**COVIBLOCK: A MERKLE DAG AND BLOCKCHAIN**

**IMPLEMENTATION FOR COVID-19 RECORDS**

A Capstone Project Presented to the Graduate Program

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Master in Information Technology

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**APPROVAL SHEET**

The capstone project hereto titled

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**IMPLEMENTATION FOR COVID-19 RECORDS**

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**Chapter One**

**INTRODUCTION**

* 1. **Background of the Study**

With the advancement of computer technology, electronic documentation and the use of electronic medical records have become more feasible. Medical records on a shared computer network that are read and written electronically on a relational database using a graphic user interface are referred to as electronic medical records. In the study entitled “A comparison of electronic records to paper records in mental health centers” (Tsai and Bond, 2007), they looked at three mental health facilities that had recently switched from paper to electronic medical records. Electronic records' documentation was shown to be more thorough and retrievable than paper records. As per the study, this finding can be a factor to take in when making treatment decisions.

In the study entitled “Perceived Benefits of Implementing and Using Hospital Information Systems and Electronic Medical Records” (Khalifa, 2018), they pointed out six ways EMRs could enable data accessibility and care organization: improving access to data during patient encounters, improving processes workflow, managing information overflow to clinicians, enhancing medical decision-making process care plans, supporting operational processes and improving financial data accessibility. They also emphasized that when a computer was used to retrieve patient information, physicians earned higher overall patient satisfaction rates, and when a computer was used to enter patient information, physicians received identical satisfaction rates.

The current technological advancements in the Philippines has yet to be manifested in its healthcare system. Though there were efforts from the government to adopt various modern tools, we are still miles behind other countries. On a study entitled “Barriers to the Adoption of Electronic Medical Records in Select Philippine Hospitals: A Case Study Approach” (Ebardo and Celis, 2019), identified barriers such as weak infrastructure, technology complexity and poor interface design of applications have made it difficult for various health organization to progress. Another study entitled “Barriers to Electronic Health Record System Implementation and Information Systems Resources: A Structured Review” (Gesulga et al., 2017), they determined another set of barriers to the adoption of EMRs in the Philippines namely: User resistance, lack of education and training, and concerns arising from data security. In a paper entitled “Identifying Healthcare Information Systems Enablers in a Developing Economy” (Ebardo and Tuazon, 2019), they discussed how the integration of existing information systems to be “paper-less” can produce potential savings. This is crucial given that the Philippines is still a developing country and has budget constraints to health systems.

Ospital ng Makati, a government-funded hospital, is one of the main facilities for COVID-19 patients in the City of Makati. Being a public hospital, it is expected to handle larger demographics compared to its private counterparts. Since the start of the pandemic, it is one of the primary health care facility in the city that facilitates COVID-19 test results and vaccination.

Presently, the hospital has no in-house molecular laboratory. They send requests to third-party laboratories in executing those tests. After successfully doing the tests, those laboratories will forward their results back to the hospital. These results are then given physically to the patient while the hospital keeps a copy in their archive. For vaccination, the City of Makati has an online web portal to assist with scheduling. This online system aims to lessen the crowd going to the vaccination site as they are guaranteed of a slot as opposed to other cities that implement a “first come first serve” basis. The proof of vaccination is a physical certificate and the patient being tagged as fully vaccinated in the system.

Other cities also had the same effort of putting up systems to cater the pandemic needs. Manila, Mandaluyong and Taguig also have their own sets of application. Though the motivation is good, the issue of how to unify these applications have risen and calls for having a unified system on a national level are being thrown in various media outlets.

* 1. **Statement of the Problem**

At present, Ospital ng Makati is using a system for keeping COVID-19 Test Results while vaccination records are maintained on a separate system used by the entire City of Makati. The patients only receive physical copies of these records as proof of execution.

Current setup for organizing and managing these records still has shortcomings. One aspect that the researcher can improve is the strategy for storing records since this is still stored or archived physically both by the hospital and patients.

* 1. **Objectives of the Study**

This study aims to develop an alternative platform to store COVID-19 related records for Ospital ng Makati.

Specifically, the study seeks to address the following objectives:

1. To develop an application that will decentralize storage of COVID-19 related files.
2. To provide an alternative way to minimize record tampering of uploaded files in CoviBlock by applying concepts of Merkle DAG and blockchain (as Proof-of-Authority).
3. To secure uploaded files in CoviBlock by using asymmetric key encryption scheme.
   1. **Scope and Limitations**

The study will be focusing on developing an application for management of COVID-related records for Ospital ng Makati. Since there are privacy regulations concerning health information, the researcher will use dummy data and instead will probe more on the processes on how these records are archived or managed.

The study will exclude the test results generation and vaccine management. Thus, it is more focused on how the result or outputs of these processes. The study assumes that outputs are already generated in computer readable format such as images (.png, .jpg) or documents (.pdf).

The study will only be concerned on two types of records: Test Results and Vaccine Certificates. The researcher will concentrate on developing an alternative storage system and accessibility strategy for patients and other verifying party.

* 1. **Significance of the Study**

Results obtained from the study will benefit the following stakeholders:

**Patients**. Above all, patients will greatly benefit on this application. Various regulations and laws have been implemented to ensure people are not spreaders or vaccinated. Currently, there are no unified way in getting and presenting these records are proof. More so, bad actors are using this pandemic to make money out of tampering records. The application will help solve the woes of patients in terms on ease of access and portability of their records. They will also have full autonomy of said records.

**Medical Personnel**. The application will help medical workers to focus on their medical line of duty and alleviating various admin jobs.

**Third Party Validators.** As mentioned above, records tampering has become rampant. Businesses or employers requiring such records can now be protected of this illegal activity.

**1.6 Definition of Terms**

**Cipher text** - A series of randomized letters and numbers which humans cannot make any sense of.

**Content addressing** - A way to find data in a network using its content rather than its location

**Content Identifier (CID)** - A label used to point to material in IPFS. It doesn't indicate where the content is stored, but it forms a kind of address based on the content itself. CIDs are short, regardless of the size of their underlying content.

**Cryptography** - Science of secret writing with the intention of keeping the data secret.

**Distributed Hash Table (DHT)** - A decentralized data store that looks up data based on key-value pairs.

**Hash Digest** - Output of the hash function.

**Hashing** - Process that calculates a fixed-size bit string value from a file

**Peer to Peer (P2P) Network** - A group of computers are linked together with equal permissions and responsibilities for processing data

**Plain Text** - Clear, basic unencrypted string of text

**Private Key** - Used to decrypt cipher text to plain text and only available to its owner

**Public Key** - Used to encypt plain text to cipher text and available to anyone accessing the application.

**Chapter Two**

**REVIEW OF RELATED LITERATURE**

This chapter covers studies and other literatures carried out by foreign and domestic researchers that have a significant impact on the variables investigated in this study. These studies focus on several factors that will help with the research's development. Literatures mentioned here will be of different sources: books, journals, articles, electronic materials such as PDF or E-Book, and other existing thesis and dissertations, foreign and local. Their inclusion will be considered supplemental in developing the proposed solution of this study.

**Merkle Tree**

In 1989, Ralph Merkle introduced the Merkle tree in his paper “A Certified Digital Signature”. The Merkle tree is a tree constructed bottom-up. More precisely, the tree discussed in this paper is a full binary tree and constructed from the bottom-up. Assume that the height of the tree is *hm*, and the tree owns 2hm data blocks *xi* and *yi=hash(xi),i∈[0,2hm−1]*, where *yi* is a leaf node value of the Merkle tree. Each value of the parent node is the hash of the concatenation of its children, *yparent=hash(yleft|yright)*, where | refers to concatenation. Below is a pseudocode format of the Classic Merkle Tree Traversal algorithm:

1. Set *leaf* = 0.

2. Output:

• Compute and output *leaf* with *LEAFCALC(leaf)*

• For each *h* ∈ [0,*H* − 1] output {*authh*}.

3. Refresh Auth Nodes:

For h such that 2h divides leaf + 1:

• Set authh be the sole node value in stackh.

• Set *startnode* = (*leaf* + 1 + 2h) ⊕ 2h.

• *stackh.initialize(startnode,h)*.

4. Build Stacks:

For all *h* ∈ [0,H − 1]:

• stackh.update(2).

5. Loop

• Set *leaf* = *leaf* + 1.

• If *leaf* < 2*H* go to Step 2

A Logarithmic Merkle Tree Traversal was proposed by M. Szydlo (2003). The main idea of the improved algorithm is, to reduce the memory requirements, by reducing the number of active treehash instances during the signature generation.. Here is the pseudocode:

1. Set *leaf* = 0.

2. Output:

• Compute and output leaf with *LEAFCALC*(*leaf*)

• For each *h* ∈ [0,*H* − 1] output {*authh*}.

3. Refresh Auth Nodes:

For *h* such that 2*h* divides *leaf* + 1:

• Set *authh* be the sole node value in *stackh*.

• Set *startnode* = (*leaf* + 1 + 2*h*) ⊕ 2*h*.

• *stackh.initialize(startnode,h).*

4. Build Stacks:

Repeat the following 2*H* − 1 times:

• Let *lmin* be the minimum of {*stackh.low*} for all *h* = 0,...,*H* − 1.

• Let focus be the least *h* so that *stackh.low* = *lmin*.

• *Stackfocus.update*(1).

5. Loop

• Set *leaf* = *leaf* + 1.

• If *leaf* < 2*H* go to Step 2.

In Fractal merkle tree representation (Micali et al., 2003) and traversal, the goal is to divide the merkle tree in subtrees and to preserve and compute these subtrees, instead of single nodes. Below is the pseudocode:

1. Set *leaf* = 0.

2. Output:

• Compute and output leaf with *LEAFCALC*(*leaf*)

• For each *j* ∈ [0,*H* − 1] output {*authj*}.

3. Next Subtree:

For each *i* for which *Existi* is no longer needed, i.e., for *i* ∈ {1, 2,...,*L*} with *leaf* = 1(*mod*2*hi*):

• Set *Existi* = *Desirei*.

• Create new empty *Desirei* (if *leaf* + 2*ih* < 2*H*).

4. Grow Subtrees

For each *i* ∈ {1, 2,...,*h*}: Grow tree *Desirei* by applying 2 units to modified treehash (unless *Desirei* is completed)

5. Increase *leaf* and return back to step 2 (while *leaf* < 2*H*).

**Distributed Hash Tables**

Distributed Hash Tables (DHTs) are widely utilized to manage metadata for peer-to-peer systems. For example, the BitTorrent MainlineDHT monitors sets of peers’ part of a torrent swarm. Kademlia was introduced in a paper titled “Kademlia: A peer-to-peer information system based on the xor metric” (Maymounkov and Mazieres, 2002). It is a DHT which provides:

1. Efficient lookup through massive networks: queries on average contact dlog2(n)e nodes.

2. Low coordination overhead: it optimizes the number of control messages it sends to other nodes.

3. Resistance to various attacks by preferring long-lived nodes.

4. Wide usage in peer-to-peer applications, including Gnutella and BitTorrent, forming networks of over 20 million nodes.

In “Democratizing content publication with coral” (Freedman et al., 2004), it examined Coral DSHT as an extension of Kademlia in three particularly important ways:

1. Kademlia stores values in nodes whose ids are “nearest” (using XOR-distance) to the key.

2. Coral relaxes the DHT API from get\_value(key) to get\_any\_values(key) (the “sloppy” in DSHT).

3. Additionally, Coral organizes a hierarchy of separate DSHTs called clusters depending on region and size.

Another approach, S/Kademlia DHT (Baumgart and Mies. 2007) extends Kademlia to protect against malicious attacks in two particularly important ways:

1. S/Kademlia provides schemes to secure NodeId generation, and prevent Sybill attacks

2. S/Kademlia nodes lookup values over disjoint paths, in order to ensure honest nodes can connect to each other in the presence of a large fraction of adversaries in the network.

Xie (2003) discussed how DHTs are implemented in P2P systems in his paper “P2P Systems based on Distributed Hash Table”. Files are connected with keys (which are generated by hashing the file name); each node in the system is responsible for storing a specific range of keys and handles a fraction of the hash space. The system will return the identity (e.g., the IP address) of the node storing the object with that key after a lookup for that key. The DHT capability allows nodes to put and get files based on their key and has shown to be a viable substrate for large distributed systems, with a number of projects proposing to overlay Internet-scale services on top of DHTs. Each node in a DHT is in charge of a specific key range and a portion of the hash space. Routing is a distributed lookup that is location-deterministic. Deterministic locating and load balance are the most significant improvements.

• No global knowledge

• Absence of single point of failures

**Blockchain**

Blockchains are a sort of decentralized distributed ledger and usually anonymous groups of agents rather than known centralized parties. This novel method of recordkeeping has introduced two economic innovations that overcome the two limitations of competition among centralized ledgers. The entry of record-keepers is unrestricted: any agent may write on the ledger as long as they follow a set of regulations. Furthermore, information on an existing blockchain is portable to a competing one. A software developer can propose to “fork off” an existing blockchain to establish one with different policies while retaining all the information contained in the original blockchain. Fork competition eliminates the inefficiencies arising from switching costs in centralized record-keeping systems (Abadi and Brunnermeier, 2018).

On an article “Blockchain Technology Overview” (Yaga et al. 2018), they mentioned four key characteristics of this technology:

• Ledger – the technology uses an append only ledger to provide full transactional history. A blockchain, unlike traditional databases, does not allow transactions and values to be overwritten.

• Secure – blockchains are cryptographically secure, ensuring that the data in the ledger has not been changed with and that the data is attestable.

• Shared – multiple participants will share the ledger. This provides transparency across the node participants in the blockchain network.

• Distributed – the blockchain can be distributed. This lets a blockchain network's number of nodes to be scaled up to make it more resilient to bad actors' attacks. By expanding the number of nodes, a bad actor's capacity to influence the blockchain's consensus procedure is lessened.

Like a traditional public ledger, blockchain is a series of blocks that carry a comprehensive list of transaction data. A block has just one parent block if the block header contains a preceding block hash. It's worth mentioning that hashes for uncle blocks (children of the block's ancestors) would be saved as well. The ﬁrst block of a blockchain is called genesis block which has no parent block (Zheng et al., 2017).

In the article of Monrat et al. (2019) titled “A Survey of Blockchain From the Perspectives of Applications, Challenges, and Opportunities”, they identified six comparison perspectives when comparing blockchain networks:

1. Consensus Determination - All the nodes can participate in the consensus process in the public blockchain such as Bitcoin, while only a few selected set of nodes are being responsible for confirming a block in the consortium blockchain. In the private blockchain, a central authority will decide the delegates who could determine the validated block.

2. Read Permission - Public blockchain allows read permission to the users, where the private and consortium can make restricted access to the distributed ledger. Therefore, the organization or consortium can decide whether the stored information needs to be kept public for all or not.

3) Immutability - In the decentralized blockchain network, transactions are stored in a distributed ledger and validated by all the peers, which makes it nearly impossible to modify in the public Blockchain. In contrast, the consortium and private Blockchain ledger can be tampered by the desire of the dominant authority.

4) Efficiency - In the public blockchain, any node can join or leave the network which makes it highly scalable. However, with the increasing complexity for the mining process and the flexible access of new nodes to the network, it results in limited throughput and higher latency. However, with fewer validators and elective consensus protocols, private and consortium blockchain can facilitate better performance and energy efficiency.

5) Centralized - The significant difference among these three types of Blockchain is that the public blockchain is decentralized, while the consortium is partially centralized and private blockchain is controlled by a centralized authority.

**Proof-of-Authority**

Proof of Authority (PoA) is a group of permissioned blockchain consensus algorithms that have gained popularity due to improved performance over traditional BFT algorithms due to fewer message exchanges. PoA was first proposed as part of the Ethereum ecosystem for private networks, and it was implemented in the Aura and Clique clients. The authorities are a group of N trusted nodes that PoA algorithms rely on. Each authority is identifiable by a unique id, and a majority of them, precisely at least N/2 + 1, is believed to be trustworthy. To execute the transactions issued by clients, the authorities run a consensus. The mining rotation schema, a commonly used way to fairly spread the burden of block creation across authority, is used to achieve consensus in PoA algorithms. Time is split into steps, each of which has a mining leader elected by the nodes. (Bitfury Group and Garzik, 2015).

There are two main PoA algorithms currently: AuRa and Clique. Aura (Authority Round) is the PoA algorithm implemented in Parity, the Rust-based Ethereum client. It is expected that the network is synchronous and all authorities to be synchronized within the same UNIX time t. The index s of each step is deterministically computed by each authority as s = t/step\_duration, where step\_duration is a constant determining the duration of a step. The leader of a step s is the authority identified by the id l = s mod N. Clique is the PoA algorithm implemented in Geth, the GoLang-based Ethereum client. The algorithm proceeds in epochs which are identified by a prefixed sequence of committed blocks. When a new epoch starts, a special transition block is broadcasted. It specifies the set of authorities (i.e., their ids) and can be used as snapshot of the current blockchain by new authorities needing to synchronize (De Angelis et al., 2018).

**Asymmetric Encryption**

Asymmetric encryption systems are typically employed for discreetly delivering a symmetric encryption scheme's session key for message encryption. In fact, asymmetric and symmetric encryption techniques are frequently used in practice. (Fujisaki and Okamoto, 2011).

Goldwasser and Micali (1984) discussed the symmetric (aka private-key) encryption scheme as follows. Given by a pair of algorithms, *Π* = (*E,D*), where for every sufficiently large *k* ∈ *N*,

• *E*, the encryption algorithm, is a probabilistic polynomial-time (in *k*) algorithm that takes secret key *a* ∈ KSP and message *x* ∈ MSP, draws coins *r* uniformly from coin space COIN, and produces ciphertext *y := Ea(x;r).* This experiment is written as *y* ← *Ea(x).* The key, message, and coin spaces, KSP, MSP and COIN, are uniquely determined by *k*.

• *D*, the decryption algorithm, is a deterministic polynomial-time (in *k*) algorithm that takes secret key *a* ∈ KSP and ciphertext *y* ∈ {0, 1}∗, and outputs message *x := Da(y).*

We require that a symmetric encryption scheme should satisfy the correctness condition: For every sufficiently large *k* ∈ *N*, every *a* ∈ KSP and every *x* ∈ MSP, we always have *Da(Ea(x)) = x*.

Bellare et al. (1998)detailed the asymmetric (aka public-key) encryption scheme. Given by a triple of algorithms, *Π = (K, E,D)*, where for every sufficiently large *k* ∈ N:

• *K*, the key-generation algorithm, is a probabilistic polynomial-time (in *k*) algorithm which on input *1k*outputs a pair of strings, (*pk,sk*), called the public and

secret keys, respectively. This experiment is written as (*pk,sk*) ← *K*(1*k*).

• *E*, the encryption algorithm, is a probabilistic polynomial-time (in *k*) algorithm

that takes public key pk and message *x* ∈ *MSP*, draws coins *r* uniformly from coin

space COIN, and produces ciphertext *y := Epk(x;r).* This experiment is written as *y ← Epk(x).* The message and coin spaces, MSP and COIN, are uniquely determined by *pk*.

• *D*, the decryption algorithm, is a deterministic polynomial-time (in *k*) algorithm that takes secret key *sk* and ciphertext *y* ∈ {0, 1}∗, and returns message *x := Dsk(y).*

We require that an asymmetric encryption scheme should satisfy the following correctness condition: For every sufficiently large *k* ∈ *N*, every (*pk,sk*) generated by *K*(1*k*)

and every *x* ∈ *MSP*, we always have *Dsk(Epk(x)) = x*.

**Decentralized Storage, Blockchain and Medical Records**

MedRec, a system proposed by Azaria el.al (2016) shows how principles of decentralization might be applied to largescale data management in an EMR system by using blockchain technology. It utilized Proof-of-Work consensus in mining transaction blocks. Patient data are stored in centralized SQL server while transaction logs of updating patient records are in the Ethereum blockchain. A study by Sharma et al. (2020) did a similar EMR model but introduced cloud storage as an alternative to a centralized on-premise server. These two studies posed limitations on storing files. Though Sharma attempted to solve this by putting a cloud application layer, Cloud providers will have autonomy to data stored in their servers.

Kumar and Tripathi (2020) presented a distributed framework handling COVID-19 patient reports. It utilized Proof-of-Work blockchain and IPFS to decentralize data storage. However, the system has no patient access interface and only shares data for provider use only. Wu and Du (2019) also added IPFS on their Delegated Proof-of-Stake blockchain implementation of EMR. They also used data-masking to protect patient data once uploaded on the network and specified Digital Imaging and Communications in Medicine (.dcm) image format of files to be uploaded. Like Kumar and Tripathi, system did not provide data access to patients.

Sun et al. (2020) proposed attribute-based encryption for EMRs with IPFS and blockchain implementation. The scheme provides good access control for the electronic medical records using attribute-based encryption technology so that people who are not related to the patient cannot see the private data of the patient without authorized. Khubrani (2021) proposed a proposed a theoretical blockchain-based framework via blockchain, IPFS and asymmetric encryption but did not mention technical specifications on how these technologies will integrate with one another.

At this point, related studies mentioned above either use Proof-of-Work (PoW) or Proof-of-Stake (PoS) as their consensus scheme for EMRs. A comparative study of existing literature for EMR system based from blockchain and IPFS was presented by Kumar et al. (2021). It compared different metrics such as Technology used, Cost-effectiveness, Complexity and Shortcomings. Most of the shortcomings were implementation-related such as lack of data formatting and workflow for data sharing, but the authors gave emphasis on the need of a cost-effective way to deploy blockchain as an immutable ledger since most of the studies were using Proof-of-Work as a consensus scheme.

On a paper by Al Asad et al. (2021), they proposed a theoretical blockchain-based framework with Proof-of-Authority (PoA) as the consensus scheme. It cited comparisons among other consensus (Proof-of-Work and Proof-of-Stake) and shown why PoA is a better alternative for EMRs. However, this paper only examined the feasibility of PoA consensus implementation and did not dwell on strategies for decentralized file storage and encryption. Reen (2019) on an earlier study, also mentioned PoA as an excellent choice for medical records. He made a conceptual model on IPFS as a decentralized file storage but did not provide technical specification about PoA and how it will be integrated in the system.

**Chapter Three**

**THEORETICAL FRAMEWORK**

**Present State of COVID-19 Tests and Vaccine Certificate Storage**

Documents and certificates given out by various units (private and public) for COVID-19 related tests such as antigen and Real-Time Polymerase Chain Reaction (RT-PCR) are still on paper-form. There are some units that store the results in their server and can be accessed online thru their website. Same is true with giving out vaccine certificates. Primary providers of vaccines are Local Government Units (LGUs) and they vary in implementation. Some only give out physical copies (certificates, cards) and others have virtual copies on their websites stored on their servers. There is a disconnect on a unified tracking of all these documents and might result to issues when these documents will be used on different areas of the Philippines. The usual proposition to solve this is to create a unified website that will be hosted in a central server.

**Proposed Documents Storage Structure**

**Figure 3.1 – Diagram of Proposed Solution**

Above is a summarized approach in solving the problem in document storage. The main components of this application will be the IPFS for file storage and blockchain to record the logs of transaction being done in the system.

The next sections will discuss the different algorithms and frameworks to be used in order to achieve the proposed solution.

**Cryptographic Hash Functions**

A cryptographic hash function is an algorithm which maps data of any size (often called the "message") to a bit array of a fixed size ("hash value", "hash", or "message digest"). It is a one-way function, that is, a function which is practically infeasible to invert or reverse the computation. Ideally, the only way to find a message that produces a given hash is to attempt a brute-force search of possible inputs to see if they produce a match, or use a rainbow table of matched hashes. Cryptographic hash functions are a basic tool of modern cryptography.

The ideal cryptographic hash function has the following main properties:

* it is deterministic, meaning that the same message always results in the same hash
* it is quick to compute the hash value for any given message
* it is infeasible to generate a message that yields a given hash value (i.e. to reverse the process that generated the given hash value)
* it is infeasible to find two different messages with the same hash value
* a small change to a message should change the hash value so extensively that a new hash value appears uncorrelated with the old hash value



**Figure 3.2 – Hashing Process**

Most cryptographic hash functions are designed to take a string of any length as input and produce a fixed-length hash value.

A cryptographic hash function must be able to withstand all known types of cryptanalytic attack. In theoretical cryptography, the security level of a cryptographic hash function has been defined using the following properties:

* Pre-image resistance

Given a hash value h, it should be difficult to find any message m such that h = hash(m). This concept is related to that of a one-way function. Functions that lack this property are vulnerable to preimage attacks.

* Second pre-image resistance

Given an input m1, it should be difficult to find a different input m2 such that hash(m1) = hash(m2). This property is sometimes referred to as weak collision resistance. Functions that lack this property are vulnerable to second-preimage attacks.

* Collision resistance

It should be difficult to find two different messages m1 and m2 such that hash(m1) = hash(m2). Such a pair is called a cryptographic hash collision. This property is sometimes referred to as strong collision resistance. It requires a hash value at least twice as long as that required for pre-image resistance; otherwise collisions may be found by a birthday attack.

**Blockchain**

In 2008, Satoshi Nakamoto released a whitepaper titled “Bitcoin: A peer-to-peer electronic cash system”. This paper proposed a system for electronic transactions which uses a peer-to-peer network. Participating nodes in the network utilize Proof-of-Work to record public history of transactions.

At its most basic level, blockchain technology permits a network of computers to have a consensus on the true status of a distributed ledger at regular intervals. Blockchain network users submit potential transactions to participating nodes. The network will then choose a publishing node to update the pending transaction. Once this is done, transaction will be propagated to non-publishing nodes. Transactions are logged chronologically – with information being passed from the first transaction (or blocks) up to the last. This repetitive process forms an immutable chain on which all blocks are interconnected with each other.

Transactions are inserted to the blockchain when a publishing node creates a block. A block may represent various types of data from simple texts to complicated ones such as digital rights or intellectual property. It is divided into two parts, header and body. Header contains metadata and body is for the actual data being persisted in the blockchain. Below is a typical specification of these 2 parts:

Block Header

* Previous block header’s hash value
* Hash representation of block data
* Timestamp
* Size of the block
* Nonce value. In Bitcoin and other Proof-of-Work blockchains, this is a number manipulated by the publishing node to solve the hash puzzle.

Block Data

* Actual data (text, files)

**Figure 3.3 – Generic Blockchain Transactions**

Figure 3.3 shows how blockchain works given we have a simple data of text. The first block is called the genesis block and is automatically generated upon the chain’s creation. This genesis block will be the seed and considered as reference of all blocks going forward. Blocks are linked through each block containing the hash value of the previous block’s header, thus creating the chain. In case a previously published block was changed, it will have a different hash. This will create a domino effect on all subsequent blocks to also have a different hash because they contain the hash of the altered block.

An essential part of the blockchain is identifying which user will publish the next block or become the next publishing node. This is solved by implementing a consensus model. The common model used is to compete on who will publish it and winning an incentive in doing so.

Once a user joins a blockchain network, they agree to the initial state of the system. This is recorded in the only pre-configured block or the genesis block. Each blockchain network have a genesis block on to which all subsequent blocks would reference to. Each block must be valid and can be validated independently by each blockchain network user.

The following properties of a consensus model are:

* The initial state of the system is agreed upon (e.g., the genesis block).
* Users agree to the consensus model by which blocks are added to the system.
* Every block is linked to the previous block by including the previous block header’s hash digest (except for the first ‘genesis’ block, which has no previous block and for which the hash of the previous block header is usually set to all zeros).
* Users can verify every block independently

**InterPlanetary File Storage (IPFS)**

IPFS is a distributed platform for storing and retrieving files, websites, applications and data. It has rules that regulate in what manner data and content move around on the network. These rules are comparable in nature to Kademlia, the peer-to-peer distributed hash table (DHT) that is widely known for its use in the BitTorrent protocol.

IPFS is essentially a peer-to-peer system for retrieving and sharing IPFS objects. An IPFS object is a data structure with two fields:

* Data: a blob of unstructured binary data of size < 256 kB.
* Links: an array of Link structures. These are links to other IPFS objects. Links have 3 sub-parts:
  + Name: the name of the Link.
  + Hash: the hash of the linked IPFS object.
  + Size: the cumulative size of the linked IPFS object, including following its links.

IPFS builds a Merkle DAG, a blend of a Merkle Tree and a Directed Acyclic Graph (DAG).

A Merkle tree summarizes all the transactions in a block by producing a digital fingerprint of the entire set of transactions, thereby enabling a user to verify whether or not a transaction is included in a block. Merkle trees are created by repeatedly hashing pairs of nodes until there is only one hash left (this hash is called the Root Hash, or the Merkle Root). They are constructed from the bottom up, from hashes of individual transactions (known as Transaction IDs). Each leaf node is a hash of transactional data, and each non-leaf node is a hash of its previous hashes. Merkle trees are binary and therefore require an even number of leaf nodes. If the number of transactions is odd, the last hash will be duplicated once to create an even number of leaf nodes.



**Figure 3.4 – Merkle Tree Implementation using hashes**

A directed acyclic graph (DAG) is a conceptual representation of a series of activities. The order of the activities is depicted by a graph, which is visually presented as a set of circles, each one representing an activity, some of which are connected by lines, which represent the flow from one activity to another. Each circle is known as a “vertex” and each line is known as an “edge.” “Directed” means that each edge has a defined direction, so each edge necessarily represents a single directional flow from one vertex to another. “Acyclic” means that there are no loops (i.e., “cycles”) in the graph, so that for any given vertex, if you follow an edge that connects that vertex to another, there is no path in the graph to get back to that initial vertex.



**Figure 3.5 – DAG Illustration**

A Merkle DAG is a DAG where each node has an identifier, and this is the result of hashing the node's contents — any opaque payload carried by the node and the list of identifiers of its children — using a cryptographic hash function like SHA256. This brings some important considerations:

* Merkle DAGs can only be constructed from the leaves, that is, from nodes without children. Parents are added after children because the children's identifiers must be computed in advance to be able to link them. Every node in a Merkle DAG is the root of a (sub)Merkle DAG itself, and this subgraph is contained in the parent DAG.
* Merkle DAG nodes are immutable. Any change in a node would alter its identifier and thus affect all the ascendants in the DAG, essentially creating a different DAG. Take a look at this helpful illustration using bananas (opens new window)from our friends at Consensys.
* Merkle DAGs are similar to Merkle trees, but there are no balance requirements, and every node can carry a payload. In DAGs, several branches can re-converge or, in other words, a node can have several parents.

Identifying a data object (like a Merkle DAG node) by the value of its hash is referred to as content addressing. Thus, we name the node identifier as Content Identifier, or CID.

**Figure 3.6 – Merkle DAG implemented on a file system**

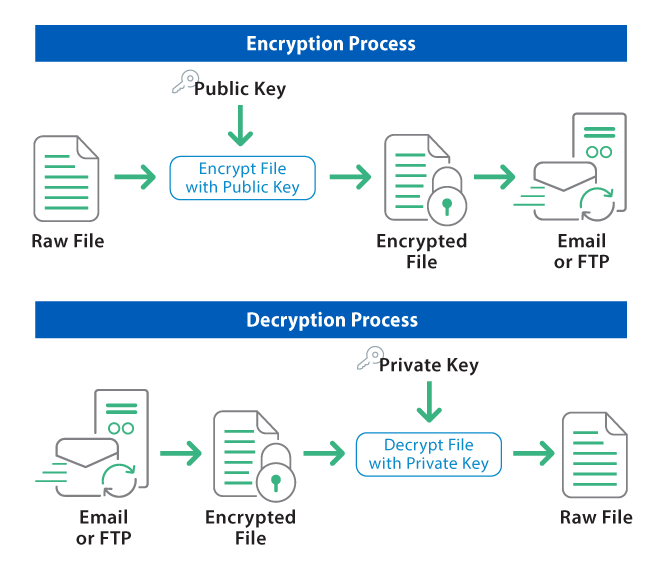
**Open Pretty Good Privacy**

OpenPGP is a key-based encryption method used to encrypt files so that only their intended recipient can receive and decrypt them. OpenPGP is used widely to secure e-mail communications, but its technology can also be applied to FTP.

OpenPGP works by using two cryptographic keys to secure files. A Public Key is used to encrypt the file so that only its corresponding Private Key can decrypt it.

The following is a step-by-step process of how OpenPGP Mode works with FTP.

1. The file to be uploaded is encrypted using a Public Key that the file's intended recipient has previously provided.
2. The encrypted file is uploaded to the FTP server.
3. The intended recipient retrieves the file from the FTP server.
4. Using the Private Key (which together with the Public Key used to encrypt the file initially comprises the Key Pair), the intended recipient decrypts the file and accesses its contents.

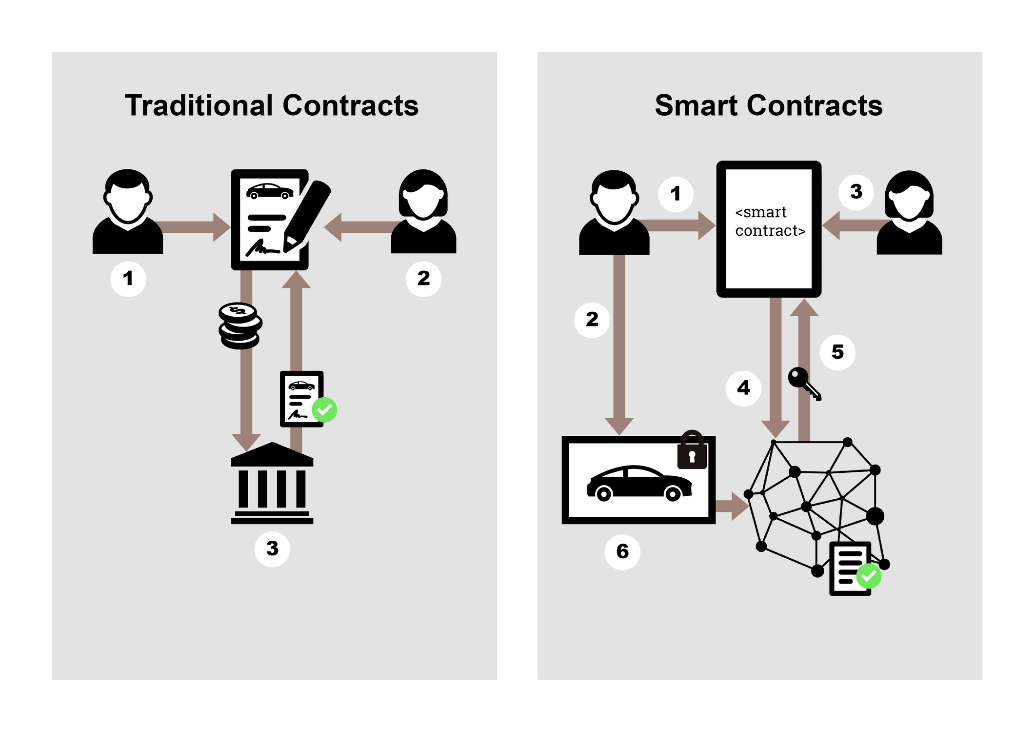


**Figure 3.7 – OpenPGP Two-way process**

**Smart Contract**

Smart Contract is a term used to describe computer code that automatically executes all or parts of an agreement and is stored on a blockchain-based platform. The code itself is replicated across multiple nodes of a blockchain and, therefore, benefits from the security, permanence and immutability that a blockchain offers. That replication also means that as each new block is added to the blockchain, the code is, in effect, executed. If the parties have indicated, by initiating a transaction, that certain parameters have been met, the code will execute the step triggered by those parameters. If no such transaction has been initiated, the code will not take any steps. Most smart contracts are written in one of the programming languages directly suited for such computer programs, such as Solidity.

If two individuals, Alice and Bob, do not know each other they also do not trust each other. When they want to make an agreement, they usually need a trusted third party that acts as intermediary. This intermediary verifies the transaction and can also enforce an action that was written into the agreement. With a smart contract in a blockchain, there is no need for a trusted intermediary because the clearing and settlement is automatically executed and enforced via blockchain technology.



**Figure 3.8 – Smart Contract comparison**

The following example in Figure shows the process of selling and buying a car between Alice and Bob. It also indicates the difference between a traditional contract and a smart contract. The comparison was originally created by BlockchainHub, this Figure was adopted by Braincept AG.

Traditional Contracts

1. Bob would like to sell his car.
2. Alice would like to buy a car.
3. A third party (intermediary) enables the trust that is needed in order to transfer the ownership of the car. Mostly different intermediaries are needed: motor vehicle registration authority, notary, insurance company. All middlemen take fees.

Smart Contracts

1. Bob would like to sell his car. He defines in a smart contract the conditions by which he will sell the car and signs the contract with his private key.
2. Bob leaves his car locked with a smart lock in his garage. The car has its own blockchain address and the smart lock is controlled by a smart contract.
3. Alice would like to buy a car. She finds Bobs car on an internet platform and signs the smart Bob’s contract with her private key. She adds the agreed amount from her blockchain address to Bob’s blockchain address.
4. As soon as the smart contract is executed the whole blockchain network will check if Bob is the real owner of the car and if Alice has enough money to buy the car.
5. If all peers in the blockchain network agree on the same state, it means that all conditions in the smart contract are met. The access code for the smart lock will be transferred to Alice and the blockchain address of the car will be registered to Alice. Bob will get the defined amount of money in his blockchain address.
6. Alice will be able to open the smart lock with her private key.

**Conceptual Framework**

This section aims to demonstrate the overview of the final product of this research. It identifies relevant variables, inputs, mappings and other components and how they will interact with each other. This includes all the underlying concepts and their associated mappings based on the system’s use.



**Figure 3.9 – Conceptual Framework**

The users of the proposed application will be patients, medical workers or other third-party requiring the patient to present a COVID-19 Test Result or Vaccine Certificate. The users will access the same application but with different levels of access depending on their role.

The input are the medical documents and distribution key. There will be different types of keys which will be discussed on Chapter 4. These keys will be used to authenticate and unlock or lock the files.

Once all required inputs are provided, the file will now go thru the necessary steps to access it. Depending on the type of transaction (insert a new file or retrieval), the keys provided should have enough privilege for it to succeed. The file hash will be then stored in the blockchain after going thru smart contracts. Once the blockchain successfully updated the network, provided file will now become an immutable component of both IPFS and blockchain network.

**Chapter Four**

**METHODOLOGY**

This chapter provides an overview of the strategies used to attain the study's goals. It describes the study's respondents as well as the research instruments that were used. It then goes on to explain the data collection strategies that contributed in the completion of the study endeavor.

**Figure 4.1 Prototype Model Phases and Process**

Figure 4.1 illustrates Prototype Model used by the researcher in developing the proposed study entitled “CoviBlock: A Blockchain and Peer-to-peer Platform for COVID-19 Test Results and Vaccine Records” which is under the family of System Development Life Cycle (SDLC). Prototyping was used to ensure faster turnaround time on each phase while addressing client’s requirements and feedbacks. This model also enables the researcher and client to have discussions in between development cycles.

The next sections of this chapter will discuss the phases of the used model.

**4.1 Requirements Modeling**

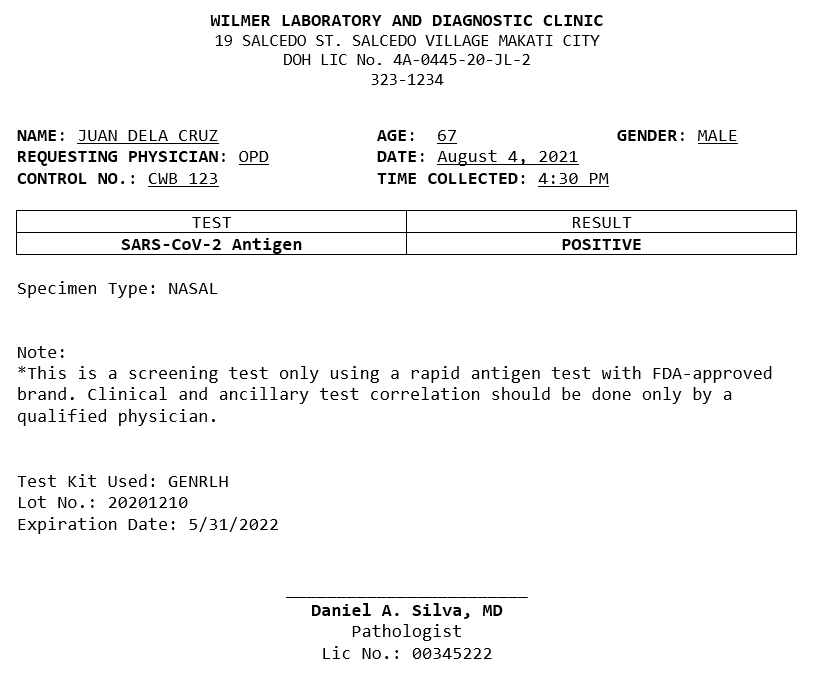
The Prototype Model starts with outlining the requirements. The researcher will conduct an initial investigation to determine the purpose and utilization of the application coupled with the nature and scope of the study. It is also in this stage that the researcher requested permission from medical unit authorities and other parties to conduct the study and all relevant data and information were examined.

Fact-finding was used via interviews and probing of processes to build a logical model of the application. With these interviews, the researcher was able to piece out a picture of transactions involved and analyzed them against the proposed solution. This information will also enable the researcher to identify critical decisions geared toward implementing the application.

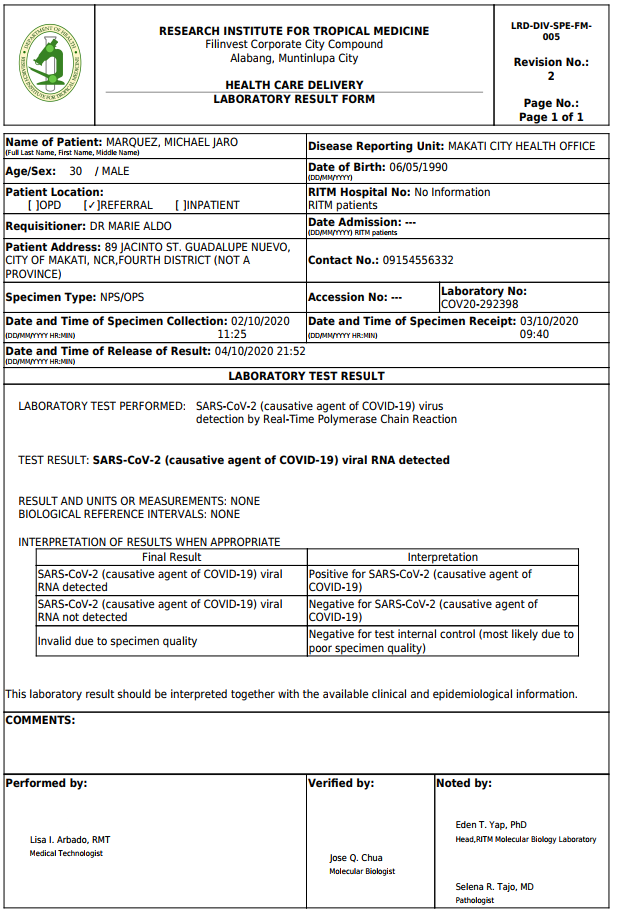
At present time, Ospital ng Makati does not have its own molecular laboratory to conduct independent COVID-19 tests. Instead, they forward test requests to their partner third party laboratories. Once requested by the patient from the hospital, they will either execute the tests in-house or hand-over the execution to the third-party lab. After results comes out, the hospital will furnish a physical copy to the patient whilst maintaining a softcopy in their archive.

For vaccination records, Makati citizens are encouraged to register online via the web portal. This will ensure a scheduled slot on a specified date. On the day of vaccination, patient will be checked up by a physician to ensure he is fit for vaccination. The physician’s findings are logged on the system. Upon issuing a go signal, patient can now be vaccinated. After vaccination, vaccination site will sign a vaccination card while tagging the patient in their system as fully vaccinated.

The study will be focused on two COVID-19 related records: Test Results and Vaccine Certificate. Mocked test data will be used and will only be for the purpose of this research. This is due to various privacy regulation such as Health Insurance Portability and Accountability Act (HIPAA). This is a United States created health law adopted by medical facilities in the Philippines.

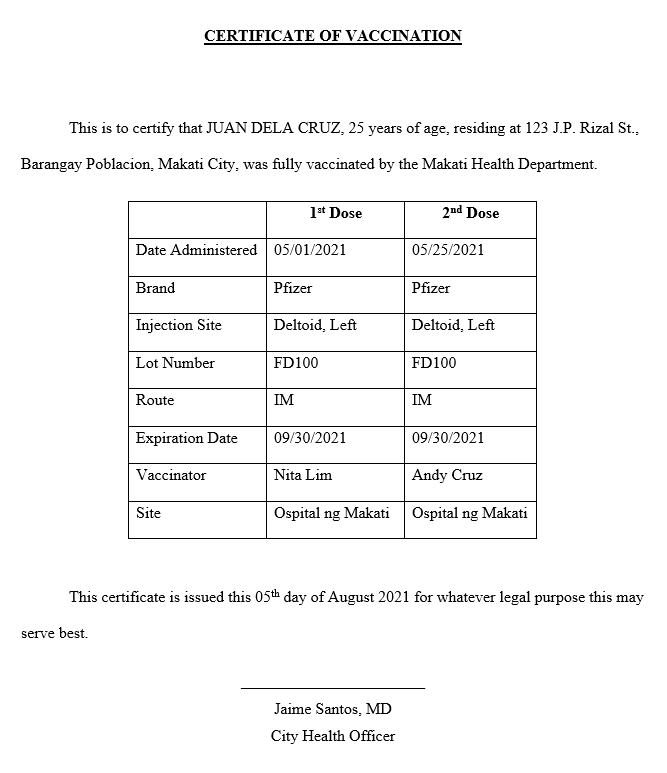


**Figure 4.2 – Sample Rapid Antigen Test Result**

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**Figure 4.3 - Sample Real-Time Polymerase Chain Reaction**

**(RT-PCR) Test Result**



**Figure 4.4 - Sample COVID-19 Vaccination Certificate**

Once above files are generated from existing system or printed by medical volunteers or workers, it is now ready to be consumed by the application.

Below are requirements grouped by specific role:

Patient

* Register and Login – register to gain access to the system
* Grant Access – Grant access to file requestors
* View Own Record – Get access to own results/certificate

Verifying Third Party

* Register and Login – register to gain access to the system
* View Patient Record – retrieve and view patient record if was given access

Physician/Medical Unit

* Register and Login – register to gain access to the system
* Upload record – upload a record for the patient

**4.1.1 Data Storage Scheme**

Since the study is primarily concerned on how medical records will be stored, this section will discuss the different schemes that will be used in the application. This will involve simulation, graphical visualizations and detailed discussions.

**4.1.1.1 IPFS – Merkle DAG**

The algorithm used in IPFS to manage content and assets is Merkle DAG. Suppose we want to upload 2 vaccine certificates. For brevity, we will use a small size text file to better illustrate the process. The default chunk size of IPFS is 256Kb but in this example we will reduce it to 32Kb to have appropriate representation using small sample files.

File 1

Name: cert\_allen\_smith.txt

Size: 86 bytes

Content:



File 2

Name: cert\_john\_doe.txt.txt

Size: 83 bytes

Content:



Generated Details for cert\_allen\_smith.txt:

|  |  |  |
| --- | --- | --- |
| Node Type | Size (Bytes) | Hash |
| Root | 0 | [QmZkJLp7PJGMc3mMSxTeLtyQCRqZ5CudGdjPB3jjTSFaoX](https://cid.ipfs.io/#QmZkJLp7PJGMc3mMSxTeLtyQCRqZ5CudGdjPB3jjTSFaoX) |
| Links | 32 | [QmdsyzBk5nWmC7a92gaAuRHxWTQu6e4wwyv2bVmZtF7mcq](https://cid.ipfs.io/#QmdsyzBk5nWmC7a92gaAuRHxWTQu6e4wwyv2bVmZtF7mcq) |
| Links | 32 | [QmPsFk9hcP4WmN96r8mXYjV5rKCNNb94c95jfqLBNZvigT](https://cid.ipfs.io/#QmPsFk9hcP4WmN96r8mXYjV5rKCNNb94c95jfqLBNZvigT) |
| Links | 22 | [QmVVrfBPAnF5DC1DXDZH2yftW6MEoCSKXEQEbY5LKfFzAt](https://cid.ipfs.io/#QmVVrfBPAnF5DC1DXDZH2yftW6MEoCSKXEQEbY5LKfFzAt) |

**Table 4.1 – Generated Hash Value for Sample Record #1**

Generated Details for cert\_john\_doe.txt:

|  |  |  |
| --- | --- | --- |
| Node Type | Size (Bytes) | Hash |
| Root | 0 | [QmanmTVLostTHeeLiz8vr99QDWmVbmbd53rSA2iFoDcmXu](https://cid.ipfs.io/#QmanmTVLostTHeeLiz8vr99QDWmVbmbd53rSA2iFoDcmXu) |
| Links | 32 | [QmdsyzBk5nWmC7a92gaAuRHxWTQu6e4wwyv2bVmZtF7mcq](https://cid.ipfs.io/#QmdsyzBk5nWmC7a92gaAuRHxWTQu6e4wwyv2bVmZtF7mcq) |
| Links | 32 | [QmTfDsTDe3nVu7b3hij43R3mBzyhJZgVm9eFBewVb5FfKV](https://cid.ipfs.io/#QmTfDsTDe3nVu7b3hij43R3mBzyhJZgVm9eFBewVb5FfKV) |
| Links | 32 | [QmRF3DNTkA43a7AG26uva4n7pgR22ctz6PjZW4KMuN5Cvu](https://cid.ipfs.io/#QmRF3DNTkA43a7AG26uva4n7pgR22ctz6PjZW4KMuN5Cvu) |

**Table 4.2 – Generated Hash Value for Sample Record #2**

We can now map out the links with their respective roots. Notice that link “Qmdsy” is referenced by both root objects.



**Figure 4.5 – Merkle DAG representing sample records**

**4.1.1.2 Blockchain**

The main purpose of using a blockchain is to validate whether a given or requested CID is authentic in the context of the system. After a doctor uploads a record in IPFS, the generated IPFS CID will then be logged to the blockchain. Blockchain validation will then be used as a proof that a CID exists in the context of CoviBlock. This will prevent illegal tampering or modification of records.

Taking our sample files from 4.1.1.1, we will create a blockchain of transactions given the files were already uploaded to IPFS and CIDs are generated. JSON Objects will be used as format of the payload.

Object for cert\_allen\_smith.txt:

{

“CID”: “[QmZkJLp7PJGMc3mMSxTeLtyQCRqZ5CudGdjPB3jjTSFaoX](https://cid.ipfs.io/#QmZkJLp7PJGMc3mMSxTeLtyQCRqZ5CudGdjPB3jjTSFaoX)”,

“MedPerson”: “Dr. Ramon Cruz”,

“LicenseNum”: “123-456”,

“DateTime”: “23/07/2021 14:00:00”

}

Object for cert\_john\_doe.txt:

{

“CID”: “[QmanmTVLostTHeeLiz8vr99QDWmVbmbd53rSA2iFoDcmXu](https://cid.ipfs.io/#QmanmTVLostTHeeLiz8vr99QDWmVbmbd53rSA2iFoDcmXu)”,

“MedPerson”: “Dr. Erik Lim”,

“LicenseNum”: “122-322”,

“DateTime”: “23/07/2021 09:00:00”

}

**4.2 Quick Design**

After identifying the requirements, a design of the proposed application is created. This is not a detailed design with complete technical specifications but a simplified one with critical aspects of the solution. This phase will give a bird’s eye view to the client of the application.

**4.2.1 Context Diagram**

**Figure 4.6 – Context Diagram**

The context diagram shown in Figure 4.6 summarizes the application on inputs and outputs of the system and targeted users. On general, users of the application will be required to provide public/private keys and raw files to be stored. It is now the application will trigger and execute various processes to upload, encrypt/decrypt, or release files. Note that this is a general illustration of inputs and outputs. Next sections of this chapter will discuss the mentioned processes on this diagram.

**4.2.2 Data Flow Diagram**

**Figure 4.7 – Data Flow Diagram**

Figure 4.7 illustrates how various types of users receives and provides information to the application and how the application provides and receives data from users. This also mentions the executing process to generate the data.

It is important to note that authorized medical personnel are the only ones allowed to upload files. Patients will have to generate private and public keys for their files to be uploaded or requested. These keys are crucial for a patient file to be encrypted or decrypted. Third parties can request for patient files and will be granted access to view decrypted files.

**4.2.3 Use Case Diagram**

**Figure 4.8 – Proposed Use Case Diagram**

The suggested application's development is not solely dependent on the system's functionality. It also depends on the workflow procedure that needs to be identified, implemented, and followed. The components of the proposed application “CoviBlock: A Merkle Dag and Blockchain Implementation for COVID-19 records”, is demonstrated in Figure 4.x and utilized a Use Case Diagram. The patient, being the central user of this system will provide appropriate keys with reference to the executing process. These in turn can trigger uploading or granting of view access to either medical unit or a third party.

**4.2.4 Transactional Operation Diagram**



**Figure 4.9 – Transactional Operation Diagram**

Figure 4.9 illustrates the operations that exist in the proposed application. It is divided according to the users triggering the process (A. B. C). The crucial process of generating the private and public keys will be prompted by the patient. Without these keys, medical personnel cannot upload files which in turn, the third parties will not be able to request any files.

**4.2.5 System Flowchart of the Proposed Application**



**Figure 4.10 – Key Generation Process Flowchart**



**Figure 4.11 – Third party access to patient file Flowchart**



**Figure 4.12 – File Uploading Flowchart**



**Figure 4.13 – File Retrieval Flowchart**

For the key generation process illustrated in figure 4.10, once the user generates keys it will then go to separate storages. Public key will be saved to the application database while private key will be the user’s responsibility to store securely. Figure 4.11 details how a third party can request for files. Logs from the blockchain will be displayed to the third party that has information about files available for viewing. They will choose the file they want to access, and a request will be sent to the patient. The application will notify the patient that a request is sent to access their files and will be asked to provide keys. It will be patient’s discretion if they will grant the request. If patient agrees, they will provide the private key to be used in decrypting the file requested.

Figure 4.12 illustrates how the application will handle uploading of files. Authorized medical personnel will trigger the upload. The application will check if the patient being referenced by the record has an existing public key. If yes, it will proceed on encrypting it using the key and uploading the encrypted file to IPFS. IPFS will generate a hash of the uploaded file. This hash will then be stored as a transaction in the blockchain. Figure 4.13 shows how the application will handle retrieval of files. The patient will provide the private key to enable decryption of files retrieved from IPFS.

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