CovidChain: An Anonymity Preserving Blockchain Based Framework for Protection Against Covid-19

Hiten Choudhury^a, Bidisha Goswami^a, Sameer Kumar Gurung^{b,*}

^aDepartment of Computer Science & IT, Cotton University, Guwahati, Assam, India. ^bDepartment of Computer Science, Saint Mary's College, Shillong, Meghalaya, India.

Abstract

Today, the entire world is facing incredible health and economic challenges due to the rapid spread of the life threatening novel Coronavirus Disease - 2019 (COVID-19). In the prevailing situation when a vaccine is many months away, the way forward seems to be a controlled exit from the lockdown - where, infected/exposed people are strictly quarantined and recovered/unexposed people are allowed to carry on with their day to day business activities. However, appropriate physical distancing norms will have to be strictly followed for such relaxations. Therefore, mechanisms are required that will assist people in following the social and physical distancing norms in public places. In this paper, we propose an anonymity preserving blockchain based framework that allows people, through use of their smart phones and other communication devices, to protect themselves from infections as they conduct their daily business activities.

Keywords: Covid-19, Coronavirus, Contact Tracing, Blockchain, Security, Privacy, Anonymity.

1. Introduction

The novel life threatening virus 'Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2)', responsible for Coronavirus Disease - 2019 (COVID-19), is one of the greatest challenges that the world is facing today. This is a respiratory virus and can spread through human to human contact. Therefore, to prevent infection and to slow transmission of COVID-19, the following physical distancing guidelines are specified by WHO [1]:

- Maintain at least 1 metre distance between you and people coughing or sneezing.
- Stay home if you feel unwell.
- Practice physical distancing by avoiding unnecessary travel and staying away from large groups of people.

^{*}Corresponding Author

Email addresses: hiten.choudhury@cottonuniversity.ac.in (Hiten Choudhury), bidishagoswami112@gmail.com (Bidisha Goswami), skg@smcs.ac.in (Sameer Kumar Gurung)

With millions of people infected worldwide and thousands dead, the Covid-19 pandemic is showing no sign of abating. A vaccine is yet to be found, and physical distancing through lockdowns seems to be the only way to slow the spread. However, the lockdowns are also pushing the world economy to the brink [2]. Millions, in countries across the world are facing the bleak reality of job losses, business closure and economic hardship. Hence, it has become imperative to find ways to allow a section of the society - those who have either recovered or are unexposed to the disease, carry on with their day to day business operations to kickstart the economy. What is desired is a system, that will enable easing of the lockdowns, allowing countries to continue with their economic activities, perhaps, in a reduced capacity, while still strictly maintaining appropriate physical distancing norms for such relaxations. Consequently, strategies have to be put in place that will assist people in practising the distancing norms in public places. Modern communication technologies and the ubiquity of smartphones use can be leveraged to devise such mechanisms.

Many countries have developed mobile applications to combat the spread of the virus by adopting technologies such as bluetooth and GPS data for contact tracing, which is a mechanism for tracing people who had come in close contact with some one who is infected with the virus [3]. Such mobile applications collect information about persons who have been in close proximity with an individual from their smart phones. If the individual is ever diagnosed with the virus, every person who had possibly been near that infected individual, during the period in which he was contagious, can be traced and directed to take measures such as self-quarantine and or testing [4]. However, such applications facilitate identification of only those people who have already been exposed to an infected individual. While there is no doubt that contact tracing can contribute immensely in containing the virus, we have certainly reached a stage where economic activities also have to be allowed in a disciplined manner. Therefore, it is highly desirable that systems be put in place that can aid in prevention of exposing an individual from infection while s/he is engaged in her/his day to day business activities. Applications should be devised in such a way that it's users can be given prior intimation about the Covid status of people in their vicinity or of people that they plan to meet. There should be provisions in the application that alerts users before they are entering a zone or an area that is certified to be a covid hotspot zone. In such a scenario, the person receiving such alerts can then take preventive measures. Since the success of such applications depend largely on people participation, user privacy concerns should be taken into account and there should be inbuilt mechanisms to provide incentives to people for their participation. The data accumulated through such a public initiative should be available to general public for scrutiny and use, so that they can reap it's benefit in their individual businesses.

1.1. Our Contribution

In this paper, we propose a framework that can be used by people to protect themselves from infections while they are involved in their activities. Individuals can use their smart phones as a digital-pass to convince authorities, institutes and business establishments that s/he is safe from the virus and has not come in close contact with anyone who is infected by the virus. This will allow him or her to move freely without restrictions to accomplish their tasks and allow for some semblance of a normal life. For individuals who fail to do so, it will be implied that he is infected or is under quarantine and is not supposed to roam around in public places. Therefore, access to public/private facilities will be denied to such individuals till his/her quarantine period is over.

We propose the use of blockchain technology for secure record keeping of persons using the application. The covid-19 status of individuals along with other relevant information such as age, pre-existing medical conditions etc., can be entered into the blockchain, while ensuring privacy and anonymity to the individuals. This public ledger will be made available to all the stakeholders. Given the immutable nature of the blockchain, the ledger will be available on a read only basis to these stakeholders. The stakeholders will include entities such as the offices and health centers of the state, central or federal government, medical research and development centers, private hospitals, business houses, and other organizations.

1.2. Paper Organization

The rest of the paper is organized as follows. In section 2, similar work carried out recently are discussed. In section 3, we present a brief overview of the blockchain technology. In section 4, the proposed blockchain based framework is presented. In section 5, we discuss the proposed work with reference to existing applications and platforms that were developed recently. Finally, in section 6, we conclude the paper.

2. Similar Work

Countries around the world have adopted mobile technologies to mitigate the spread of corona virus and are also relying on such technologies to provide data to augment their decisions making on the exit strategy for lockdowns [5]. China [6], Singapore [7], South Korea, Israel [8] and Australia [9] have taken the lead in asking their citizens to install surveillance apps to facilitate contact tracing. India has developed Aarogya Setu app for the same purpose [10]. These government initiatives have little or no privacy protections built into their systems which have raised concerns of the applications being used for surveillance beyond their stated purpose. For example, the South Korean app uses GPS location data and citizens are required to provide their real names and their government issued identity numbers [11]. This means that privacy is non-existent in the contact tracing mechanism and citizens using the app can be tracked anytime and anywhere. Singapore's *TraceTogether* app stores anonymised IDs of nearby phones exchanged through bluetooth, in encrypted form. The IDs are generated by encrypting with a private key held by the Ministry of Health and hence can be decrypted by only this government agency. This does not reveal the users identity to other parties but is known to the government. Hence, users have no privacy from government surveillance. India's Aarogya Setu seeks the users bluetooth connectivity and location data at the time of installation, which is sent to government servers effectively allowing government agencies to know the users whereabouts. Hamagen (Hebrew for the shield) app, endorsed by Israel's Ministry of Health, periodically (typically one hour) downloads anonymous GPS location data of patients diagnosed as covid positive from the MoH cloud service. It then compares this list with location data Hamagen has stored of the user in the phone. This cross-referencing can then determine if the user has been in

presence of anyone who has been tested as positive. User location is not sent to the government servers and the comparing of location data is done on-device of the user. Location history and WIFI networks that the user came within range, is stored on device for two-weeks. Future versions would keep track of bluetooth connections and data over sound. The Israeli government has plans of making the app open source in the near future.

Private organisations have also jumped in the fray and are offering mobile app based solutions. PHBC [12] is a consortium of various health stakeholders such as universities, health care providers, government agencies, etc which has developed virus record keeping blockchain that allows the monitoring and verification of workplaces and geographical zones that are free from corona virus [13]. Such zones are designated as safe zones. The system tracks the whereabouts of uninfected persons and aims to constrain their entry into uninfected areas if they have visited infected areas by requiring them to be in the quarantine zone before they are allowed into the safe zone. The system integrates AI and GIS technologies and draws information in real time from agencies that provide up to date virus infection information.

IT Researchers have also proposed a variety of approaches to control and track the spread of the virus. The authors in [14] propose a blockchain and AI based 4 layer framework where corona virus data is collected from various sources such as laboratories, hospitals, social media, patient generated data and wireless network operators. They propose to ensure privacy of such data by use of the blockchain. AI models can then harness the data to provide solutions for outbreak estimation, virus detection, analytics, assisting in vaccine development and predicting of similar virus outbreak in future. However, the framework is conceptual and does not provide implementation details.

Covid-watch is group of volunteers spread over multiple continents and countries comprising security, policy and public health experts. The group has developed a bluetooth based privacy-preserving mobile app that aims to reduce the spread of corona virus [15]. Their scheme works by generating and broadcasting random numbers whenever a user of the app is in close proximity to another user. Bluetooth signal strength is used to estimate proximity. In every phone a record is kept of each random number the device has transmitted or received. If any phone app user is diagnosed as positive the local health authority gives them a permission number which after verification is sent to a public server along with the persons history of sent and received random numbers and is also transmitted to all other phones. If any of the phones find a match with its stored list of random numbers, it means that they were in close contact with the infected person. While simple and elegant, the scheme can be compromised if there is a man-in-the-middle attack on the bluetooth connections. Also, this app is designed only for contact tracing. However, a lot more data could be collected that might be of great use for epidemiological purposes which the app is not designed for.

De Carli et al. presents a privacy-preserving mobile tracing application -WeTrace in [16]. Mobile phones that have the application installed, periodically broadcast the app generated public key. Like Covid-watch, other phones in close proximity (estimated using Bluetooth Low Energy) record these public keys locally. When users change their status from "not infected" to "infected", messages encrypted with all the public keys available in its local storage is sent to the backend, which broadcasts it to all users. Those who were in close proximity to this user can now decrypt the message with their private key and know they were near an infected person. The backend does not store any data, it only serves to broadcast messages to the mobiles in the system. However as the authors acknowledge, such a system can suffer from DDOS attacks on the backend, the backend can be susceptible to impersonation and rouge users may issue false notifications.

Torky and Hassanein propose a blockchain based framework for mitigating the spread of coronavirus [17]. Their framework consists of four subsystems -Infection Verifier Subsystem (IVS), P2P Mobile App, Blockchain Platform and Mass Surveillance System. The IVS is the part of the system that records covid positive persons in the blockchain by using "infection patterns" which are regular expressions. The patterns derived from this regular expression, the "infection instances" are used to digitally represent people or places who have been infected by this patient. These are also recorded in the blockchain. A finite automaton can verify if a regular expression instance conforms to the infected pattern which will indicate a high probability of contagion. By representing people as regular expressions, the system does anonymise the users. These instances are also used in their proposed P2P mobile application. In their scheme, the authors use the blockchain for storing the infected pattern and all confirmed cases (infected instances) based on the pattern. The P2P application serves to notify the populace that they might have been in contact with an infected person or been to a place visited by an infected person. The Mass Surveillance System component is responsible for contact tracing and for identifying the public places the infected person may have visited in the last few days, which is sent to the blockchain to be stored as infected patterns and infected instances. However, it is unclear what underlying communication technology is employed to implement this mass surveillance scheme. It is also unclear who the block miners are in this system and what incentives they have. In Table 2, a summary of important features of the various schemes discussed in this section is presented.

3. Overview of Blockchain

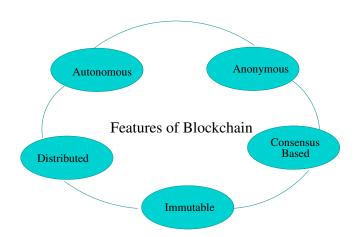


Figure 1: Features of blockchain.

Blockchain as a concept was first coined in the white paper of Bitcoin by Satoshi Nakamoto in 2009 [18]. It is a mechanism for the storage of decentralized, time stamped and immutable data. As it is decentralized and distributed in nature, it is not owned by a single authority and is kept as a distributed ledger. As shown in Figure 1, some intriguing features of blockchain that motivated us in adapting this technology in our proposal, are described as follows:[19]

Autonomous. Transactions in a blockchain can be carried out without the involvement or control of a central authority or a single authority governing the network. This architecture provides the benefits of a decentralized system with reduced operational costs and avoiding performance bottlenecks at the central location. Any node can add transactions and review them at any time.

Distributed. Transactions in a blockchain are virtually impossible to tamper as they are recorded in blocks spread over the entire network with each block validated by other nodes. In such a scenario any false transaction or changes can be detected very easily.

Immutable. All transactions and blocks added chronologically to a blockchain ledger are verifiable and all changes are traceable. Additionally, a consensus mechanism synchronizes the blocks in all the nodes. These measure ensures that data in the blockchain cannot be altered and changed.

Consensus based. New transactions and blocks are added in the blockchain based on a previously agreed upon mechanism called consensus method. All the stakeholders update their copy of the ledger by adding the same block to their individual blockchains (ledger) with the help of this consensus mechanism. Therefore, each individual at a particular instance of time has the same copy of the blockchain, synchronized with every other individual.

Anonymous. In blockchain, information about individuals can be recorded with a generated address, which does not reveal the real identity of the individual. Thereby, facilitating anonymous storage of individual records.

A schematic view of how a Blockchain works is shown in figure 2.

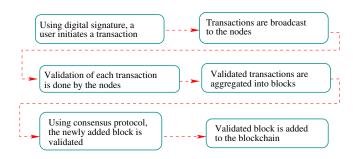


Figure 2: Stages of a blockchain.

When a new transaction is initiated, it is broadcast among the nodes, and based on a consensus algorithm, a miner adds the transaction into the block. The *nodes* in Blockchain can be any device (computer, mobile phone) that contains a copy of the Blockchain. The *miners* are nodes that create blocks after validating new transactions and adhering to a accepted consensus mechanism. Without involvement and authentication from any central authority, these blocks are validated using the *consensus algorithm* which establishes mutual trust and enables a decentralized network to take a decision. Consensus algorithm plays a significant role in maintaining the safety and regulation of the Blockchain. Common consensus algorithms are 'proof of work', 'proof of stake' and 'proof of existence' [20].

Proof of Work (PoW) is a popular consensus method used by various cryptocurrencies. It's popularity is due to the fact that it provides safety from various attacks. PoW is used to validate transactions and add new blocks to the chain by solving a complex computational problem. Miners race against each other to solve the problem and create the blocks. The first miner to solve the problem gets to add the new block into the blockchain and claim a reward. The reward is an incentive mechanism that ensures the participation of miners in the blockchain. PoW has some limitations like it is computationally intensive and vulnerable to attack from 51% of the nodes in the network. To overcome the limitations of PoW method, Proof of Stake (PoS) method was introduced that determines the block creator based on a combination of node's wealth, the staking age and random selection. Selection purely on the basis of the node's wealth would result in the node with the most wealth having a constant advantage in block creation. Hence a combination of various strategies have been adopted. The staking age ensures that nodes that hold the stake longer have a better chance to forge blocks which decreases the chances of malicious attacks. As a reward transaction fees are given to the block validators.

The Blockchain consists of *chain of blocks* as shown in the figure 3.

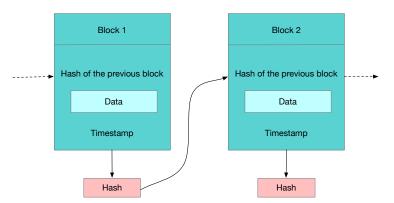


Figure 3: Structure of a blockchain.

Each block is arranged in chronological order, consisting of block header and block body. Every block also contains the hash of the previous block, its data, merkle root and timestamp. As each block contains the hash value of the previous block, it is ensured that blocks are linked and changes cannot be made in any one of the blocks without being reflected in all subsequent blocks. This makes data in the Blockchain virtually impossible to alter and change. A block contains a number of transactions, and all these transactions have a hash associated with it. Each pair of these hashes are then concatenated to compute another hash and so on. Such hashing is used to build a tree of hash values. The merkle root is then the hash of all the transactions a block contains. *Merkle Root* is used to provide integrity of all the transactions in a block, as changing any one transaction will change the merkle root.

Depending on various conditions, Blockchain can be categorized into public, private and consortium.

Public Blockchain. Public Blockchains are fully decentralized, the ledgers are open and transparent. Anyone can be part of this Blockchain as a miner or as a node without any restriction. Example of public Blockchain are Ethereum, Monero, Bitcoin, etc. Bitcoin is a decentralized cryptocurrency in the absence of a central administrator in which everyone can invest.

Private Blockchain. Private Blockchains are similar like that of public Blockchain following a set of conditions. It is governed by an organization and only those who have permission or invitation to access can participate. Private Blockchains are also called permissioned Blockchain. It is also a decentralized peer-to –peer network but the participants are decided by an organization. Hyperledger is an example of Private Blockchain.

Consortium Blockchain. In a Consortium Blockchain, a group of companies or stakeholders comes together to develop a Blockchain. It is partly private and partly public Blockchain and is also referred to as a semi-decentralised Blockchain. Consortium Blockchain consists of pre-determined group of nodes and validation of blocks are also determined by specific group. Also in this type of Blockchain, certain operations may be open to other participants. Example of of consortium Blockchain are R3, EWF, Libra, etc.

Blockchain is widely used in the field of cryptocurrency - Bitcoin being its most popular implementation. However, other than Bitcoin, Ethereum, Monero, Litecoin are some examples of cryptocurrencies where blockchain is used to maintain the distributed ledger of transactions. Furthermore, Blockchain technology has found use in areas other than cryptocurrency and is transforming these fields. A few areas where blockchain is proving particularly effective are:

- *Electronic Health Records (EHRs)* based on Blockchain provides patients access to immutable and complete records of their own medical history without any service providers, as opposed to the traditional method where electronic records of patient's health are held by the respective hospitals. [21]
- Product Ownership Management System (POMS): Blockchain is used for anti-counterfeits in the RFID enabled supply chain in which a customer can reject purchase of counterfeits products even with a genuine RFID tag if the seller does not have the ownership of the product. The "proof of possession balance" of public ledger of the blockchain is used to verify th said ownership. [22]
- In *cloud computing*, metadata that keeps a record of the history of creation and operations that have been performed on a cloud data object is of utmost importance. It is used to provide accountability, forensics and privacy. Blockchain-based data provenance architecture can be used to ensure transparency of such data, and can provide tamper-proof records

which is essential for transparency of data accountability and can enhance availability and privacy of provenance data. [23]

- A Blockchain-based access control model in IoT is introduced to manage access control, where smart contract is used for contextual access control policies to make authorization decisions. This blockchain based solution ensures user privacy by avoiding the use of a third party to handle and implement access control policies. [24]
- A Blockchain-enabled platform can be used for processing insurance transactions to speed up the processes in the insurance industry, to make client data confidential, to reduce operational costs, transaction processing times and payment settlement duration and provide security in the whole insurance mechanism. [25]

Given the inherent benefits of blockchain technology, it was felt that it can contribute immensely in designing a platform that can be used in fight against the spread of the COVID-19 virus.

4. The Proposed Blockchain Framework

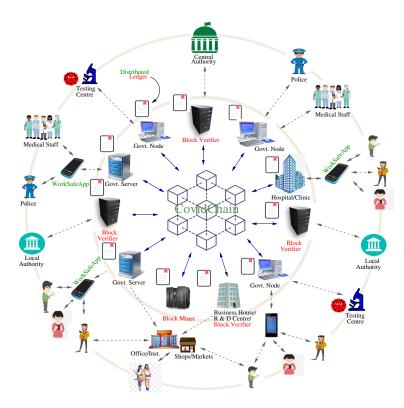


Figure 4: Blockchain framework for protection against COVID-19.

In this section, we present our blockchain based framework called 'CovidChain' for protection against COVID-19. Compared to majority of the applications

that have been developed in the recent past with an intention to contain the spread of COVID-19, our proposal differs with regards to the following aspects.

- Most of the apps are specifically designed for tracing and alerting those people who might have come in contact of an infected person. Such a mechanism helps the intimated people to take precautions with regards to their own health and social behaviour. However in addition to this aspect, in our framework, we focus on another issue: which is that of allowing those individuals of the society who have not tested positive or have not come in close contact with a corona positive person, to continue with his/her economic activities while protecting himself/herself against the virus.
- The data generated in most of the apps are stored in a single location that is under the control of a single authority. In our proposal, the generated data is recorded in a consortium blockchain in the form of a distributed ledger that is accessible to every section of the society. Such an approach will increase transparency and will allow the entire population to garner it's benefit. It also helps in avoiding confusion about the current status of the infection as reliable data is available to everyone at the same time.
- The framework is designed keeping privacy, anonymity and incentive for the stakeholders in mind.

The various stakeholders and entities associated with the framework are as follows Figure 4.

- *Medical professionals*: They are people who perform random testing. In addition to their testing kits, they are equipped with a bluetooth enabled smartphone and Internet connectivity. They have read-only access to the ledger and generates transactions comprising of covid status of individuals based on their test report (for example: +ive, -ive, number of days of quarantine required, etc.).
- *Hospitals/Clinics/Laboratory*: They have read-only access to the ledger and can generate transactions comprising of covid status of individuals based on their test report (for example: +ive, -ive, number of days of quarantine required, etc.), for onward transmission to the block miner.
- *Testing Centres*: These are centres established by the Govt. with facility for COVID-19 testing. They are equipped with a bluetooth enabled smart phone, computer and Internet connectivity. They have read-only access to the ledger and generates transactions comprising of covid status of individuals based on their test report (for example: +ive, -ive, number of days of quarantine required, etc.).
- *Govt. nodes*: These are computers established by the authority having readonly access to the ledger. They facilitate testing centres, law enforcement personals, medical professionals and individuals to access the ledger and communicate transactions generated by them.
- Business houses, Research and Development Centers, etc.: They are nodes with read-only access to the blockchain. They are interested in the data getting appended in the blockchain for research and business purpose. Such organizations can even participate in the system as a Block Evaluator.

- *Institutes, shops, offices, etc.*: These establishments have read-only access to the ledger through a Govt. node or a Business house. They are interested in the data that is getting generated, so that they can use it for smooth running of their business activities.
- *Individuals*: Through their smart phones, they have read-only access to the ledger through a Govt. node or a node belonging to a business house. They can use the data to protect themselves from infection as they go about their day to day business activities.
- Law enforcement personals: These are people like policeman etc., who suggests quarantine to individuals with recent travel history or having been contact traced to covid positive individuals, by generating such transactions for onward transmission to the block miner. They also demarcate a locality, district, etc. into red, orange, green zone based on number of people infected in a locality, so that people outside such zones can be alerted about their proximity to such a zones. Such personals have to be equipped with Internet and bluetooth enabled smartphones or computers.
- *Block Miner*: It is a centrally located node in the blockchain that receives all the transactions generated by the various stakeholders. These transactions are then put together into blocks.
- *Block Verifier/Validator*: These are nodes that validates all the transactions by examining their digital signatures. A Block Validator is either owned by the state/central government of a country or are owned/monitored by establishments that are nominated by the civil society.
- Local Authority: A local government of a state or a province.
- Central Authority: The central government of a country.
- WorkSafeApp: It is a smart phone application that is used as an interface to interact with CovidChain. WorkSafeApp requires the smart phone of an individual to be bluetooth enabled. Like many recently developed applications for contact tracing through bluetooth [10][15][7], WorkSafeApp also collects anonymized tokens from the smart phones of all such individuals with whom a person has come in close proximity in the past few days. If the person is ever tested positive for COVID-19, all the collected tokens are mapped to their corresponding contact numbers and all such individuals are either tested for COVID-19 or are suggested to be in quarantine by medical professionals or law enforcement agencies. WorkSafeApp also has a self assessment module, using which a user can assess his health status by answering certain queries. Depending on the answers and severity of the symptoms, the module suggests people to either self quarantine or to get in touch with a Testing Centre. As the blockchain data is publicly available, applications similar to WorkSafeApp with CovidChain as the backend data may be developed by individual businesses.

We split the functionality of the entire framework, including the process of adding a block in the blockchain, into the following activities.

4.1. App Initialization

When WorkSafeApp is installed in a smart phone, a pair of public-private key is generated by taking an OTP verified phone number as input from the user. Hence forth, the phone number is neither recorded nor used for any other purpose. For all subsequent purposes, the public key is used as it's identity by the user.

4.2. Transaction Generation

A transaction may be of two types, viz., transactions indicating individual status ' T_{Ind} ' and transactions indicating location status ' T_{Loc} '. ' T_{Ind} ' is a statement that represents the covid status of an individual as determined by a medical professional, a testing centre, a hospital or a law enforcing personal. It has three components, viz., the hash of the public key of the individual $(H(K_{pub_{Ind}}))'$, the COVID status 'CS' of the user, the Date, the Time and a minimal set ' S_{Epid} ' of epidemiological information like age, gender, blood group, state/province, pre-existing disease, etc., that is required by the Govt. to make a general study on the overall data, so that new knowledge about the proliferation pattern of the virus may be derived. ' S_{Epid} ' should contain minimum number of attributes required for data analysis. It should not contain information like House-no, Street-no, etc. that may compromise anonymity and privacy of an individual. Before including the set S_{Epid} in the transaction, it is encrypted using the public key ' $K_{pub_{CA}}$ ' of the Central Authority. A transaction is uniquely identified by a transaction identity TID', which is the hash value of the transaction. This is further encrypted with the Testing Centre's private key $E_{K_{pri_{TC}}}$, for generating a digital signature DS_{TC} so that the genuineness of the transaction may be verified by the Block Validators.

Therefore,

$$S_{Epid} = \{age, gender, state, ..\}$$
(1)

$$S_{Enc} = E_{K_{pub_{CA}}}(S_{Epid}) \tag{2}$$

$$TID = H(H(K_{pub_{Ind}}), CS, Date, Time, S_{EncEpid})$$
(3)

$$DS_{TC} = E_{K_{pri_{TC}}}(TID) \tag{4}$$

$$T_{Ind} = \{TID, H(K_{pub_{Ind}}), CS, Date, Time, S_{Enc}, DS_{TC}\}$$
(5)

Where, 'E' is an encryption function and 'H' is a one way hash function like SHA-256. The various symbols and acronyms used in this section are presented in Table 1 for quick reference. T_{Loc} is a transaction made by a local authority or a law enforcement agency that identifies a locality, district, etc., as a red zone, orange zone or a green zone, based on the number of infected people in

	Table 1: Acronyms and symbols
Acronym/Symbol	Description
T_{Ind}	Transaction related to CS of an individual.
T_{Loc}	Transaction related to CS of a zone.
$\frac{K_{pub_{Ind}}}{\text{CS}}$	Public key of an individual.
CS	COVID-19 (C19) status.
S_{Epid}	Epidemiological information about an individual.
S_{Enc}	Encrypted Epidemiological information.
$K_{pub_{CA}}$	Public key of Central Authority.
TID	Transaction identity.
$E_{K_{pri_{TC}}}$	Private key of a testing centre.
DS_{TC}	Digital signature of testing centre.
Н	One way hash function.
E	Encryption function.
D	Decryption function.
lt, ln	Latitude, longitude.
radius	Radius of a zone.
zoneType	Zone type: red/orange/green.
zoneId	Zone identity.
DS_{LEA}	Digital signature of Law Enforcing Agency.
$K_{pri_{LEA}}$	Private key of Law Enforcing Agency.

a particular area, so that people outside such zones can be alerted about their proximity to such zones. Such transactions help the authority to disseminate (and people to acquire), timely and reliable information about crucial decisions. To demarcate a locality, the GPS coordinates ('lt', 'ln'), radius of the zone 'r', date, time, zone type 'zoneType' (red/orange/green) are recorded in a transaction. Zone identity 'zoneId' which is the hash of the location coordinate, 'TID' which is the hash of the entire transaction, and the digital signature of the authority 'DS_{LEA}' that is obtained by encrypting the 'TID' with the private key of the Law Enforcing Authority ' $K_{pri_{LEA}}$ ', are also recorded in a location transaction. Therefore,

$$zoneId = H(lt, ln) \tag{6}$$

$$TID = H(zoneId, lt, ln, r, Date, Time, zoneType)$$
⁽⁷⁾

$$DS_{LEA} = E_{K_{pri_{LEA}}}(TID) \tag{8}$$

$$T_{Loc} = \{TID, zoneId, lt, ln, r, Date, Time, zoneType, DS_{LEA}\}$$
(9)

After a transaction is generated $(T_{Ind} \text{ or } T_{Loc})$, it is transmitted to the Block Miner.

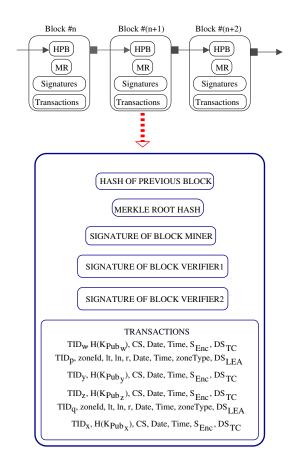


Figure 5: Structure of a block in CovidChain.

4.3. Block Mining

The Block Miner contains a single or multiple servers that receive the transactions from all the testing centres, hospitals, etc. When the total size of the received transactions reaches a predetermined block size (say 1 MB), they are bundled together into a block (Figure 5). Each transaction in the block is then verified by validating the digital signature of the Testing Centres that signed it. The Merkle Root Hash (MRH) of the block is calculated from the hash of all the transactions by pairing the hash values and rehashing the sum of the pairs as depicted in (Figure 6).

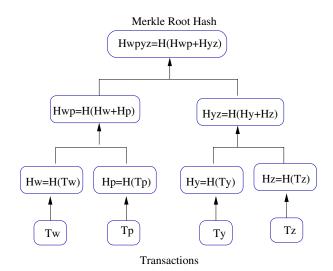


Figure 6: Calculation of Merkle Root Hash from the Transactions.

After this, the Block Miner adds the MRH to the block and digitally signs the MRH with its Private Key $K_{pri_{BM}}$. Therefore, if ' T_w ', ' T_w ', ' T_w ' and ' T_w ' are the transactions in a block, then the MRH ' H_{wpyz} ' of this block is calculated and digitally signed as fols.

$$H_w = H(T_w) \tag{10}$$

$$H_p = H(T_p) \tag{11}$$

$$H_y = H(T_y) \tag{12}$$

$$H_z = H(T_z) \tag{13}$$

$$H_{wp} = H(H_w + H_p) \tag{14}$$

$$H_{yz} = H(H_y + H_z) \tag{15}$$

$$H_{wpyz} = H(H_{wp} + H_{yz}) \tag{16}$$

$$DS_{BM} = E_{K_{pri_{BM}}}(H_{wpyz}) \tag{17}$$

After this, the Block Miner forwards the block to a couple of Block Verifiers/Validators 'BV1' and 'BV2', selected randomly from among all the available Block Verifiers. Each transaction in the block is then verified by validating the digital signature of the Testing Centres that signed it; after which, the Block Verifiers digitally sign the MRH of the block with their respective private keys $K_{pri_{BV1}}$ and $K_{pri_{BV2}}$.

$$DS_{BV1} = E_{K_{pri_{BV1}}}(H_{wpyz}) \tag{18}$$

$$DS_{BV2} = E_{K_{pri_{BV2}}}(H_{wpyz}) \tag{19}$$

The signed block is then sent back to the Block Miner. After receiving the block, the Miner verifies the signatures of the Block Verifiers. The block is then broadcast to all the nodes/stakeholders in the network. Upon validation of the digital signatures, each node in the network adds the block to their individual ledger (or their individual copy of the blockchain). While adding the block to the block to the blockchain, the Hash of the Previous Block (HPB) is added to the current block.

4.4. COVID status verification

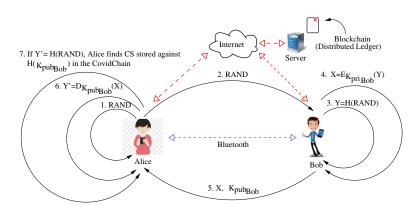


Figure 7: COVID status verification.

'CovidChain', the proposed blockchain framework will aid people by providing an additional layer of protection from the virus while engaged in their activities. It will enable entities in the society like offices, businesses, shops, markets, educational institutes, traffic police, law enforcement agencies, etc., to verify employees and clients at entry points based on data available in the blockchain. An individual will also be able to verify another individual through the bluetooth interface of his/her smart phone as they engage in day to day business activity. For example, Alice will be able to verify the covid status of Bob, a plumber, before letting him into her premise. Similarly, Bob will be able to verify the covid status of Alice before entering her premise. A delivery boy will be able to verify his client's covid status through a web interface, before setting off for delivery. Therefore, CovidChain on one hand will allow Alice to verify the covid status of Bob and on the other hand will allow Bob to present his smart phone as an E-pass to Alice. The sequence of steps involved, when Bob presents his credentials to Alice for verification, is follows (Figure 7).

- 1. Alice: Generates a fresh random number *RAND*.
- 2. Alice: Transmits RAND and request for C19 status to Bob.
- 3. Bob: Calculates the following

$$Y = H(RAND) \tag{20}$$

$$X = E_{K_{prip,1}}(Y) \tag{21}$$

Where, $E_{K_{pri_{Bob}}}$ is the private key of Bob, 'E' is an encryption function and 'H' is a one way hash function.

- 4. Bob: Transmits 'X', and his Public Key ' $K_{pub_{Bob}}$ ' to Alice.
- 5. Alice: Calculates the following.

$$Y' = D_{K_{pub_{Bob}}}(X) \tag{22}$$

Where, 'D' is the decryption function.

- 6. Alice: Compares Y' and H(RAND). If Alice finds that Y' = H(RAND), it is convinced that $K_{pub_{Bob}}$ is the public key of Bob. After this, Alice finds the covid status of Bob from the CovidChain using $K_{pub_{Bob}}$ (i.e., $H(K_{pub_{Bob}})$).
- 7. Alice: If the COVID Status against $H(K_{pub_{Bob}})$ is neither '+ive' nor 'IQ' (ie., in quarantine), or if there is no transaction against ' $H(K_{pub_{Bob}})$ ', Alice may allow Bob to have access to her premise with additional social distancing precautions.

Bob can also verify the covid status of Alice in a similar manner.

4.5. Accessibility of Data

With the rapid spread of the virus, the numbers of infection, case fatality, etc., and administrative decisions like declaring a zone to be a containment zone changes rapidly. In such a fluid scenario, disseminating reliable timely information that policy makers, epidemiologists, news agencies and people in general depend heavily on, becomes a challenging affair. Especially so, when the data is in control of a single authority. Since the proposed framework is based on blockchain technology, the data is stored in distributed ledgers that are open for public access. The data is immutable, updated in real time, and is available for public scrutiny and audit. The possibility of the data being manipulated by any stakeholder with malicious intention is negligible because of its immutable nature. The availability of the data to various sections of the society like shops, businesses, offices, households, etc., will empower them to take crucial decisions with regards to their economic activities. For instance, allowing uninfected people or people who are not in quarantine to join work, etc.

4.6. Anonymity and Privacy of Data

Anonymity and privacy of data related to individuals is an important aspect for the success of such a platform. If an individual gets the perception that his/her anonymity or privacy of data is not being respected, s/he will be apprehensive about using such an application. Such applications will be successful in its objective, only if there is widespread adoption among the populace. Taking this into cognizance, we have designed the framework on blockchain. In our framework, any stakeholder including the Central Authority, having access to the distributed ledger or the blockchain, will not be able to link a particular transaction in the ledger with any individual, because the anonymity of transactions are guaranteed as follows.

- While creating a block, the Block Miner bundles the transactions in the same order as it receives from the different stakeholders. Therefore, a single block will have multiple transactions, originating at different sources, shuffled together. This will make it extremely difficult for anyone having access to the blockchain to link the data available in a transaction to its origin.
- Since the Testing Centres, Hospitals, etc., records the Hash of the Public Key in a transaction, any node/stakeholder having access to the blockschain will not be able to traceback any data to any individual because it will not be able to map a given Hashed Public Key to its corresponding Public Key.
- When an individual (say Alice) has to present his identity to another individual (say Bob) located a few feet away, s/he transmits his/her Public Key $K_{pub_{Alice}}$ through the bluetooth interface. Bob searches through the ledger for any transaction that is recorded against $H(K_{pub_{Alice}})$. If Bob finds any such transaction, the only thing he gets to know about Alice is her COVID status and nothing else, because the rest of the epidemiological data is encrypted with the private key of the Central Authority.
- The Central Authority, having access to the epidemiological data through it's private key, can only link the data in a transaction to a hash value that cannot be mapped to its corresponding Public Key. Therefore, it cannot link any data with any particular individual. Such data, will only help the authority to carry out epidemiological analysis without compromising anyone's privacy.
- While analyzing the epidemiological data, the Central Authority cannot traceback a particular transaction of interest to its origin. But, if the Central Authority wishes, it can collect the public key of an individual through the bluetooth interface (say at a entry point to a public facility) and locate his epidemiological information in the blockchain through the hash of this public key. However, such an effort will be herculean for the Central Authority, specially if it wishes to carry out a mass surveillance of it's citizens. Moreover, once the pandemic gets over, people will either uninstall the WorkSafeApp from their smart phone or will keep their bluetooth interface switched off, which will put an end to any such effort by the authority.

4.7. Alert Mechanism

The proposed framework enables the authority to demarcate an area as a red/orange/green zone. The data regarding the same (GPS coordinates, radius, date and time of declaration, etc.), are added as a transaction in the blockchain. Since the blockchain is publicly available, people will get timely information about the same through the distributed ledger. Also, an individual who happens to be in the vicinity of containment zone or is about the enter said zone, may be alerted through the App.

4.8. Incentive for Stakeholders

Success of a framework like this, requires participation from almost every individual of a Country. However, it is difficult to realize such a participation if there is no clear thought on how various sections of the people are going to benefit from their participation. Apart from the broader social goal of containing the virus, there has to be perceivable incentive for the individual. In order to have an idea of how different sections of the society are going to benefit from this framework, the stakeholders of this framework are categorized into the following groups, based on their similarity of interest.

- Category-I:Individuals.
- category-II: Business houses, Office, shops, Institutes, etc.
- Category-III: Testing Centre, Hospitals, Laboratories, police personals.
- Category-IV: Authority.

Category-I contains two kind of individuals: a) an individual whose covid status is '+ive' or is 'In Quarantine (IQ)' b) an individual whose covid status is 'Out of Quarantine (OQ)', or an individual who never had any symptoms and never meet an infected person. While people of the first kind would like to see the change of their status (say from '+ive' to '-ive', '-ive' to 'IQ' and 'IQ' to'OQ', etc.) in the public ledger, people of the second kind would like to carry on with their day to day work with minimal restrictions while remaining protected from infection. If the authority, shops, markets, offices, businesses, etc., allows access of their facilities only to those individuals that are found safe, then installation of the WorkSafeApp will enable people to use their smart phone as a digital-pass to access these facilities.

Entities in category-II would like to carry on with their day to day business while taking care of their own and other's safety. By verifying the covid satus of every individual at entry points, these individuals will be able to offer a safe environment to their employees and clients.

Entities in Category-III are the ones that generate transactions for the blockchain by performing clinical test on the individuals. Based on the previous status of an individual (say '+ive'), in his next visit, new transaction with status (say 'IQ' or 'OQ') may be created. This category will have their obligations to the government and to the society in general to carry out their responsibilities.

Category-IV will have social obligations to protect the society by containing the spread of the virus. They are the ones that will be responsible for setting up such a system and keeping it running. They will be able to enforce strict

AsiA noitosfnI to noitoibor	Z	Z	Z	Z	Z	Z	Z	Z	Х	z	
noitasitirsV sutat2 bivoO swollA	П	Υ	Z	Υ	н	Z	Υ	Г	н	Ч	
Data Recorded in Distributed Ledger	z	Z	z	z	Z	Z	Х	Y	Y	Y	
msinahəəM trəlA na zaH	П	Ι	Υ	П	I	Ζ	I	γ	Ч	Υ	
can be Used as a Digital Pass	н	Х	z	н	н	Z	Ч	Г	z	Y	
Records Contact Tracing Data	Υ	Υ	Υ	Υ	Υ	Υ	I	Υ	Υ	Υ	
noitomrofal noito201 293 232U	Z	Υ	Υ	Z	Υ	N	Υ	Υ	Ι	Υ	
upolondəəT diootəul ${f B}$ eseU	Υ	Υ	z	Υ	Υ	Υ	Z	Y	Г	Υ	
${ m R}$ ecords Epidemiological Data	Z	Υ	Z	Υ	Υ	Z	Υ	Z	Z	Υ	
winodiu A tamnot wimpnon A	Z	Z	Z	z	Ζ	Υ	I	Υ	Υ	Υ	
erse U rsht O mort ytimynon A	Υ	Υ	Υ	Υ	Ч	Υ	Г	Υ	Υ	Υ	
Developer	Govt. of Singapore	Govt. of India	Govt. of Israel	Govt. of Australia	Govt. of South Korea	Arx et al.	Hazra et al.	Carli et al.	Torky et al.	Choudhury et al.	on; P : Partially Yes
Application	PraceTogether [7]	Aaroyga Setu [10]	Hamagen [8]	CovidSafe [9]	South Korea	Covid-Watch [15]	Virusblockchain [13]	WeTrace [16]	Covid-19 BlockChain Framework [17]	CovidChain	Y: Yes; N: No; I: Insufficient Information; P: Partially

quarantine for people who are recorded as '+ive' or 'IQ' in the blockchain. People without a WorkSafeApp installed smart phone, may not be allowed to work or move freely. To enforce such restrictions, several countries have adopted the technique of stamping the hand of quarantined people. However, stamping has its own limitations like the following.

- Stamp impression may fade away before the end of the quarantine period.
- Stamp impression may persist even after the quarantine period is over.
- People with stamp impression may have to face social stigma.

Another incentive for the Authority to set up such a system is generation of epidemiological data that may help in finding novel facts and statistics for containing the virus.

5. Discussion

In this section, we discuss the different features of the proposed framework with reference to the applications and proposals discussed in Section 2. A summary of the comparison of our proposal 'CovidChain' with the other applications and proposals developed in recent times is presented in Table 2.

In all the related works we have analysed in this area, there is anonymity from other individuals, but very few have anonymity from the authority or government. However, in order to gain confidence of the population so that adoption rate of application increases, ensuring anonymity of individual from the authority is of paramount important. CovidChain framework takes care of both the aspects. In CovidChain, an individual gets to know only the covid status of another individual and though the authority has access to epidemiological data, it cannot trace it back to any particular individual.

In many of the works, epidemiological data is not collected. However, an application like this is possible only if the authority mobilizes and invests a significant amount of public resources. In return, it is desirable that new knowledge is derived about the spread pattern of the virus so that novel strategies for containing the virus may be planned. Therefore, it is important that epidemiological data is collected taking care of the anonymity of individuals. In CovidChain, there is provision for recording of epidemiological data that can only be accessed by the authority; the general public cannot see the content as it is encrypted.

Apart form Internet connectivity, two technologies that are commonly used in these applications are bluetooth and GPS information. While both these technologies are crucial in exchanging information about the spread of the virus, it is important that the information that are transmitted does not lead to compromise in security and anonymity of an individual. Moreover, one should not be able to transmit misleading information by impersonating as someone else. In CovidChain, there is proper mechanism to authenticate an individual. Here, GPS data related with an individual is never recorded in the blockchain. Only GPS data related with a containment zone is stored, using which an individual is alerted by measuring his her distance from a containment zone.

As evident from the table, the focus of most of the work in this area is on contact tracing of people who might have come in close contact of an infected individual. Such works are of great importance as it may contribute significantly in identifying at-risk individuals who needs to be urgently quarantined and tested for the virus. However, in addition to contact tracing, it is equally important to ensure that quarantined individuals do not put other individuals at risk by coming out in public. Since, the CovidChain framework allows individuals to verify each other's covid status, like a digital-pass it may help in restricting quarantined individuals from accessing public facilities.

In most of the works, accumulated data about the spread of the virus is stored in a centralized location under the control of a single authority. For such an arrangement, it is difficult to gain public support and confidence due to peoples' reservation regarding the privacy and safety of their data. It becomes difficult to assure people that their data will not be used for any other purpose after this crisis is over. Therefore, it becomes imperative that the structure and relevant portion of the data is publicly made available, so that it is open for scrutiny and audit. Such an approach not only helps in garnering public support but also helps various sections of the society to remain well informed with reliable data that they can use in their individual businesses. In CovidChain, blockchain technology is used for record keeping. As a result, same copy of the ledger is maintained at several locations with immutable data that can be accessed by all sections of the society.

6. Conclusion

To contain the rapid spread of COVID-19, several smart phone based applications have been developed and proposed in recent times. Most of the solutions are focused on contact tracing of people who might have come in close proximity of an infected individual. However, in the current scenario when continued lock downs have brought the economy of several countries to the edge, there is a need to explore technical ways to facilitate both social distancing and economic activities to go hand in hand. Off late, quite a few countries are contemplating on allowing a section of their uninfected citizens to use smart phone applications as digital pass to join their respective work. However, success of such an approach depend highly on people participation, which is possible only when data are maintained transparently taking security and privacy concerns into consideration. In this paper, we propose a framework that can be used by people to protect themselves from infections while they are involved in their day to day business activities. The framework uses blockchain technology for secure and anonymous record keeping. The distributed nature of blockchain makes relevant data accessible to all stakeholders for their use and public scrutiny.

References

- WHO, Coronavirus Prevention, Tr, World Health Organization (2020). URL https://www.who.int/health-topics/coronavirus/
- [2] G. Gopinath, The Great Lockdown: Worst Economic Downturn Since the Great Depression, Tr, International Monetary Fund (2020). URL https://blogs.imf.org/2020/04/14/the-great-lockdownworst-economic-downturn-since-the-great-depression/

- [3] K. T. Eames, M. J. Keeling, Contact tracing and disease control, in: Proceedings of the Royal Society of London. Series B: Biological Sciences, Royal Society of London, 2003, p. 2565–2571.
- [4] D. Normile, Coronavirus cases have dropped sharply in South Korea. Whats the secret to its success?, Tr, ScienceMag.org (2020). URL https://www.sciencemag.org/news/2020/03/coronaviruscases-have-dropped-sharply-south-korea-whats-secret-itssuccess
- [5] Whose coronavirus strategy worked best? Scientists hunt most effective policies, accessed: 2020-04-30. URL https://www.nature.com/articles/d41586-020-01248-1
- [6] China rolls out fresh data collection campaign to combat coronavirus, accessed: 2020-04-30. URL https://www.reuters.com/article/us-china-health-datacollection/china-rolls-out-fresh-data-collection-campaign-tocombat-coronavirus-idUSKCN20K0LW
- [7] Tracetogether, accessed: 2020-04-30.URL https://www.tracetogether.gov.sg/
- [8] Hamagen: The Ministry of Health App for Fighting the Spread of Coronavirus, accessed: 2020-04-30. URL https://govextra.gov.il/ministry-of-health/hamagenapp/download-en/
- [9] Australian Government, Department of Health COVIDSafe App, accessed: 2020-04-30. URL https://www.health.gov.au/resources/apps-and-tools/ covidsafe-app
- [10] Government of India Aarogya Setu Mobile App, accessed: 2020-04-30. URL https://www.mygov.in/aarogya-setu-app/
- [11] Australia has COVIDSafe. Here is how other countries are using contact tracing apps in the fight against coronavirus, accessed: 2020-04-30.
 URL https://www.abc.net.au/news/2020-04-28/coronavirus-covid19-contact-tracing-apps-around-the-world/12189438
- [12] www.phbconsortium.org, accessed: 2020-04-23. URL https://www.phbconsortium.org/
- [13] www.virusblockchain.com, accessed: 2020-04-26. URL https://www.virusblockchain.com/coronavirus-blockchain. html
- [14] D. Nguyen, M. Ding, P. N. Pathirana, A. Seneviratne, Blockchain and AI-Based Solutions to Combat Coronavirus (COVID-19)-like Epidemics: A Survey.

URL https://www.techrxiv.org/articles/Blockchain_and_AIbased_Solutions_to_Combat_Coronavirus_COVID-19_-like_ Epidemics_A_Survey/12121962/1

- [15] Slowing the spread of infectious diseases using crowdsourced data, accessed: 2020-04-28. URL https://www.covid-watch.org/article
- [16] A. De Carli, M. Franco, A. Gassmann, C. Killer, B. Rodrigues, E. Scheid, D. Schoenbaechler, B. Stiller, WeTrace – A Privacy-preserving Mobile COVID-19 Tracing Approach and Application (2020) 1–15arXiv:2004. 08812. URL http://arxiv.org/abs/2004.08812
- M. Torky, A. E. Hassanien, COVID-19 Blockchain Framework: Innovative ApproacharXiv: 2004.06081. URL http://arxiv.org/abs/2004.06081
- [18] S. Nakamoto, Bitcoin: A peer-to-peer electronic cash system, Tech. rep., Manubot (2019).
- [19] Q. Feng, D. He, S. Zeadally, M. K. Khan, N. Kumar, A survey on privacy protection in blockchain system, Journal of Network and Computer Applications 126 (2019) 45–58.
- [20] Sankar, Lakshmi Siva and Sindhu, M and Sethumadhavan, M, Survey of consensus protocols on blockchain applications, in: 2017 4th International Conference on Advanced Computing and Communication Systems (ICACCS), IEEE, 2017, pp. 1–5.
- [21] R. Guo, H. Shi, Q. Zhao, D. Zheng, Secure attribute-based signature scheme with multiple authorities for blockchain in electronic health records systems, IEEE access 6 (2018) 11676–11686.
- [22] K. Toyoda, P. T. Mathiopoulos, I. Sasase, T. Ohtsuki, A novel blockchainbased product ownership management system (poms) for anti-counterfeits in the post supply chain, IEEE Access 5 (2017) 17465–17477.
- [23] X. Liang, S. Shetty, D. Tosh, C. Kamhoua, K. Kwiat, L. Njilla, Provchain: A blockchain-based data provenance architecture in cloud environment with enhanced privacy and availability, in: 2017 17th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGRID), IEEE, 2017, pp. 468–477.
- [24] A. Ouaddah, A. A. Elkalam, A. A. Ouahman, Towards a novel privacypreserving access control model based on blockchain technology in iot, in: Europe and MENA Cooperation Advances in Information and Communication Technologies, Springer, 2017, pp. 523–533.
- [25] M. Raikwar, S. Mazumdar, S. Ruj, S. S. Gupta, A. Chattopadhyay, K.-Y. Lam, A blockchain framework for insurance processes, in: 2018 9th IFIP International Conference on New Technologies, Mobility and Security (NTMS), IEEE, 2018, pp. 1–4.