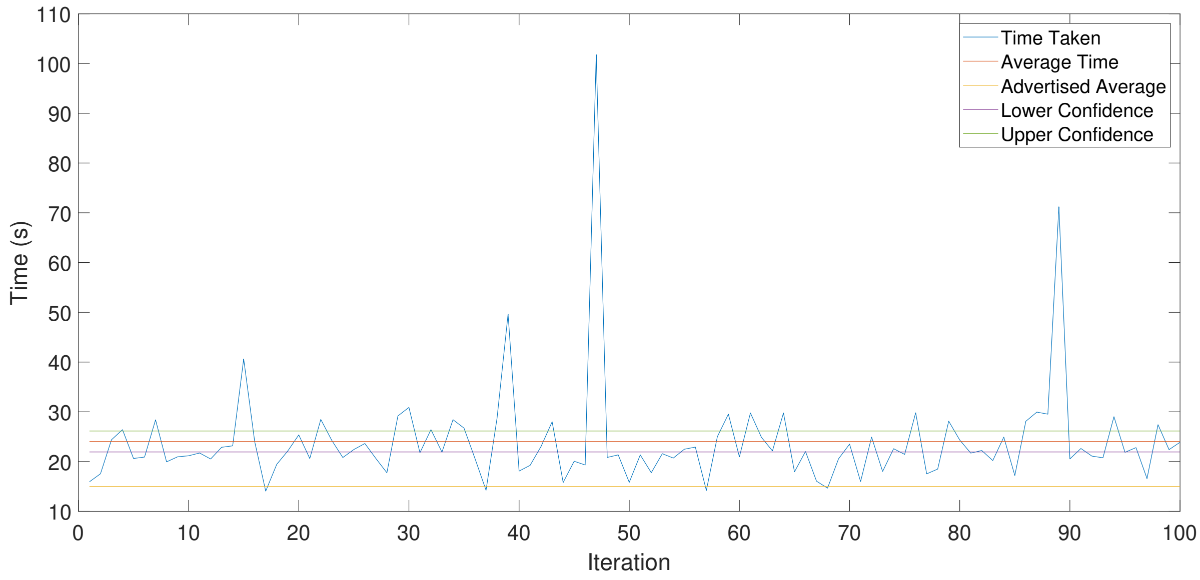

(a) Offload Decision



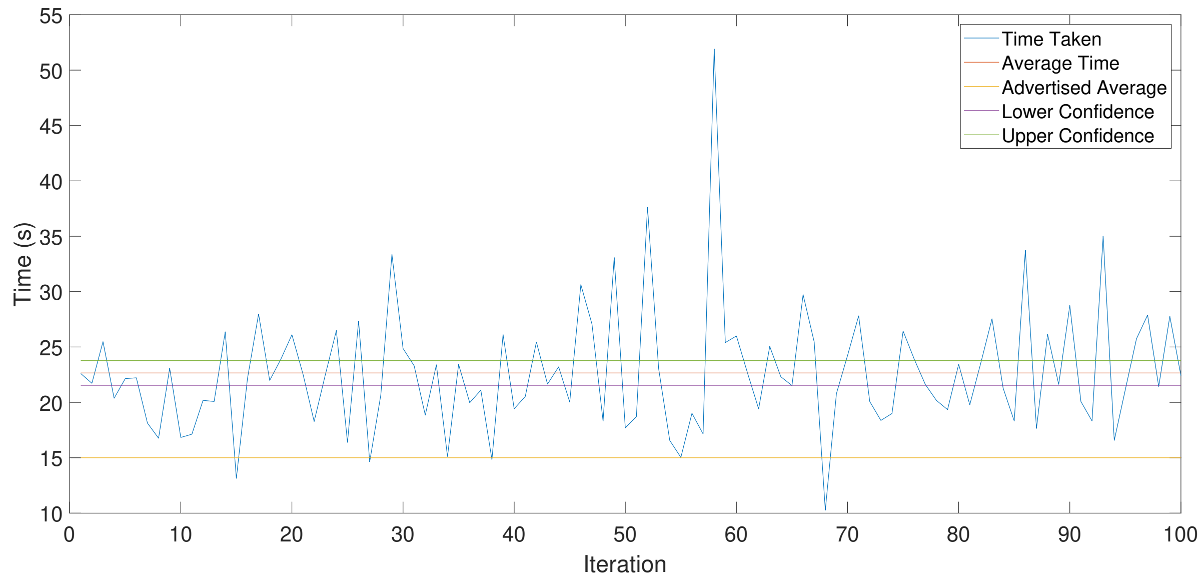

(b) Network Selection

Figure 5.2. Execution time for network selection and offload decision processes

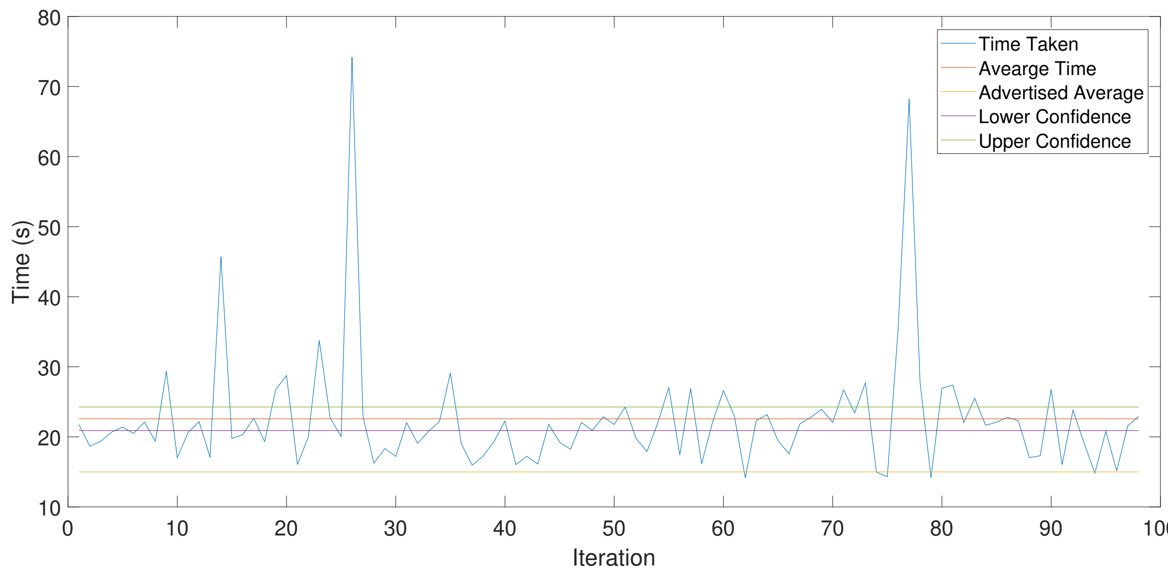
Figure 5.2 exhibits the time taken to execute the offload decision and network selection smart contracts. In both the cases, written code contributes to discover the optimum network operator for each subscribers at a given situation. Therefore, both the graphs expresses similar latency measurements with a negligible time difference. Based on figure 5.2a average time taken taken to receive a decision whether to offload the subscribers is nearly 25.49 s and varies between 22.61 s to 28.35 s, while the average time taken to implement network selection procedures is approximately 25.81 s with a time deviation of 2.95 s. However, a slight change is observable between theses two functionalities due to the the number of parameters used in each of their computations are varying. Also, the factors that required to calculate their own rating scores are dissimilar as discussed under chapter 3. For instance, offload decision score mainly depends on network capacity and bandwidth while the network selection score depends on signal strength.




(a) Reputation Management




(b) Usage Limit




(c) Cost Calculation

Figure 5.3. Execution time for reputation management, dynamic agreement and billing processes

Figure 5.3a shows the latency measurement corresponding to execution of the Reputation Management contract. Average time taken to calculate the reputation score for each network operator after a successful session is approximately 24 s ranging from 21.93 s to 26.14 s. Next Figure 5.3b depicts the time taken to implement the Usage Limit contract which is responsible for the end agreement between MNO and L5GO. For this process, estimated latency is around 22.7 s ranging between 21.54s and 23.77s. Further, the time taken to calculate the billing charges based on the provided services by the L5GO are presented in the Figure 5.3c. Estimated average time for this complete process is nearly 22.6 s. Measured latency values for both Usage Limit and Cost Calculation contracts are quite similar despite they invoke distinct operations. However, these two contracts interact with User Registration contract during the execution of their codes, which is, both these functions utilize similar transaction time period to extract user details. Out of these 3 approaches, Reputation Management contract use more time to carry out its operations. This is because, it consists of more computations and requires to invoke Network Registration contract to obtain network operator's details and also to update reputation score back to the Network Registration contract.

Statistics for offloading delay and roaming delay are presented in figures 5.4 and 5.5 respectively with a 95% confidence interval. These results are obtained by running the experiment for 100 times.

### *5.1.1 Offload Delay*

Offload delay is the summation of the time taken to execute the offload mechanism and the dynamic agreement and the hand-off latency. The existing systems' handover latency for a non-roaming situation is approximately 20ms [52].

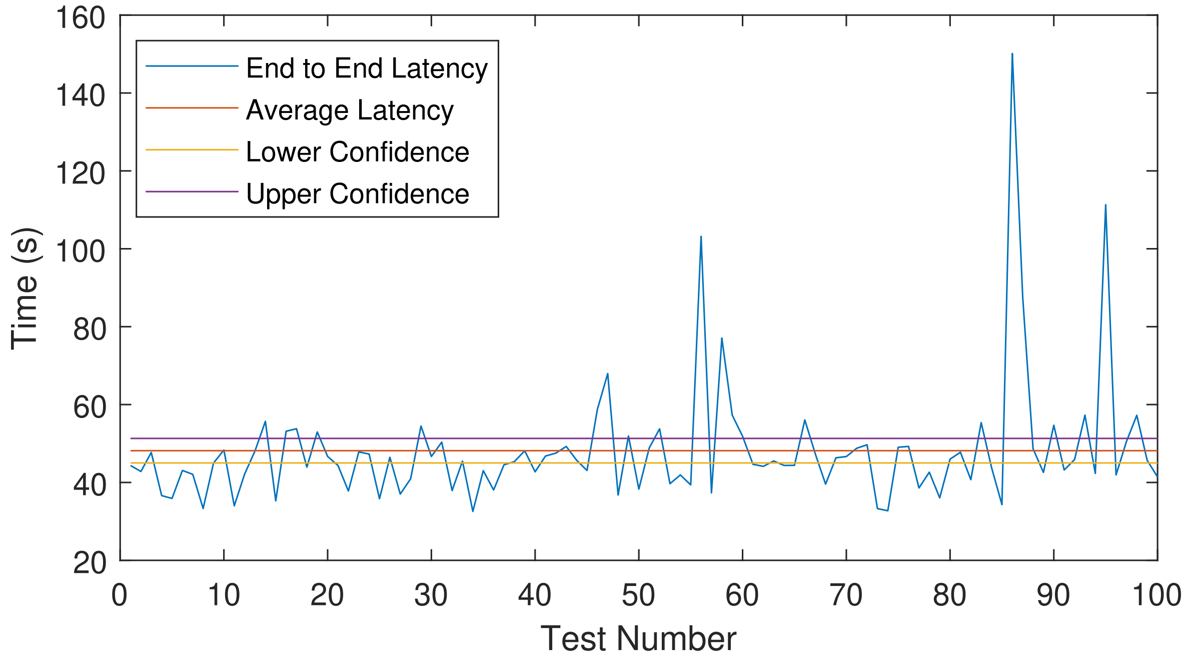



Figure 5.4. End to end latency of the offload process

From Figure 5.4, the average offload delay is approximately 48.1 s. That is the time it takes from operator sensing the traffic congestion in the network to offloading the tenants to another operator. This offload delay consist of the time taken to execute the offload decision and usage limit contracts and the latency of network level hand-off.

### *5.1.2 Roaming Delay*

Roaming delay is the total time elapsed for a roaming activation process to be completed. For this calculation, handover latency and execution time for Network Selection and Usage Limit smart contracts are considered. The standard handover latency for a roaming situation is approximately 50ms [52].

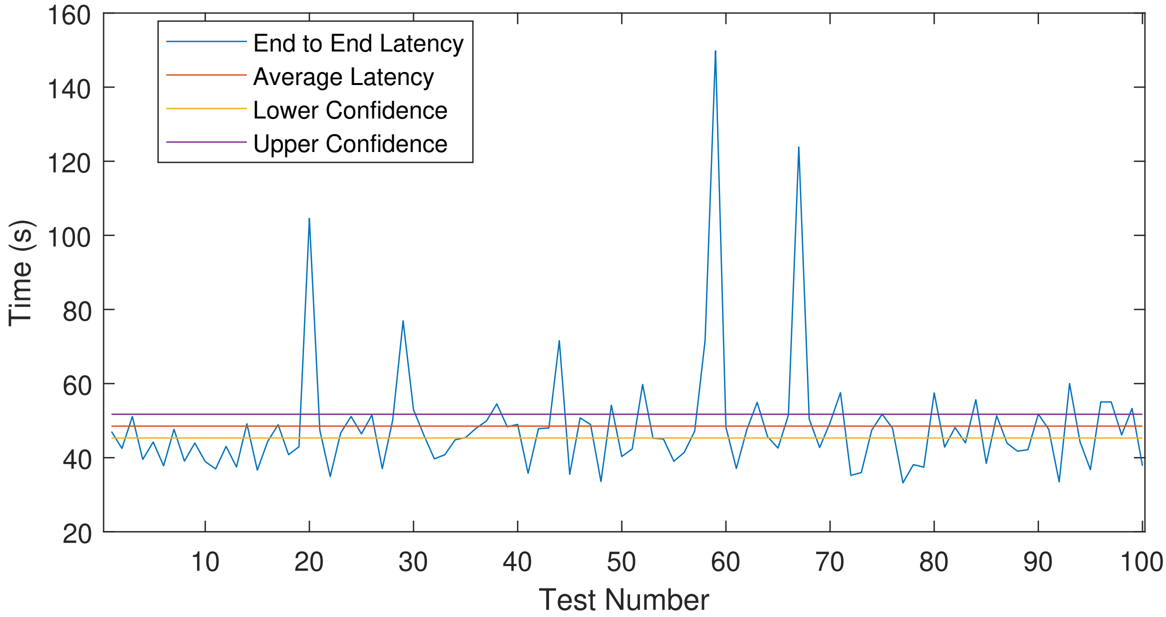



Figure 5.5. End to end latency of the roaming process

Based on Figure 5.5, subscriber is connected with the roaming connection after 48 s from the beginning of the process (sending access requests to the network). This roaming delay consists the time taken to execute the network selection and usage limit contracts and to perform the network level hand-off.

As per [9], the legacy roaming and offloading scenarios have about 1.75-3.5 s latency. In the proposed scenario, latency increased due to the process of selecting the visitor network. This process is happening before the real migration happen. Therefore, impact of this delay is not critical.

## 5.2 Cost Calculation for Smart Contracts

Ethereum blockchain is a peer-to-peer network which basically crowdsourcing all of its computational power. Some of its nodes are tailored into the mining process which is the mechanism of creating transactions and writing data to the public ledger. These nodes are agreed to exploit their computational resources to run the blockchain network. In return they are rewarded in terms of gas fees by the sender. Moreover, Gas is defined as a unit for the cost of a transaction. Gas price is the unit of gas expressed in the ether [53]. In real time, the miners receive multiple transaction requests in the same block. Hence, they sort the transactions by the gas price which means the miners would mine the transactions which has the highest gas price. Thus, the gas price in our experiment is set to 1 Gwei to mitigate competition. The term gas limit represents the maximum amount of gas that could be expended on a transaction and the remaining gas is refunded. In our system, the gas limit of each contract is set to 2000000.

Two types of costs encountered when deploying any smart contract on Ethereum are transaction cost and execution cost. The transaction cost is the gas consumed when a smart contract is sent for validation along with necessary data. Transaction cost is computed by multiplying gas price by cost of utilized gas and the execution cost is the gas consumed for executing a smart contract. it depends on the number of variables used, the number of operations performed, and the number of function calls made. Remix is used to calculate the costs for each contract and they are listed in the plotted in 5.6 and table 5.2.


Figure 5.6. Cost comparison between smart contracts

From the graphical results, it is observed that the network registration contract consumes highest transaction gas price compared to the others, as it contains a lengthier code. Also, it has numerous functions that are required by other contracts for their operations. For instance, Reputation Management contract calls a function named "getReputation" from the Network Registration contract, because it requires the current reputation score of the given network operator which is stored in the blockchain by invoking the Network Registration contract. Further, the Usage Limit contract consumes much less transaction gas price compared to other contracts since it has a shorter code compared to others. Therefore, it can be seen that the gas cost varies depending upon the length of the code.

Table 5.2. Cost Calculation for Smart Contracts

| Contract Name | Execution Cost | | Transaction Cost | |
|---|---|---|---|---|
| | Gwei | EUR[a] | Gwei | EUR[a] |
| User Registration | 111415 | 0.0202 | 928099 | 0.1686 |
| Network Registration | 52050 | 0.0094 | 1287451 | 0.2339 |
| Offload Decision | 88373 | 0.0160 | 792045 | 0.1439 |
| Network Selection | 68954 | 0.0125 | 631856 | 0.1148 |
| Usage Limit | 27782 | 0.0050 | 228536 | 0.0415 |
| Reputation Management | 58553 | 0.0106 | 466961 | 0.0848 |
| Cost Calculation | 52504 | 0.0095 | 474746 | 0.0862 |

1 Ether = $10^9$ Gwei,[a]1 ether = EUR 181,69 on 13.05.2020

From the tabulated results, it is obvious that operational cost of smart contracts is quite low. This cost can be further reduced by moving to a low cost blockchain system. Therefore, it is beneficial from both the user's and operator's perspective. The operator can increase the revenue while the subscriber being benefited with reduced costs.

# 6 DISCUSSION

This section presents a critical comparison between the work that has been carried out in this thesis and work that has been contributed by other researchers with similar research interests. The performance and functionalities of the proposed system is compared against the similar work previously done in this field, highlighting advantages and disadvantages of it. Further to that, an evaluation is presented taking into consideration the results achieved by executing proposed techniques, focusing on the effectiveness of meeting the final objectives of the thesis. Lastly, the areas of future improvements have been briefly discussed including indications on how blockchain technology can be used to solve many problems currently prevails in the field of 5G.

## 6.1 Comparative Analysis with Similar Work

Till date various ideas have been introduced to explain the way blockchain can be utilized for 5G. Among them, few research studies demonstrate on how blockchain can be used to facilitate roaming services. Mainly, they have addressed the potential opportunities and benefits of using blockchain in a roaming platform as one of the many applications [54].

Most of the proposed approaches have means to solve issues related to International roaming [7], [8], [9] and their solutions have aimed to eliminate solely the third party service providers using blockchain. In the [8] research study, authors have proposed a blockchain based architecture to remove DCH and its business value is validated through a process of analysis. However, in the reference [7], a smart contract is written to settle and notify the roaming charges between HPMN and VPMN. Moreover, a blockchain based user balance transfer through online and offline is proposed. Nevertheless, another literature study [9] has proposed a blockchain based architecture for a roaming platform and has carried out a case study to analyze its performance in both the operator's and user's perspective. However, the implementation of the proposed method is not presented. Hence, there still remains the need for a new model to enable better roaming services, addressing its potential challenges.

Table 6.1 depicts a comparison between our proposed method with pertinent existing solutions. This table clearly confirms the novelty of our approach.

## 6.2 Evaluation on Meeting the Thesis Objectives

The research focused on developing a blockchain based platform to securely, efficiently and automatically share services between MNO and L5GOs. That is the process of selling services of L5GOs to MNOs which have limitations in coverage within L5GO's domain. This procedure is renowned as roaming service. Therefore, the thesis mainly focused on intensifying standards of roaming service delivery by addressing all its current issues such as roaming frauds, lack of transparency in static agreements, service interoperability issues and quality of experience (QoE) is impacted with bill-shocks.

The occurrence of a roaming fraud is eradicated by triggering the Usage Limit contract which estimates the maximum rate of service a L5GO should provided to the a roaming customer. Non repudiation is enforced with the replacement of agreements between MNO

Table 6.1. Comparison with Related Works

| Features | Legacy | Blockchain-based | | | Proposed Model |
|---|---|---|---|---|---|
| | Ref [19] | Ref [7] | Ref [8] | Ref [9] | |
| Universal Wallet | No | Yes | No | No | Yes |
| Network Operator Prioritization | No | No | No | No | Yes |
| Load Balancing Technique | No | No | No | No | Yes |
| Reputation System | No | No | No | No | Yes |
| Quality of User Experience | No | Yes | Yes | Yes | Yes |
| Incentive/ Penalty Scheme | No | No | No | No | Yes |
| Fraud Prevention Technique | No | No | No | No | Yes |
| No Intermediary Parties | No | Yes | Yes | Yes | Yes |

and L5GO by Ethereum based smart contracts, which ensure the transparency of the roaming system by eliminating intermediary parties who were responsible in exchanging CDR. Now with our platform, this role is played by the blockchain with the exploitation of distributed features in-built. All the CDR data will be available to MNO and L5GO where less possibility for discrepancies on billing charges lead to disputes. In addition, the user experience is improved with lowering charges. Further, the interoperability issues are eliminated by exploring the best-suited L5GO for a subscriber at any roaming instance based on critical parameters such as signal strength, cost scheme and so on.

With the intention of improving the value stack of the roaming service delivery, real-time attributes such as traffic load, network bandwidth are considered which have not been examined in the current platform. For instance, whenever the traffic load is exceeded to a pre-defined level, subscriber with least signal strength is offloaded to the highest rated network nearby. Reputation management system is maintained to create a competition among network operators, which compels them to offer finest services. Also, it ensures QoS within the proposed model.

The thesis proves that the service sharing between L5GO and MNO is securely achieved with the use blockchain technologies, since all the transaction records are secured via cryptography. Also, the service sharing is effectively accomplished with the introduction novel features and functionalities. For instance, universal wallet concept, optimum network selection, reputation management system.

Therefore, the end result of the thesis induces efficient roaming service delivery in L5GO ecosystem and also supports to intensify the L5GO concept further. Thus, the complete thesis manifests the fact that the thesis objectives have been achieved successfully also with extra value added services. Furthermore, the outcome of the thesis, a blockchain-based roaming and offload service platform can be implemented within L5GO ecosystem in the future.

## 6.3 Future Research Directions

In this thesis, we have addressed only one aspect of the service delivery, which is known to be the roaming. Still there are existing challenges in L5GOs that need to be addressed and to develop a favourable L5GO environment. This thesis have already proposed solutions for set of investigated challenges within L5GO network in the chapter 3.2. For a instance, L5GOs can lease the spectrum band from various MNOs and operate locally through the execution of blockchain-based auctioning platform. Therefore, we can proceed to the next stage of our thesis by executing all the proposed approaches real-time.

In the future, we are planing to optimize the functionalities such as selection of best-rated network and establishment of agreements between L5GO and MNO further with the intention of minimizing the roaming and offload delay. Based on latency measurements obtained in this thesis, the end to end latency of roaming and offloading processes are approximately around 48s. That is the total time taken to invoke Network Selection and Usage Limit contracts, and to accomplish the network level hand-off. Thus, more impact is visible from time taken to execute smart contracts. Therefore, the best way to improve latency factors is to fine tune the operations corresponding to the aforementioned smart contracts. To achieve this objective, we can conduct more research explorations specific to the necessary functionalities and investigate more novel features.

The gas cost spent for the execution and transaction can be still reduced by adding more novelties to the proposed approaches and by optimizing the written smart contracts. Therefore, we will continue carrying out more research works related to proposed functionalities in the thesis.

Currently in this thesis, a simple DApp is developed to test the validity of the project. However, in future, a comprehensive DApp will be created with more interesting features which stakeholders might value the most.

The research work will be extended to carry out to analyze the system's revenue parameter from MNO's and L5GO's perspective based on domestic cost, roaming cost, transit cost, offloading cost and so on. Further, the cost parameter can be analyzed based on utility charges for the domestic and roaming usage. To ease the investigation, we may derive a comprehensive equation for the both cases. Moreover, a survey can be carried out to explore, the way how the proposed platform is viewed by the subscriber, MNOs and L5GOs. Feedbacks will be beneficial for the further developments of the platform.

From all the discussed future directions, most prominent work is to incorporate additional services such as spectrum sharing, IoT management, data management and security managements to the proposed platform.

# 7 CONCLUSION

The L5GOs are one of the most powerful 5G technique which has distinguishing potential in different application contexts. The massive connectivity requirements in the future will overflow the capabilities of current telecommunication design architectures with the extensive demand varieties. We identified that the blockchain as one of the most promising technology enablers to cater the futuristic telecommunication demands.

We proposed a novel blockchain-based service architecture to facilitate the roaming service in the L5GOs. The proposed solution introduces a universal wallet account to the roaming tenants for seamless connectivity regardless of MNOs associated to each L5GOs. In addition to that, we utilized smart contracts for decision making in the different value-added services including MNO connectivity offloading to the L5GOs after smart contract based assessment scoring mechanism. The value-added features include a smart contract-based reputation management system.

The proposed architecture is evaluated on Ethereum blockchain platform and performance factors were analyzed including gas consumption and latency on different defined operations. The development of smart contracts was carried out using the browser integrated Remix IDE. In order to carry out testing, contracts were deployed on a Rinkeby Public Ethereum Test Network. Use of the MetaMask browser plugin enabled us to create multiple accounts and manage them within the browser itself.

To measure the functional performance of the proposed system, a web interface was built with the help of Web3.js library and the average offload and roaming delay of the proposed system is found to be about 48 seconds. It was clear that the higher delay was caused due to the user's manual selection of the visitor network, and it will not be of any significance to the final system. Owing to the use of a blockchain architecture, the cost of operation has come down significantly, giving benefits not only to the user, but also to the operators.

Further to that, we proposed means to eliminate the inevitable issues that currently hinder the conventional roaming techniques. Roaming frauds, being in the top of the list, have been taken care of by making sure usage limits are made known to the L5GO before a session is initiated. The transparency between each stakeholder has been improved with the adoption of the distributed architecture. Implementation of reputation management smart contract is making sure that consumer's QoE values are maintained to be at the highest level possible.

Apart from the techniques we discussed in this thesis with regards to improving Roaming and Offloading problems with the use of blockchains, there are countless other opportunities where we can leverage the power of blockchain based distributed networks to overcome many current challenges of 5G commercialization. One of the main aspects we will be focusing on in future will be extending our work towards exploring spectrum sharing options which will involve developing a blockchain based auctioning platform. Security management and data management for L5GO will be another two key areas where the application of blockchain technology can improve on. We will also be looking at possible ways to support the ever-growing demand of IoT, and its implementation. The IoT's need for novel distributed networks in place of traditional centralized networks now becoming more and more relevant as it scales up. Blockchain technology will play an essential role in making concepts like smart cities a reality.

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# 9 APPENDICES

| | |
|---|---|
| Appendix 1 | Solidity code/ Smart contract written for the network selection function |
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| Appendix 3 | Solidity code/ Smart contract written for the cost calculation function |
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## Appendix 1 Solidity code written for the network selection function

```
pragma solidity ^0.5.17;
pragma experimental ABIEncoderV2;
import 'NetworkRegister.sol';

contract NetworkSelection{

    event selected(
        string networkName,
        int256 rating
    );

    struct DetectedNetworks{
        address networkAddress;
        uint8 signalStrength;
    }

    address addressNetCon;

    function setNetworkContractAddress(address _addressNetworkContract) public {
        addressNetCon = _addressNetworkContract;
    }

    function selectNetwork(address[] memory _aroundNetAddress, uint8[] memory _signalStrength )
    public payable returns(string memory, int256){

        uint256 dataLength = _aroundNetAddress.length;
        int256[25] memory calculatedRating;
        uint256 i = 0;
        uint256 selectedIndex;
        address tempAddress;

        contractNR NetCon = contractNR (addressNetCon);


        for(i=0; i<dataLength; i++){
            tempAddress = _aroundNetAddress[i];
            calculatedRating[i] = ( (NetCon.getCostRating(tempAddress) * NetCon.getCostWeight()) +
                                    (NetCon.getReputation(tempAddress) * NetCon.getReputationWeight()) +
                                    (_signalStrength[i] * NetCon.getStrengthWeight()) );
        }

        selectedIndex = 0;

        for(i=0; i<(dataLength-1); i++){
            if(calculatedRating[i+1]>calculatedRating[selectedIndex]){
                selectedIndex = i+1;
            }
        }

        emit selected( NetCon.getNetworkName(_aroundNetAddress[selectedIndex]),
        calculatedRating[selectedIndex] );
    }

}
```

# Appendix 2 Solidity code written for the reputation management

```
pragma solidity ^0.5.17;
import 'NetworkRegister.sol';

contract Reputation{
    int256 private allowedlatency = 10;
    int256 private allowedpacketLoss = 15;
    int256 private allowedJitter = 8;
    int256 private allowedblockingProb = 2;

    int private latencyWeight =7;
    int private packetLossWeight =7;
    int private jitterWeight =7;
    int private blockingProbWeight =7;

    address addressNetworkRegister;
    uint256 public reputation_index = 0;

    event reputation(
        int256 score
    );

    function setAddress(address _addressNetworkRegister) public {
        addressNetworkRegister = _addressNetworkRegister;
    }

  function reputationManagement(address _networkAdd, int256 _latency, int256 _packetLoss, int256 _jitter, int256 _blockingProb)
  public returns(int256){
        int256 latency;
        int256 packetLoss;
        int256 jitter;
        int256 blockingProbability;
        int256 reputationScore;
        int256 networkCount_rep;
        int256 avgReputation_rep;

        contractNR netReg = contractNR (addressNetworkRegister);

        latency= allowedlatency - _latency;
        packetLoss = allowedpacketLoss - _packetLoss;
        jitter = allowedJitter - _jitter;
        blockingProbability = allowedblockingProb - _blockingProb;

        reputationScore = latency*latencyWeight + packetLoss*packetLossWeight + jitter*jitterWeight +
        blockingProbability*blockingProbWeight;

        netReg.updateReputation(_networkAdd,reputationScore);
        networkCount_rep = netReg.getNetworkCount();

        avgReputation_rep = netReg.getAvgReputation();

        avgReputation_rep = (avgReputation_rep*(networkCount_rep-1) + reputationScore)/networkCount_rep;
        netReg.updateAvgReputation( avgReputation_rep);

        emit reputation(reputationScore);
        reputation_index++;
    }

}
```

## Appendix 3 Solidity code written for the cost calculation function

```
pragma solidity ^0.5.17;
import 'RegisterUsers.sol';
import 'NetworkRegister.sol';

contract costCalculation {

    address addressNetworkContract;
    address addressUserContract;
    uint256 callBalance;
    uint256 smsBalance;
    uint256 dataBalance;

    event UO(
        int256 _incentivePenality
    );

    event deductBalance(
        uint256 _balance
    );

    function setNetworkContractAddress(address _addressNetworkContract) public {
        addressNetworkContract = _addressNetworkContract;
    }

    function setUserContractAddress(address _addressUserContract) public {
        addressUserContract= _addressUserContract;
    }

    function sessionData (string memory _userId, int256 _callAmount, int256 _smsAmount, int256 _dataAmount) public returns(int256){

        int256 _totalAmount;
        uint256 _userBalance;
        address uOAddress = msg.sender;
        int256 UOReputation = 0;
        int256 adjustments = 0;
        int256 upperThreshold = 101000;
        int256 lowerThreshold = 99000;

        contractNR NC = contractNR (addressNetworkContract);
        contractUR UC = contractUR (addressUserContract);

        _userBalance = UC.getUserBalance(_userId);

        _totalAmount =  _callAmount * NC.getMNOCallCost() +
                        _smsAmount * NC.getMNOSmsCost() +
                        _dataAmount * NC.getMNODataCost();

        UC.deductUserBalance(_userId, _totalAmount) ;


        UOReputation = NC.getReputation(uOAddress);


        if(UOReputation >= upperThreshold && _userBalance>0)
        {
            adjustments = (UOReputation - upperThreshold)/upperThreshold;
        }
        else if(UOReputation <= lowerThreshold && _userBalance>0)
        {
            adjustments = (UOReputation - lowerThreshold)/lowerThreshold;
        }

            emit UO( ( (_totalAmount) * (10 + adjustments))/100 );
        }

}
```

## Appendix 4 JavaScript code written to execute the user registration function

```html
<!DOCTYPE html>
<html lang="en">

<head>
    <meta charset="utf-8">
    <meta http-equiv="X-UA-Compatible" content="IE=edge">
    <meta name="viewport" content="width=device-width, initial-scale=1">
    <title>User Registration</title>

    <!-- Bootstrap -->
    <link href="https://stackpath.bootstrapcdn.com/bootstrap/4.4.1/css/bootstrap.min.css" rel="stylesheet">

</head>

<body>
    <h1>User Registration</h1>
    <h6 class="text-left">User ID    <input type="text" id="_id"></h6>
    <h6 class="text-left">Name      <input type="text" id="_name"></h6>
    <h6 class="text-left">E-mail      <input type="text" id="_email"></h6>
    <button class="btn btn-primary text-left" id='_createUser'>Create User</button>
    <br><br>
    <h5> End to End Latency</h5>
    <h7 class="text-left">Start Time</h7>
    <h7 class="text-left" id="startTime"></h7>
    <br>
    <h7 class="text-left">End Time</h7>
    <h7 class="text-left" id="endTime"></h7>
    <br>
    <h7 class="text-left">Latency</h7>
    <h7 class="text-left" id="_latency"></h7>
    <br><br><br>

    <!-- JQuery -->
    <script src="https://ajax.googleapis.com/ajax/libs/jquery/1.12.4/jquery.min.js"></script>
    <!-- Bootstrap -->
    <script src="https://stackpath.bootstrapcdn.com/bootstrap/4.4.1/js/bootstrap.min.js"></script>
    <!-- Web3.js -->
    <script src="https://cdn.jsdelivr.net/gh/ethereum/web3.js@1.0.0-beta.34/dist/web3.min.js"></script>

    <script>
        if (typeof web3 !== 'undefined') {
            web3 = new Web3(web3.currentProvider);
        } else {
            web3 = new Web3(new Web3.providers.HttpProvider('http://localhost:8080'))
        }

        // Set Contract Abi
        var contractAbi = [
            {
                "constant": false,
                "inputs": [
                    {
                        "internalType": "string",
                        "name": "_id",
                        "type": "string"
                    },
                    {
                        "internalType": "string",
                        "name": "_name",
                        "type": "string"
```

```
                },
                {
                    "internalType": "string",
                    "name": "_email",
                    "type": "string"
                }
            ],
            "name": "createUser",
            "outputs": [],
            "payable": false,
            "stateMutability": "nonpayable",
            "type": "function"
        },
        {
            "constant": false,
            "inputs": [
                {
                    "internalType": "string",
                    "name": "_id",
                    "type": "string"
                },
                {
                    "internalType": "int256",
                    "name": "_amount",
                    "type": "int256"
                }
            ],
            "name": "deductUserBalance",
            "outputs": [],
            "payable": false,
            "stateMutability": "nonpayable",
            "type": "function"
        },
        {
            "constant": false,
            "inputs": [
                {
                    "internalType": "string",
                    "name": "_id",
                    "type": "string"
                },
                {
                    "internalType": "int256",
                    "name": "_amount",
                    "type": "int256"
                }
            ],
            "name": "rechargeUserBalance",
            "outputs": [],
            "payable": false,
            "stateMutability": "nonpayable",
            "type": "function"
        },
        {
            "inputs": [],
            "payable": false,
            "stateMutability": "nonpayable",
            "type": "constructor"
        },
        {
```

```
            "constant": true,
            "inputs": [
                {
                    "internalType": "string",
                    "name": "_id",
                    "type": "string"
                }
            ],
            "name": "getUserBalance",
            "outputs": [
                {
                    "internalType": "int256",
                    "name": "",
                    "type": "int256"
                }
            ],
            "payable": false,
            "stateMutability": "view",
            "type": "function"
        },
        {
            "constant": true,
            "inputs": [
                {
                    "internalType": "string",
                    "name": "",
                    "type": "string"
                }
            ],
            "name": "users",
            "outputs": [
                {
                    "internalType": "string",
                    "name": "simID",
                    "type": "string"
                },
                {
                    "internalType": "string",
                    "name": "name",
                    "type": "string"
                },
                {
                    "internalType": "string",
                    "name": "email",
                    "type": "string"
                },
                {
                    "internalType": "int256",
                    "name": "balance",
                    "type": "int256"
                },
                {
                    "internalType": "bool",
                    "name": "isRegistered",
                    "type": "bool"
                }
            ],
            "payable": false,
            "stateMutability": "view",
            "type": "function"
```

```
            },
            {
                "constant": true,
                "inputs": [
                    {
                        "internalType": "string",
                        "name": "_id",
                        "type": "string"
                    }
                ],
                "name": "verifyUser",
                "outputs": [
                    {
                        "internalType": "bool",
                        "name": "",
                        "type": "bool"
                    }
                ],
                "payable": false,
                "stateMutability": "view",
                "type": "function"
            }
        ];
        // Set Contract Address
        var contractAddress = '0x096aa6E05f67c868d56C32E5b36DE048d6687B4D';

        var delay = [];
        var i = 0;

        // Set the Contract
        var contract = new web3.eth.Contract(contractAbi, contractAddress);

        $('#_createUser').click(function () {

            var d1 = new Date();
            $('#startTime').html(d1.getTime());
            var idVal = $("#_id").val();
            var nameVal = $("#_name").val();
            var emailVal = $("#_email").val();

            web3.eth.getAccounts().then(async (accounts) => {
                await contract.methods.createUser(idVal, nameVal, emailVal).
                send({ from: accounts[0], gas: 3000000 }).then(function (tx) {
                    console.log(tx);
                    var d2 = new Date();
                    $('#endTime').html(d2.getTime());
                    var difference = d2.getTime() - d1.getTime();
                    $('#_latency').html(difference + " milliseconds");
                    delay[i] = difference;
                    i = i + 1;
                    console.log(delay);
                });
            });
        });

    </script>

</body>

</html>
```